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ASPECTS OF NATURAL VENTILATION IN PASSIVELY HEATED BUILDINGS

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1 Summary

Ventilation plays an important role in ensuring the health and well being of building occupants. In the passively heated home, ventilation and air movement may additionally be expected to transfer heat from the solar areas to the living space. The objective of this paper is to outline some of the basic physical concepts behind ventilation and to present some simple examples illustrating how these concepts can be applied to the optimum ventilation of solar buildings. The discussion concentrates on natural ventilation systems and provides some indication of the range of ventilation rates that can be expected for the weather conditions appropriate to the winter climate of the United Kingdom. The basic equations necessary for design calculations are presented.

2 Introduction

Ventilation plays a vital role in the health and well-being of building occupants. Apart from its essential need for the support of metabolism, a continuous supply of fresh air is needed to dilute and purge internal pollution. On the other hand, excessive ventilation is responsible for significant heat loss and for generally cold and draughty living conditions which could equally result in deleterious health problems. Careful design of ventilation approach is therefore essential if optimum conditions of health and comfort are to be attained. In addition to these stringent requirements, the passively solar heated building may ultimately rely upon ventilation and air movement to provide the medium of heat transfer. While mechanical assistance may be utilized for such a task, frequently in keeping with the passive nature of building operation, this too can be expected to be naturally driven. Thus a very complex pattern of air flow must be established to fulfill the combined needs of health, comfort, energy efficiency and heat transfer. The objective of this paper is to consider some of the mechanisms involved in the movement of air and to outline practical methods of analysis of ventilation configurations as appropriate to the passively heated building. The intention is to provide some numerical guidance which may usefully be applied at the design stage.

3 Existing Practices

In the UK there is very little in the way of formal ventilation, especially for dwellings. Requirements of the current building regulations[1] are very sketchy and tend to assume that needs will be met either by natural infiltration or by the occupant use of windows. Both approaches are very haphazard and are unlikely to produce the required air flow patterns for optimum heat transfer or, indeed, for good indoor air quality. In countries such as France and the Netherlands, naturally ventilated buildings must generally be fitted with purpose provided ventilation stacks. These are designed to promote the effect of stack action with the chimneys being designed to terminate within the negative pressure region, above the roof space.

In countries afflicted with a severe climate, such as Canada and parts of Scandinavia, the sealed building with purpose provided mechanical ventilation has become increasingly common. These offer complete control over air flow and provide the opportunity for heat recovery as a means to reduce energy consumption. The resultant energy savings offset part of the additional installation and running costs, therefore making them a generally attractive technique. Unfortunately, at current costs and building quality, such a method is less likely to be as cost effective (or possibly even energy effective) in the UK, especially at the lower end of the housing market. However, future trends towards improved building quality, competitive pricing of mechanical ventilation systems and the integration of heat recovery with domestic central heating systems[2] could alter the economics at some future date. In the meantime, passive ventilation with, possibly, basic mechanical assistance in the form of extract fans, probably offers the most viable alternative for the UK climate. Additionally, and perhaps most importantly, this approach demands the least user intervention and is therefore the least likely of all methods to be abused or misused by the occupant.

4 Concepts

The natural ingress of air into buildings is dependent on climatic conditions, topography, surrounding obstructions, overall building airtightness and the type and distribution of openings. Each of these parameters may normally be analysed in sufficient detail to predict ventilation rates and air flow patterns. Also, by careful design and construction, the driving forces of wind and temperature can be harnessed to provide a measure of controlled ventilation. The various theoretical concepts and an example of their application is presented in the following sections.

5 Air Flow

Air flow through openings is commonly described by a power law equation of the form

$$Q = k(\Delta p)^n \quad m^3/s \qquad (1)$$

where Δp = pressure difference across opening (Pa)
k = flow coefficient
n = flow exponent

The flow coefficient, k, provides a measure of the size of the opening, while the flow exponent, n, is dependent on the nature of flow. For fully turbulent flow, as may be experienced for example through a discrete opening such as a vent, the flow exponent takes on the value of 0.5, whereas for laminar flow, such as may be experienced through a narrow crack with a relatively long flow path, the flow exponent takes on a value of unity. If all the openings in a typical UK dwelling were to be aggregated, as is the case when the air leakage performance of the building is tested by artificial pressurization, then the overall flow coefficient is normally found to have a value in the range 0.6 to 0.7.

Sometimes a quadratic formulation of the flow equation is preferred, in which the laminar and turbulent flow parameters are separated. Such an equation can be expressed in the form

$$\Delta p = \alpha Q + \beta Q^2 \tag{2}$$

where α, β are constants.

No matter which flow equation is used, the approach to calculating the rate and magnitude of air flow into buildings is identical.

6 Flow Openings

Ideally, the location, size and flow characteristics of each opening should be defined. In practice, however, this is rarely possible and, instead, an approximation or an amalgamation of flow paths is almost always necessary. In general it can be assumed that the larger the total area of openings, the greater will be the infiltration rate for any given set of external conditions. However, this relationship need not be linear and depends to some extent on the flow characteristics of each opening and on the distribution of openings. For accurate results, it is essential that all sources of air infiltration are identified.

Flow paths may usefully be analysed in terms of component openings such as vents, grilles, flues, etc. about which the designer has total knowledge, and "background" or "adventitious" openings which creep in during building construction. It is this latter source of infiltration which causes the most difficulty in flow path analysis. Organisations in many countries now define background leakage in terms of air changes/hour (ach) at a specified reference pressure. This is determined by building pressurization in which a suitably rated fan is used to create incremental pressure differences between the interior and exterior of a building in the ± 10-100 Pa range. For each pressure increment the corresponding air flow rate through the fan is measured. The instrumentation is frequently built into a door (blower door) which is temporarily placed in an existing entrance to the building. In Sweden and Norway such testing is mandatory for new dwellings and Swedish requirements demand that background leakages in single family dwellings should not exceed 3 ach at 50 Pa. The natural ingress of air through such a building would be insufficient to meet normal occupancy requirements, therefore legislation also requires that ventilation requirements are satisfied by the installation of either mechanical or purpose provided stack ventilation. In the United Kingdom, where purpose provided ventilation is less common, airtightness regulations do not exist, although BRE Digest No.306[3] recommends values in the range 10-20 ach at 50 Pa. In the design of a passively heated solar home, something closer to the Swedish requirements for background air leakage, with the addition of component openings, would be necessary to promote optimum air flow patterns. Although the diversity of construction techniques used in the United Kingdom adds to the range of leakage values likely to be found, with careful construction and choice of materials, leakage values of below 10 ach at 50 Pa are easily achievable. Guide values (assuming good quality construction) would be 8 ach at 50 Pa for an insulated brick and block dwelling with weatherstripped windows and doors, and 3 ach at 50 Pa for a weatherstripped timber frame construction with a continuous internal polyethylene vapour barrier. From a design aspect, values such as these may be used. On completion of construction, the initial air leakage specification should be verified by pressurization testing and remedial adjustments made where necessary.

For calculation purposes, the adventitious or background leakage component may be distributed linearly about the exposed surfaces of the building. These surfaces normally include the top floor ceiling, the exterior walls and the ground floor (if ventilated). Within the limitations of this approximation, party walls are normally assumed to be sealed. Purpose provided openings are then distributed according to the designers proposals, their dimensions and location being precisely known.

Since air flow into a building must be exactly balanced by the flow rate out of the building, the application of equation (1) to each of the flow paths yields

$$\sum_{i=1}^{j} k_i \, (p_{i_{ext}} - p_{int})^{n_i} = 0 \qquad (3)$$

where a well mixed single interior zone is assumed and

j = total number of flow paths

$p_{i_{ext}}$ = external pressure acting on flow path, i.

p_{int} = internal pressure of zone

k_i and n_i = flow coefficient and exponent of the i'th flow path

If the interior of the building itself is divided into identifiable zones separated by flow resistances, then the flow balance equation (3) must be applied to each zone.

7 Driving Forces

The forces driving natural air exchange are maintained by the action of wind and temperature.

7.1 Wind pressure

Relative to the static pressure of the free wind, the pressure resulting from wind impinging on the surface of a building is given by

$$p_w = \frac{\rho}{2} C_p V^2 \quad \text{(Pa)} \qquad (4)$$

where ρ = air density (kg/m^3)
C_p = pressure coefficient
V = wind speed at a datum level (usually building height)(m/s)

Since the strength of the wind close to the earth's surface is influenced by the roughness of the underlying terrain and the height above ground, a reference level for wind velocity must be specified for use in the wind pressure calculation. In UK natural ventilation studies, a roof height wind speed value is recommended[4]. However, as a rule "on site" data is rarely available and therefore measurements taken from the nearest climatological station must be applied. It is essential that such measurements are corrected to account for any difference between measurement height and building height and to account for intervening terrain roughness. By nature of the square term in equation (4) wind pressure is very sensitive to the wind velocity and, as a consequence, the arbitrary use of raw wind data will invariably give rise to misleading results. This is, perhaps, one of the most common causes of error in the calculation of air infiltration rates. An appropriate correction is given by

$$\frac{V}{V_m} = \alpha z^{\gamma} \qquad (5)$$

where α and γ are coefficients according to terrain roughness and

z = datum height, i.e. building height (m)
V = mean wind speed at datum height (m/s)
V_m = mean wind speed at local weather station (m/s at 10m above surface)

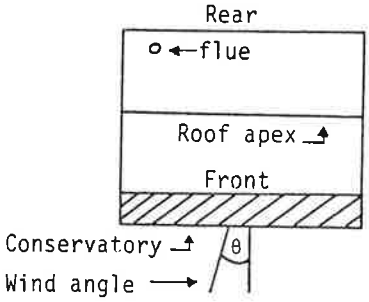
Such an approach is generally acceptable for winds measured between roof height and a recording height of 10m. It is inappropriate for the reduction of wind speeds measured in the upper atmosphere.

The pressure coefficient, C_p, is an empirically derived parameter which is a function of the pattern of flow around the building. It is normally assumed to be independent of wind speed but varies according to wind direction and position on the building surface. It is also significantly affected by neighbouring obstructions with the result that similar buildings subjected to different surroundings may be expected to exhibit markedly different pressure coefficient patterns. Accurate evaluation of this parameter is one of the most difficult aspects of air infiltration modelling and, as yet, is not possible by theoretical means alone. Although pressure coefficients can be determined by direct measurements of buildings, most information comes from the results of wind loading tests made on scale models of isolated buildings in wind tunnels. Examples of such coefficients for simple building shapes are given in BS5925[4]. However, there are limitations regarding the applicability of these results in infiltration studies, since very often no consideration is given to the shielding effects of surrounding obstructions. Nothwithstanding these problems, information based on the results of data presented at a wind pressure workshop[5] has been used to compile basic data for low rise buildings exposed to varying degrees of shielding and wind direction[6]. An example of the data is presented in Table 1 and may be used in conjunction with equation (4) to calculate wind pressures on buildings surrounded by structures of similar height.

TABLE 1 Wind Pressure Coefficient Data

Low rise building (up to 3 storeys)

Length to width ratio : 1:1 to 1:5
Shielding condition : Surrounded by buildings of equal height
Wind speed reference level : Building height
Roof pitch angle : ∿11° - 30°



Location	Wind Angle θ			
	0°	90°	180°	270°
Wall (front)	+0.2	-0.25	-0.25	-0.25
Wall (rear)	-0.25	-0.25	+0.2	-0.25
Roof (front)	-0.3	-0.5	-0.3	-0.5
Roof (rear)	-0.3	-0.5	-0.3	-0.5
Flue (dependent on level above roof)	-0.3	-0.3	-0.3	-0.3

(Further data covering side walls and intermediate wind directions published in ref. 5)

7.2 Stack pressure

The stack effect arises as a result of differences in temperature and hence air density between the interior and exterior of a building. This produces an imbalance in the pressure gradients of the internal and external air masses, thus creating a vertical pressure difference. When the internal air temperature is higher than that of the outside air mass, air enters through openings in the lower part of the building and escapes through openings at a higher level. This flow direction is reversed when the internal air temperature is lower than that of the air outside. The level at which the transition between inflow and outflow occurs is defined as the neutral pressure plane. In practice, the level of the neutral plane is rarely known although it can be predicted for straightforward leakage distributions. More generally, the stack pressure is expressed relative to the level of the lowest opening or to some other convenient datum (for example ground level). Taking two openings in the envelope of a building at levels h_1 and h_2 respectively, the stack induced pressure difference is given by

$$p_s = -\rho_o g \, 273 \, (h_2 - h_1) \left(\frac{1}{T_{ext}} - \frac{1}{T_{int}} \right) \text{(Pa)} \quad (6)$$

where T_{ext} = absolute external pressure (K)
T_{int} = absolute internal pressure (K)
ρ_o = air density at 273K (6°C)
g = acceleration due to gravity (m/s^2)

7.3 Relative magnitude of stack and wind pressures in the urban environment

Table 2 illustrates the relative magnitudes of pressure due to wind and temperature that act on the envelope of a typical low rise building located in an urban environment. Both mechanisms are clearly comparable in strength although for winter periods the driving force due to temperature will normally be expected to provide the dominant flow mechanisms.

TABLE 2 Comparison Between Relative Strengths of Wind and Stack Pressures

Building height	6.6m
Vertical height of openings :	5m
Urban terrain	

(a) Wind Pressure

Wind (m/s)		Wind Pressure (Pa)			
		Wall		Roof	
Met. Station (10m)	Roof height (6.6m)	front	rear	front	rear
1	0.56	0.04	-0.05	-0.06	-0.06
2	1.12	0.2	-0.2	-0.2	-0.2
4	2.24	0.6	-0.8	-0.9	-0.9
10	5.61	3.8	-4.8	-5.7	-5.7

(b) Stack

Temperature Difference (K)	Pressure (relative to lowest opening)(Pa)
5	-1.1
10	-2.2
15	-3.3
20	-4.3

8 Example

The basic theory and data presented in the preceeding sections may be readily applied to the design of natural ventilation. The example considered in this section is a passively heated, naturally ventilated dwelling comprising a south facing conservatory, living accommodation and a ventilated roof void. Construction to the Swedish airtightness standard of 3 ach at 50 Pa is assumed and the combined living and conservatory volume is approximately 350 m^3.

The ideal ventilation design criteria are

- sufficient ventilation in all rooms to dilute and disperse internally created pollution
- movement of warm air from heated conservatory to living area
- uniform ventilation rate
- removal of moisture at source

A possible solution is illustrated in Figure 1 in which air inlets are placed at a level of between 0 and 1m above floor level in the conservatory and corresponding air outlets are located in the top floor ceiling. The roof void is ventilated using a combination of roof ridge and roof tile ventilators. This configuration maximises the roof void suction relative to the conservatory for both wind and stack effect. Furthermore the direction of air flow is invariant to wind direction and in essence follows the desired flow route. The low level of conservatory vents enhances stack flow and eliminates the possibility of stack induced return flow resulting from the conservatory air temperature being at a higher temperature than the living space. The results of a simple analysis of this network, based on the solution of equation (3) is presented in Figure 2. This illustrates the ventilation performance in terms of air changes/hour for the range of wind conditions and internal/external temperature differences most likely to be experienced. Two wind scales are presented; these represent the Meteorological Office value based on 10m measurements made at the nearest measurement station and the corresponding local roof height value based on the assumption of an urban terrain and a 6.6m building height. The total open areas of vents are 500 cm^2 for the conservatory and 500 cm^2 for the ceiling. If adequate ventilation is taken as between 0.5 and 1.0 ach, then these conditions are met subject to temperature differences of greater than 10°C between the living space and the outside. Wind ventilation is seen to be highly variable but in itself is not a major consideration in terms of overall air change rate, provided that the building is surrounded by similar sized obstructions. The main benefit of this configuration as regards wind, however, is that the airtight construction and placement of vents minimises the risk of backdraughting due to northerly winds.

Although the particular ventilation pattern satisfies the general air flow requirement and provides for an overall air change in the 0.5 to 1.0 ach range, it does present some fundamentally undesirable features. Of particular concern is the chance of excessive moisture entering the roof space, with the consequent risk of condensation. Secondly, zones away from the immediate vicinity of the conservatory are likely to be poorly ventilated since there are no exit paths. Both problems can be reduced by adopting the approach outlined in Figure 3. In this example, the moisture producing areas, i.e. the kitchen and bathroom, are positioned on the north facing side of the building and are vented directly to the outside via ventilation stacks. Some ceiling porosity is still required but internal moisture migration is much reduced while flow paths to the remote rooms are also established. The general magnitude of air change rates remains essentially as with the previous example. Examples such as these may be readily analysed by straightforward consideration of the flow equations and driving forces as presented in this paper. For more specific information on calculation techniques and design data, the reader is referred to the Air Infiltration and Ventilation Centre's Calculation Techniques Guide[6].

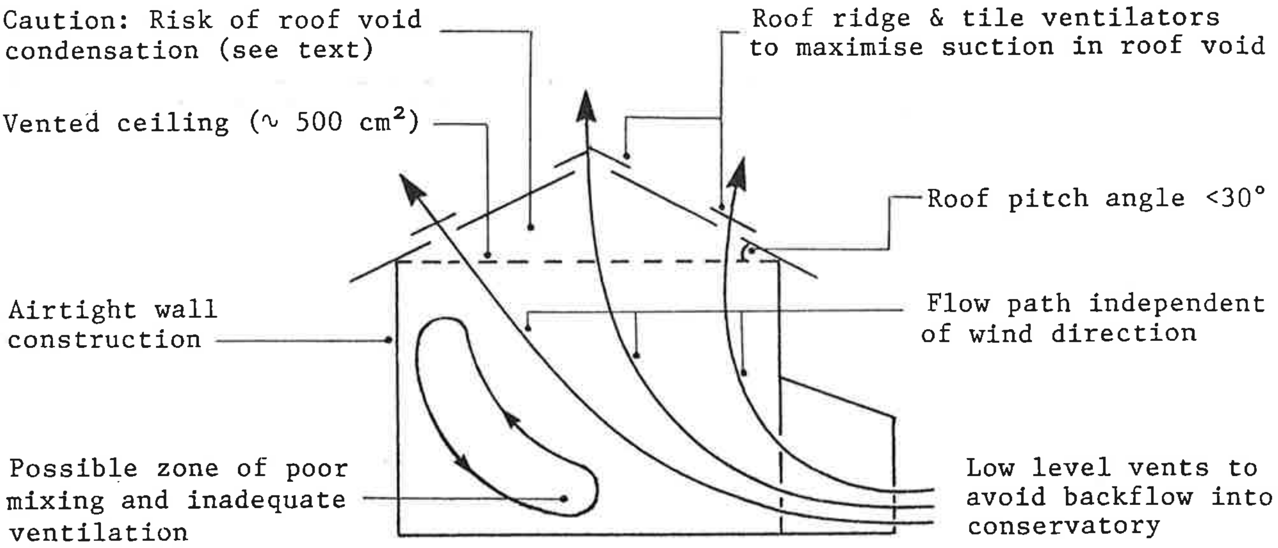


Figure 1 Designing for natural ventilation:- vented ceiling

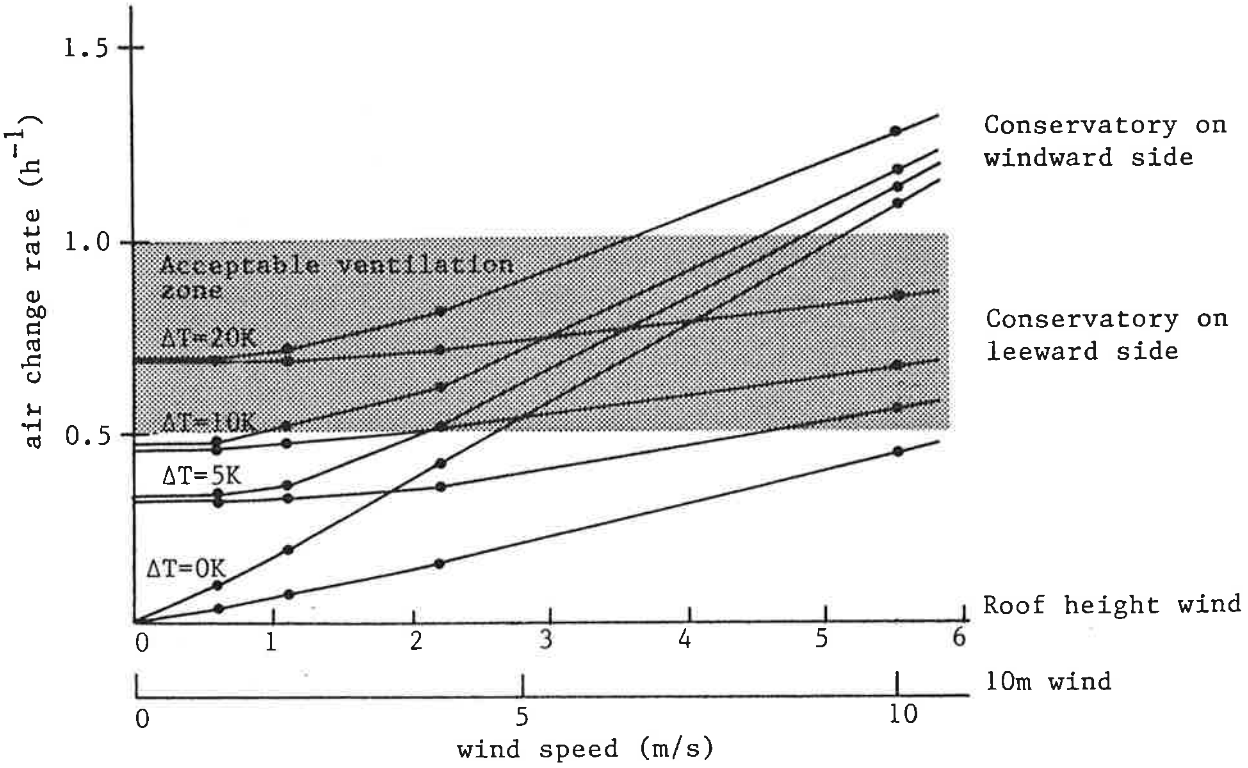


Figure 2 Ventilation characteristics for naturally ventilated building

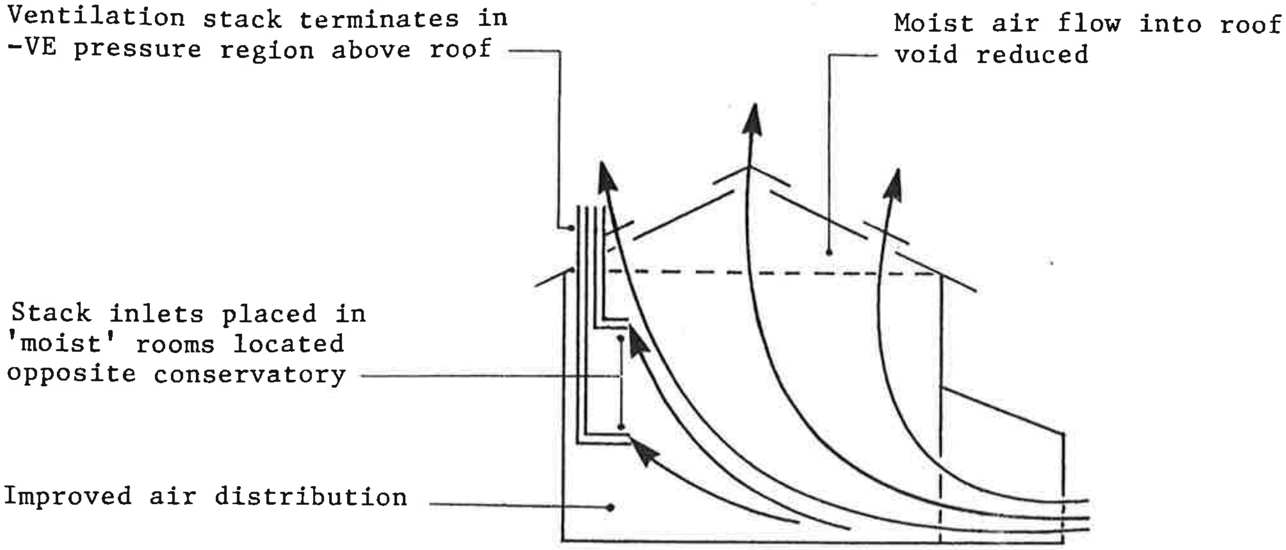


Figure 3 Designing for natural ventilation:- stack

9 Conclusions

Ventilation is of vital importance in any building and its role in passively heated buildings is particularly demanding. Nevertheless, ventilation needs can be adequately met without serious difficulties and appropriate design configurations can be readily assessed using relatively simple flow equations.

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