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INFILTRATION-PRESSURIZATION CORRELATION: SURFACE PRESSURES AND TERRAIN EFFECTS

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ABSTRACT

Expressions for theoretical predictions of infiltration due to combined stack and wind effects are derived. The surface pressure distribution around the shell of a structure can be estimated from measurements of the neutral pressure levels and weather and terrain parameters. A simple linear model of infiltration is used to calculate the infiltration from the surface pressure distribution and leakage measurements. An experimental procedure is outlined for measuring the neutral level.

Keywords: Neutral pressure level; Terrain effects; Leakage; Pressurization; Modeling; Correlation; Weather

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INTRODUCTION

In the past, the main concern for studying air flow around buildings has been to describe wind loads for design purposes, to locate intake and exhaust ports for HVAC systems, and to insure adequate stack effect for combustion processes. Recently, designing for energy conservation has underlined the importance in understanding how air flow around buildings affects heat loss through infiltration.

The energy consumption due to air infiltration can be a significant amount (20-40%) of the energy consumed in single-family dwellings. Reduction of this energy use will come through improved design, improved construction practices, and through improvements in existing buildings. In this paper we look at the effect of air flow around buildings on air infiltration for residential construction.

Two general procedures exist to test for infiltration—pressurization air leakage (both AC and DC types) and tracer gas concentration measurements. Several research groups are attempting to determine if it is possible to find a correlation between air leakage rates using fan pressurization and infiltration rates measured using a tracer gas.

Many reasons motivate the search for a correlation between the two procedures. The most important is the relative simplicity of the pressurization technique when compared to an infiltration measurement made with a tracer gas. In the pressurization technique a pressure difference is achieved by temporarily sealing a fan to the building shell. Mass flow continuity then predicts that the air flow rate through the fan is equal to the air leakage rate of the structure at the working pressure difference. A fan pressurization measurement of air leakage is not an analog of natural infiltration because the pressure distributions on the building shell are quite different in the two cases. In the first, the pressure over the entire shell is quite uniform while in the second, the pressures vary in a complicated manner both in space and in time. But measurements of air leakage in two structures using the same working pressure does allow one to compare the two structures. If this comparison can also be used to predict comparative air infiltration rates for the two structures then the fan pressurization measurement will be very useful, indeed.

We are currently attempting to find a correlation by investigating the relationship between infiltration rates and surface pressures on a building. Measurement of the air leakage of the building shell as a function of pressure yields an average leakage function. Knowledge of the average surface pressure on the shell and the leakage function permits calculation of the natural infiltration rate. While measurements of the surface pressures are useful for developing and refining a model of infiltration, they are impractical on a large scale; surface pressures must be determined by calculation.

In this paper we develop expressions to calculate the surface pressure when wind speeds and indoor-outdoor temperature differences are known. We identify the neutral pressure level, the height at which the indoor and outdoor pressures are equal, as an important parameter for characterizing surface pressures. Tamura(1) has previously discussed the importance of the height of the neutral pressure level in determining natural infiltration rates. Our analysis extends his results and shows that the neutral pressure level depends upon wind speed and direction, and will therefore be different for each face of the building. The neutral pressure level can be measured in the field (a procedure is described below) or estimated from weather and terrain parameters combined with a measurement of the neutral level in a no wind condition.

In order to calculate the infiltration from known surface pressures we use the model of Grimsrud, et al(2). In this model the infiltration (excluding large openings) is proportional to the average positive surface pressure and the exfiltration is proportional to the average negative surface pressure. The proportionality constant is the leakage function.

$$Q^{+} = \sum_{j=0}^{5} A_j l_j \Delta P_j^{+} \tag{1}$$

$$Q^{-} = \sum_{j=0}^{5} A_j l_j \Delta P_j^{-} \qquad (2)$$

The index j denotes the six faces of the structure with j=0 being the floor, j=1,2,3,4 for the walls and j=5 represents the ceiling. (See the symbol table at the end for the list of definitions.)

If we assume that the leakage through each face is the same, then the equations simplify.

$$Q^{\pm} = L \sum_{j=0}^{5} \Delta P_j^{\pm} \frac{A_j}{A} \qquad (3)$$

where L is the leakage constant derived from fan pressurization measurements.

In order to account for the presence of large openings and other non-linear effects this model assumes that all of these effects will show up as difference between Q^{+} and Q^{-}.

$$\Delta Q = Q^{+} - Q^{-} \quad , \qquad (4)$$

where ΔQ is the air flow through vents.

Actual infiltration is the larger of Q^{+} and Q^{-}.

$$Q = MAX(Q^{+}, Q^{-}) \quad . \qquad (5)$$

For a more complete description see the section on vents below.

Grimsrud, et al. (3) compared predicted infiltration from the above model with measured infiltrations. Several houses in different climates were tested and the results grouped, yielding the relationship

$$\frac{\text{actual infiltration}}{\text{predicted infiltration}} = 1.35 \pm .58 \quad . \tag{6}$$

The scatter in results was, in part, due to the insensitivity of the measurement procedure to stack effect pressures; pressures resulting from density differences could not be measured.

STACK EFFECT

The calculation of the stack effect pressures is derived for the general case in Appendix A and outlined briefly below. The stack effect is a pressure difference caused by a temperature difference between inside and out. If we assume an isothermal atmosphere and expand the expression for the pressure as a function of height, to first order it has a linear dependence on height. Pressure will decrease linearly both inside and outside the structure, but if the temperatures are different the slopes will be different. Hence, the pressure drop (otherwise called the surface pressure,) will also be linear in height with a slope given by the difference in the interior and exterior slopes. Accordingly, there will be some height at which the internal pressure is equal to the external pressure; this height is the neutral pressure level. If the temperature inside is greater than out, then below the neutral level the outside pressure is larger than the inside pressure while above it the opposite occurs. The dependence of the stack effect pressures on height is fixed by the temperatures. But the actual pressure difference depends on the height of the neutral pressure level. Referring to Eqs 3 and 5 the infiltration is a function of the neutral pressure level because this level determines which air flow will be larger, Q^+ or Q^-.

WIND EFFECTS

The above discussion makes no reference to wind effects. In this paper we make a set of simplifying assumptions about the effects of the wind: (See Appendix A for general case.)

1) the wind pressure is uniform on each face and

2) is proportional to the square of the wind velocity;

3) only steady state terms are important.

Thus the wind pressure on a face can be expressed as

$$[\text{wind pressure on face } j] = C_j \ {}^1\!/\!_2 \rho v^2 \tag{7}$$

where the shielding coefficient, C_j, is a function of wind angle for each face.

In general the shielding coefficients will be functions of both wind direction and terrain orientation, but we assume that the shielding is approximately the same everywhere around the house. Then the shielding coefficients will be functions of incident wind direction only. We take j=1 to be the face on which the wind is incident with j increasing clockwise as seen from above. Since we have defined the subscript in terms of the wind direction, we can use as a working hypothesis the assumption that the C_j's are constants. Values of C_j with particular emphasis on shielding effects are reported in studies of Bailey and Vincent (4), Eaton and Mayne (5), Mattingly and Peters (6), and Buckley, Harrje, Knowlton and Heisler (7).

Since we are making the simple assumptions that the shielding coefficients are constant everywhere on a structure face, and that the stack effect is a linear function of height alone, the surface pressure, (as derived in Appendix A), is a linear function of height.

$$\Delta P(\beta) = P_s(\beta_j^0 - \beta) \tag{8}$$

where

$$P_s = \rho g H \frac{\Delta T}{T_i}$$

$$\beta = \frac{h}{H}$$

$$\beta_j^0 = \beta^0 + (C_j - C^0)\sigma$$

$$\sigma = \frac{\frac{1}{2}\rho v^2}{P_s}$$

β^0 is the height of the neutral level in the absence of wind while β_j^0 is the height of the neutral level for a particular face in the presence of wind. For example, when the wind blows directly on a given face the neutral level will be shifted upward. P_s, the stack pressure, is the difference between the surface pressure at the top of the structure and the bottom of the structure. C^0 is a shielding-like term that is due to the leakage of the wind through the walls. As air moves through a wall the internal pressure can shift to compensate. For example, if one side were very leaky and the structure tight otherwise then C^0 would equal the C_j corresponding to that side, since in steady state the pressure would rise to counteract the wind effect.

Eq 7 can be used to find the surface averaged differential pressure on each face. In the case of the floor or ceiling this results from Eq 7 at the appropriate height; for the vertical faces it is necessary to integrate Eq 7 over the height of the face. These average surface pressures are displayed in Table 1 for all possible values of the neutral level. Fig 1 is a graphical representation of these pressures. Once ΔP_j^+ and ΔP_j^- have been found they can be inserted into Eq 3 to calculate the infiltration.

EXPERIMENTAL TECHNIQUES

In order to calculate infiltration we must know the average surface pressures on each face. These, in turn, can be calculated by knowing the stack pressure, P_s, and the neutral level for that face, β_j^0. The stack pressure can be calculated from the height of the structure and the indoor/outdoor temperatures. The neutral level is a much harder quantity to determine.

There are two approaches to determine the neutral level: either measure the quantity continuously or measure C^0, C_j and β^0 once, assume they remain constant, and predict β_j from these and the wind strength. In either case some direct measurement of a neutral level is necessary. The most direct method of measuring the neutral level is to pierce the envelope with a differential pressure transducer. The pressure, $\Delta P(\beta)$, can then be used to find the neutral level by a straightforward application of Eq 8.

$$\beta_j^0 = \beta + \frac{\Delta P(\beta)}{P_s} \quad . \tag{9}$$

However, except for specially built test structures it is not practical to make penetrations in the envelope. Some method that does not require a penetration in the envelope must be used instead.

Since stack effect pressures are affected by density differences care must be taken not to allow density difference to occur in any test lines used for making pressure measurements. For example, in Ref (3) a line was strung from a tap on the exterior surface, around the structure to an existing opening (e.g. outside air intakes or dryer vent) and into the house to the pressure transducer. Because there was a thermal gradient in the line as it went through the shell, the density of air within the line changed and made this measurement technique insensitive to stack pressures.

A better method would be to measure the interior and exterior pressure against the same fixed reference and subtract to find the difference, but it is impossible to use a reference that is fixed to 1 ppm of an atmosphere. The need for a fixed reference could be eliminated provided that both references were the same; this would allow differential measurements in an acceptable range.

In our measurements we use a helium filled line connecting the interior of the house with the exterior to transmit the pressure information. Helium was chosen because it is the lightest gas available; having a density only 4/29 that of air, it is relatively unaffected by temperature changes. We use two sensors, one inside and one outside, connected to each other by the helium filled line. If an infinitely elastic membrane were available to hold the helium in the line, only one sensor would be necessary, but the only practical method of containing the helium without losing the pressure information is with a second sensor. Fig 2 is a diagram of a typical experimental set-up. In Appendix B we calculate the actual pressure difference from the two measured differential pressures.

MEASUREMENTS

Using the technique from the previous section it is possible to measure continuously the neutral levels for a structure and from this predict the infiltration. The technique for measuring the neutral level is rather cumbersome for long term testing; it would be better if an easier set of parameters could be measured on a long term basis. Consider the expression for the neutral level:

$$\beta_j^0 = \beta^0 + (C_j - C^0)\sigma \quad . \tag{10}$$

The only dynamic parameter is the wind strength, σ. It can easily be measured by a weather tower, which need not be located exactly on site. C_j is, presumably, a continuous function of direction. β^0 is only a function of structural configuration; that is, only the leakiness of the structure will affect the height of the neutral level in no wind. C^0 is both a function of configuration and angle of wind incidence.

In principle, by measuring the neutral levels for a short period of time it is possible to extract the quantities β^0, C^0, C_j by linear regression. Once that is done for all the various configurations normally encountered it is possible to calculate the neutral levels knowing only the weather parameters. Once the secondary quantities, β^0, C^0, C_j have been determined, only the primary quantities, T_i, T_e and v, are necessary to predict the infiltration.

A preliminary run was done on our research house in Walnut Creek, California (cf. ref 2), using the measurement technique mentioned above. The experiment was carried out at night when there was virtually no wind; the inside temperature was maintained at 30°C by the house furnace. The inside and outside temperatures were measured on a chart recorder as were the readings from the two pressure sensors. The raw data is shown in Fig 3 for that entire night; however, only those data points in which the inside-outside temperature difference was greater than 20°C were used in the analysis.

Table 2 shows the result of that experiment. The temperature and pressure reading were averaged for the hour surrounding the indicated times and errors in those measurements were estimated. The experimental error associated with each measurement of the neutral level is made by combining the errors in the measurement of the temperatures, heights and pressures. The mean is a weighted average of all of the individual measurements of the neutral level and hence has a lower standard deviation than any of the individual measurements.

SPECIAL CASES AND EXAMPLES

It is difficult, in general, to determine the values of β^0 and C^0; however with some plausible assumptions they can be estimated. β^0 will be close to the mid height of the structure if the structure is free from vents. In many houses it may be somewhat higher than this due to the presence of flues, vents and chimneys. The C_j's can be approximated from the tables in Refs. (4) - (7). For the sake of simplicity we shall assume that the structure we are dealing with is a perfect cube and that each structure face has the same leakage value. In this case the leakage-area weighting drops out of eq 3.

$$Q^{\pm} = \frac{1}{6} L \sum_{j=0}^{5} \Delta P_j^{\pm} \quad . \tag{11.1}$$

In the special case of no wind, all the the neutral levels will be equal. If there are no large openings in the structure then the neutral level, β^0 will be equal to $1/2$ and the infiltration will be minimized. Using Table 1 with $\beta_j^0 = 1/2$ we can find the infiltration.

$$Q^{+} = Q^{-} = \frac{1}{16} LP_s \tag{11.2}$$

Figure 4a shows the direction and relative magnitude of the air flow through a structure for the special case of symmetric leakage, no vents, and no wind. However, in any real situation there will probably be vents or some non-symmetrical leakage which would move the neutral level either up or down; this would cause a rapid increase in the infiltration. Figure 5 is a graph of the predicted infiltration in no wind as a function of the neutral level. The graph extend the neutral level beyond floor and ceiling because a tall chimney or flue could raise the neutral level beyond the ceiling level.

Wind Strength

A quantitative measure of the wind strength is given by σ. The concept of a wind strength parameter allow the problem of predicting infiltration to be broken up into regimes.

$\sigma \ll 1 \Rightarrow$ light wind

$\sigma \simeq 1 \Rightarrow$ intermediate

$\sigma \gg 1 \Rightarrow$ heavy wind .

Evaluating the intermediate case of $\sigma = 1$ will give an estimate of the point at which stack and wind effects are equally important.

$$\frac{\Delta T}{v^2} = 6 \left[\frac{C^o}{(m/s)^2\text{-story}}\right]$$

$$= 3 \left[\frac{F^o}{mph^2\text{-story}}\right]$$

Thus for a 25°C(45°F) temperature difference the wind must be much faster than 2m/s(4mph) on a single story structure to be considered heavy. Of course this is modified by the shielding around the structure. Figure 6 is a graphical depiction of the wind dominated and stack dominated regimes, separated by the curve $\sigma = 1$.

Light Wind Case

When the wind is either very weak or very strong the analysis can be extended theoretically, that is, without knowing any specific values for the shielding or weather parameters. When there is a light wind there will be a shift in each of the β_j^0's away from β^0 that is small compared to one. Since the behavior of the envelope changes when one of the neutral levels crosses the floor or ceiling boundary, it is neither sufficient nor necessary to assume that the shift is small; β^0 may be close to 0 or 1. Rather we assume,

$$0 \leq \beta_j^0 \leq 1 \tag{12}$$

for all j.

Thus for every vertical face there will be some area that is subject to a positive pressure and some area that is subject to a negative pressure; this condition is shown graphically in fugure 4b. From Table 1 we can get the average surface pressure in the light wind case, knowing the neutral levels. Remembering that j=0 is for the floor, j=5 is for the ceiling, and j=1,2,3,4 is for the walls,

$$Q^{+} = \frac{1}{6} LP_s(\beta_5^0 + \sum_{j=1}^{4} (\beta_j^0)^2) \tag{13.1}$$

$$Q^{-} = \frac{1}{6} LP_s(1 - \beta_0^0 + 1/2 \sum_{J=1}^{4} (1 - \beta_j^0)^2) \quad . \tag{13.2}$$

If we assume, as above, that there are no vents then Q^+ must equal Q^- and β^0 must be $1/2$. Inserting this into both of the above equations we find

$$C^0 = \frac{1}{6} \sum_{j=0}^{5} C_j \quad . \tag{14}$$

This result, like the result $\beta^0 = 1/2$, applies only in the limit of ventless, symmetric leakage. Just as β^0 is pulled toward the height at which a leak occurs, C^0 approaches the C_j of the leakiest face.

Notice that to this point there has been some quadratic dependence of the infiltration on β_j^0. This indicates that the temperature effects (P_s, β^0) and the wind effects (σ, C^0) are not separable. That is, there are cross terms of the form $P_s \beta^0 \sigma C$ which mix the effects of wind and temperature. This implies that it will not be possible to separate the wind and stack effects by linear regression techniques.

Heavy Wind Case

For the light wind case we assume all neutral levels to be between the floor and the ceiling. A heavy wind is just the opposite:

$$\beta_j^0 < 0 \quad \text{or} \quad \beta_j^0 > 1 \tag{15}$$

for all j.

In this case every face has either only a positive differential surface pressure or only a negative differential surface pressure, but not both. This is shown graphically in fig 4c.

Referring to Table 1 we see that in a heavy wind there are no terms in either ΔP^+ or ΔP^- for any face that have a quadratic dependence on β_j^0. Therefore there are no terms that mix the stack effect with the wind effect. From this we can conclude that in a high wind the infiltration will be of the form

$$Q = b\ LP_s + c\ L\ \tfrac{1}{2}\rho v^2 \tag{16}$$

The two overall constants, b and c, relate infiltration to stack effect and wind pressure; b only depends on the configuration and c is approximated by the weighted sum of the shielding coefficients.

VENTS

Since a real structure is likely to have large openings in the envelope, a reasonable method for taking them into account must be found. Treating air as an incompressible gas, flow continuity would predict that Q^+ would equal Q^-. Our calculation of Q^+ and Q^- was based on the assumption that the flow is proportional to the pressure across the envelope. A large opening will not respond to the average pressure difference between the inside and one of the faces, but rather will respond to the specific pressure drop in a way much different than Eq 3. Therefore, there is no reason to expect that the calculated values of Q^+

and Q^- will be equal in the presence of vents.

We can use this difference to help calculate the infiltration by assuming that the total flow through the vents is accounted for by the difference between Q^+ and Q^-. Accordingly, the assumption is made that the flow through all the vents is unidirectional, that is, the vents will have air either going in or coming out; we assume that at any one time it does only one or the other. In general this is a reasonable assumption since vents tend to be placed in or near the ceiling of a structure.

If there are no vents or other large openings we expect the calculated values of Q^+ and Q^- to equal; furthermore, if the leakage distribution is vertically symmetric then the neutral level must be half of the structure height to assure continuity. Thus we see that the common assumption that the neutral level is half the building height is a consequence of assuming no vents and a vertical symmetry in the leakage pattern.

If there are vents in the structure there will be a shift in the neutral level towards the position of that vent. This shift is just the shift that is required to let in (or out) an extra quantity of air to account for the air going out the vents. Once this shift in the neutral level has occured, the flow out of the vents can be ignored. Figure 7 shows graphically the effect that a vent can have on the neutral level and the flow through the structure for a condition of no wind and light wind. This should be compared with the ventless situation in figure 4.

NUMERICAL EXAMPLES

we have examined above some special cases of the theoretical model; in this section we will work out two examples numerically. Some typical values for tight, single story mid-west houses are listed below:

T_i = 21°C (70°F)
T_e = -9°C (25°F)
H = 2.5m (8.2 ft.)
L = 50 m^3/hr-Pa (7 ft^3/hr-in. (H_2O))

If we use eq. 11.2 we can calculate the stack pressure and infiltration under the assumption of no wind. This corresponds to a moderate calm winter day.

P_s = 3 Pa (.012 in. (H_2O))
Q = 9.5 m^3/hr (5.6 cfm) .

In the second example we assume a two story house in a moderately well shielded environment, using some typical shielding values from refs (4)-(8). We assume a leakier structure, but again having no large vents or openings. We also assume that the floor and ceiling are isolated from wind induced pressures (e.g. slab on grade and full unoccupied attic).

STRUCTURAL PARAMETERS

NAME	SYMBOL	VALUE
Structure height	H	5.5 (m)
Neutral level	β^0	0.50
Shielding coefficient	C^0	-.10
	C_0	0.00
	C_1	0.50
	C_2	-.30
	C_3	-.50
	C_4	-.30
	C_5	0.00
Leakage coefficient	L	100 (m^3/hr)

Using typical values for the weather variables, we can calculate the wind and stack parameters.

WEATHER PARAMETERS

$\Delta T = 30\ ^oC$ $\qquad$ $P_s = 6.58$

$V = 4$ m/s $\qquad$ $\sigma = 1.46$

We can combine the shielding coefficients, the neutral level, and the wind strength parameter to find the neutral level on each face. Using these values we can look up the appropriate value for the infiltration or exfiltration from table 1.

j	β_j^0	Q^+ term	Q^- term
0	0.65	0.65	0.00
1	1.38	0.88	0.00
2	0.21	0.02	0.31
3	-0.08	0.00	0.58
4	0.21	0.02	0.31
5	0.65	0.00	0.35
sum	-	1.57	1.55

The two sums should be the same as a direct result of our assumption that there were no vents in the structure (i.e. $\beta^0 = 1/2$). We can now calculate the expected infiltration:

$$Q = \frac{1}{6} LP_s \times 1.56 \tag{17}$$

$$= \frac{1}{6} \times 100 \times 6.58 \times 1.56$$

$$= 171 \left(\frac{m^3}{hr}\right)$$

For a house of 500 m^3 this corresponds to an air change rate of .34 .

DISCUSSION

In this paper we have extended our previous models relating infiltration to average surface pressures on the envelope(2,3). Those models assume that flow through the building envelope is linearly proportional to the indoor-outdoor pressure difference. Detailed measurements(9) show that for crack widths up to 1 mm this is a good assumption. In (2) we examined experimentally the assumption that the flow is proportional to the average positive or negative surface pressure when this pressure was caused by the wind and when all major vents were sealed. Agreement between predicted and measured infiltration rates was good. The work was extended in (3) to include houses in their normal operating conditions (several with open vents) some of which were located in the northern part of the United states (where stack effects can be important). In this case the agreement between measured and predicted infiltration values was not as good. The ratio was $\simeq$ 1.35. This was encouraging but indicated the need for a refined model.

This paper describes a general model which will accommodate wind pressures, stack effect and ventilation openings provided the vents are either all above or all below their respective neutral pressure level. In this case the flows through the vents are all into or out of the building. The predicted infiltration is then the larger of the calculated infiltration or exfiltration.

The main innovation in this model is expressing the infiltration as a function of the shell leakage and of the neutral heights of each face, β_j^0, in turn, that can be determined by the weather parameters and by the leak distribution or measured directly. The model further introduces shielding coefficients, C_j, which are semi-empirical constants that scale the wind velocities and directions measured at a weather tower or station to produce the resulting surface pressures.

The procedures in this paper are complex; we feel that this complexity is necessary in order to define the areas in which simplifications to the model may be made. For example, our results point out the difficulty in attempting to find linear fits of infiltration rates with ΔT and v or ΔT and v^2. Our results indicate that this procedure will not succeed except in strong wind situations.

This work is continuing in several directions. Ultimately we seek to define a simple set of measurements which can be used to characterize the natural ventilation of a house. Before that goal can be reached, however, several extensions of the work described herein must be made. We must go beyond the simple manner in which wind was treated in this paper. Measurements must be made of surface pressure distributions in simplified geometries when wind direction and speed, temperatures and leakage openings can be varied. Infiltration must be measured when the ventilation openings are located both above and below the neutral pressure level; this condition must also be included in the predictive model. The effects of pressure fluctuations should also be examined and included in the model. When these results are obtained we shall be much closer to a correlation between pressurization and natural infiltration.

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SYMBOL TABLE

A Total surface area

A_j Surface area of face j

C_j Wind shielding coefficient for face j

C^0 Wind response factor

e as a subscript refers to exterior of structure

g Acceleration of gravity

h Height

H Structure height

i as a subscript refers to interior of structure

j as a subscript refers to an exterior face of the structure. (j=0 for the floor, j=1,2,3,4 for the walls with j=1 being the wall with the wind incident on it (increasing clockwise), and j=5 for the ceiling)

l Specific leakage [velocity/pressure]

L House leakage [flow/pressure]

M Molar mass of air

M_l Molar mass of light gas

P Pressure

P_a Atmospheric Pressure

P^0 Internal reference pressure

P_s Stack pressure

Q Total Infiltration

Q^+ Infiltration due to positive surface pressures

Q^- Exfiltration due to negative surface pressures

R Ideal gas constant

T Absolute temperature

v Wind speed

β Height divided by structure height

β^0 Normalized neutral pressure level(In no wind)

ΔP Differential pressure (outside-inside)

ΔP^+ Area averaged positive surface pressure

ΔP^- Area averaged negative surface pressure

ΔQ Difference between infiltration and exfiltration (vent flow)

ΔT inside-outside temperature difference

ρ Density of outside air

σ Wind strength

APPENDIX A

In this appendix we will derive the average surface pressures induced on a structure by a combination of stack effect and wind. The stack effect is caused by a difference in density between inside and outside air which is due to a temperature difference between inside and out. Even with large temperature differences, the pressure differences induced are very small compared to atmospheric pressure ($\approx$10 Pa vs $\approx 10^5$ Pa) so some ambiguity exists for defining absolute references. We take the exterior of the structure in no wind at ground level to be our reference; that is, atmospheric pressure is the pressure at that point; our measurement of height begins at that point as well.

If we assume the atmosphere near the surface is isothermal then the pressure can be calculated as a function of height.

$$P_e(h) = P_a e^{-\frac{Mgh}{RT_e}} \tag{A1}$$

Inside a structure the atmosphere can be treated as isothermal also, but with two differences:

1) The temperature will be different and

2) the pressure at zero height could be different

$$P_i(h) = P^0 e^{-\frac{Mgh}{RT_i}} \tag{A2}$$

where P^0 is as yet undetermined.

Using the ideal gas law for outside air,

$$MP_a = \rho RT_e \tag{A3}$$

and normalizing the height to the height of the structure ,

$$\beta = \frac{h}{H} \tag{A4}$$

Eq. A1 and A2 become,

$$P_e(\beta) = P_a e^{-\frac{\rho g H}{P_a}\beta} \tag{A5}$$

$$P_i(\beta) = P^0\ e^{-\frac{\rho g H}{P_a}\frac{T_e}{T_i}\beta} \tag{A6}$$

Since ρgH is typically about 30 Pa the exponents in the above equations are very small and thus the exponentials can be expanded to first order.

$$P_e(\beta) = P_a - \rho gH\ \beta \tag{A7}$$

$$P_i(\beta) = P^0 - \rho gH\ \beta\ \frac{P^0}{P_a}\ \frac{T_e}{T_i} \tag{A8}$$

Since P^0 differs from P_a by less than one part per thousand, no significant error is introduced by replacing it in the last term above; that term is already less than one-thousandth of an atmosphere.

$$P_i(\beta) = P^0 - \rho gH\ \beta\ \frac{T_e}{T_i} \tag{A9}$$

The neutral level, β^0, is the level at which the interior pressure and exterior pressure are equal.

$$P_i(\beta^0) = P_e(\beta^0) \tag{A10.1}$$

$$P_a - \rho g H\,\beta^0 = P^0 - \rho g H\,\beta^0\,\frac{T_e}{T_i} \tag{A10.2}$$

solving for P^0,

$$P^0 = P_a - \rho g H\,\beta^0\,\frac{\Delta T}{T_i} \tag{A11}$$

The pressure drop across a vertical face can be calculated in terms of the neutral level, β^0

$$\Delta P(\beta) = P_e(\beta) - P_i(\beta) \tag{A12.1}$$

$$\Delta P(\beta) = \rho g H\,\frac{\Delta T}{T_i}\,(\beta^0 - \beta) \tag{A12.2}$$

We can now define the stack pressure.

$$P_s = \rho g H\,\frac{\Delta T}{T_i} \tag{A13}$$

Rewriting some of the above equations in these terms,

$$P_e(\beta) = P_a - P_s\,\frac{T_i}{\Delta T}\,\beta \tag{A14.1}$$

$$P_i(\beta) = P_a - P_s\beta^0 - P_s\beta\,\frac{T_e}{\Delta T} \tag{A14.2}$$

$$\Delta P(\beta) = P_s \; (\beta^0 - \beta) \tag{A14.3}$$

To include the effects of the wind Eq A14 must be expanded. In our simple model the wind affects the exterior of each face; each face may have a different wind pressure on it, but every part of a given face is affected the same way. Thus, instead of having only one exterior pressure function, we have a different one for each face of the building. Accordingly, we must subscript the exterior pressure to denote the difference.

$$P_e \rightarrow P_j = P_e + C_j \; \tfrac{1}{2}\rho v^2 \tag{A15}$$

where C_j is the shielding coefficient for that face.

While the interior pressure is not directly affected by the wind, it is affected by the average exterior pressure on it. There may be a shift in the interior pressure induced by a change in the exterior pressure profile.

$$P_i \rightarrow P_i + C^0 \; \tfrac{1}{2}\rho v^2 \tag{A16}$$

Introducing, as a dimensionless parameter, the wind strength,

$$\sigma = \frac{\tfrac{1}{2}\rho v^2}{P_s} \tag{A17.1}$$

$$= \frac{v^2}{2gH} \frac{T_i}{\Delta T} \tag{A17.2}$$

we can rewrite Eq A14.

$$P_j(\beta) = P_a - P_s \frac{T_i}{\Delta T} \beta + C_j \; P_s \; \sigma \tag{A18.1}$$

$$P_i(\beta) = P_a - P_s\beta^0 - P_s\frac{T_e}{\Delta T}\beta + C^0 P_s\sigma \tag{A18.2}$$

$$\Delta P_j(\beta) = P_s(\beta^0 - \beta + \sigma(C_j - C^0)) \tag{A18.3}$$

Hence there is a height for every face at which the inside and outside pressures are equal. (This height may not actually be between the floor and the ceiling, but would be if the structure were tall enough.) The height may well be different for every face.

$$P_j(\beta_j^0) = P_i(\beta_j^0) \tag{A19.1}$$

$$\beta_j^0 = \beta^0 + \sigma(C_j - C^0) \tag{A19.2}$$

Thus the pressure drop across a face is a deceptively simple looking function of height:

$$\Delta P_j(\beta) = P_s(\beta_j^0 - \beta) \tag{A20}$$

In order to use these surface pressures in the infiltration models they must be averaged over each face for their positive and negative parts. For horizontal faces like the floor and the ceiling this is simple, since Eq A20 need only be evaluated at the appropriate height. However, since the pressure drop is a function of height, the pressure averages involve an integral over the vertical component of each face. These averages will be functions of only β_j^0.

The problem can be divided into three cases for calculation:

1): $\beta_j^0 < 0$ (neutral level below floor)

$$\Delta P_j^+ = 0$$

$$\Delta P_j^- = P_s \int_0^1 (\beta - \beta_j^0)\, d\beta$$

$$= \tfrac{1}{2} P_s (1 - 2\beta_j^0)$$

2): $0 < \beta_j^0 < 1$ (neutral level between floor and ceiling)

$$\Delta P_j^+ = P_s \int_0^{\beta_j^0} (\beta_j^0 - \beta)\, d\beta$$

$$= \tfrac{1}{2} P_s (\beta_j^0)^2$$

$$\Delta P_j^- = P_s \int_{\beta_j^0}^1 (\beta - \beta_j^0)\, d\beta$$

$$= \tfrac{1}{2} P_s (1 - \beta_j^0)^2$$

3): $1 < \beta_j^0$ (neutral level above ceiling)

$$\Delta P_j^+ = P_s \int_0^1 (\beta_j^0 - \beta)\, d\beta$$

$$= \tfrac{1}{2} P_s (2\beta_j^0 - 1)$$

$$\Delta P_j^- = 0$$

The results of the above calculations are compiled in Table 1.

APPENDIX B

In this appendix we will derive the expression for the actual pressure difference between any point on the inside of the structure and any point on the outside of the structure, using the measurement scheme proposed in the text. There are two differential pressure sensors, one on the inside of the structure and one on the outside of the structure; their reference ends are connected together by a flexible line filled with a low molecular weight gas (helium). (cf. Fig 2).

To begin, we start with Eq A18 adding subscripts to denote inside and outside height variables.

$$P_j(\beta_j) = P_a + C_j\ P_s\sigma - P_s \frac{T_i}{\Delta T}\beta_j \tag{B1.1}$$

$$P_i(\beta_i) = P_a - P_s\beta^0 + C^0\ P_s\sigma - P_s \frac{T_e}{\Delta T}\beta_i \tag{B1.2}$$

For this experiment we assume zero wind pressures.

$$\Delta P_j(\beta_i,\beta_j) = P_s(\beta_j^0 + \frac{T_e}{\Delta T}\beta_i - \frac{T_i}{\Delta T}\beta_j) \tag{B1.3}$$

$$\Delta P_j(\beta_i,\beta_j) = P_s(\beta_j^0 + \frac{T_i}{\Delta T}(\beta_i - \beta_j) - \beta_i) \tag{B1.4}$$

Solving for β_j^0,

$$\beta_j^0 = \beta_i + \frac{\Delta P_j(\beta_i,\beta_j)}{P_s} + \frac{T_i}{\Delta T}(\beta j - \beta_i) \tag{B2}$$

a measurement of $\Delta P_j(\beta_i,\beta_j)$ along with the other quantities will determine β_j^0.

Consider the set-up shown in Fig. 2 where the line connecting the two sensors is filled with a light gas of mass M_1. The measured values from the two instruments can be written in the terms shown in that figure.

$$\Delta P^1 = P_i - P_i^0 \tag{B3.1}$$

$$\Delta P^2 = P_j - P_j^0 \tag{B3.2}$$

The equation of hydrostatic equilibrium can be used to relate the pressures inside the line.

$$P_j^0 = P_i^0 + \rho_1 gH \int_{\beta_i}^{\beta_j} \frac{T_e}{T} \cos\theta \, d\beta \tag{B4}$$

where ρ_1 is the density of the light gas

T is the Temperature at any point in the line

$\cos\theta$ is the angle between vertical and the line path

In general the above path integral will be very complicated. In order to simplify it we will assume (for the moment) that all of the temperature change occurs during a horizontal section at height β'.

Then the equations become,

$$P_j^0 = P_i^0 + \rho_1 gH \frac{T_e}{T_i} \int_{\beta_i}^{\beta'} d\beta + \rho_1 gH \int_{\beta'}^{\beta_j} d\beta \tag{B5.1}$$

$$= P_i^0 + \rho_1 gH[(\beta' - \beta_i) - \frac{\Delta T}{T_i}(\beta' - \beta_i) + (\beta_j - \beta')] \tag{B5.2}$$

$$= P_i^0 + \rho_1 gH(\beta_j - \beta_i) - \rho_1 gH \frac{\Delta T}{T_i}(\beta' - \beta_i) \tag{B5.3}$$

The last term is smaller than the previous term by a factor of $\frac{\Delta T}{T_i}$, and the previous term was smaller than any other by a factor of $\frac{\rho_1}{\rho}$. For this reason we can justify neglecting the last term as long as the mass of the light gas is small compared to the mass of air. If the temperature change does not occur over a horizontal section then only the last term is affected. Thus if a light gas is used the last term can be neglected for any reasonable line path.

$$\Delta P_j(\beta_i,\beta_j) = \Delta P^2 - \Delta P^1 + \rho_1 gH(\beta_j - \beta_i) \tag{B6}$$

Combining this with Eq B2,

$$\beta_j^0 = \beta_i + \frac{\Delta P^2 - \Delta P^1 + \rho_1 gH(\beta_j - \beta_i)}{P_s} + \frac{T_i}{\Delta T}(\beta_j - \beta_i) \tag{B7}$$

and using the definitions of the stack pressure and gas density,

$$\beta_j^0 = \beta_i + \frac{\Delta P^2 - \Delta P^1}{P_s} + (1 + \frac{M_1}{M}) \frac{T_i}{\Delta T}(\beta_j - \beta_i) \tag{B8}$$

which only differs from Eq B2 by a correction factor for the light gas.

Eq B8 relates the measured quantities (β_i,β_j,ΔP^1,ΔP^2) to the desired quantity, β_j^0. Note also that Eq B6 can be used to measure the absolute pressure difference between two points at the same temperature.

TABLE 1a

Table of the positive average differential surface pressures as a function of the height of the neutral level for that face.

$\frac{\Delta P_j^+}{P_s}$	$\beta_j^0 < 0$	$0 \leq \beta_j^0 \leq 1$	$1 < \beta_j^0$
ceiling	0	0	$\beta_j^0 - 1$
walls	0	$\frac{1}{2}(\beta_j^0)^2$	$\beta_j^0 - \frac{1}{2}$
floor	0	β_j^0	β_j^0

NOTE: If $\Delta T < 0$ then ΔP^+ and ΔP^- interchange values and Table 1a and Table 1b interchange meaning.

TABLE 1b

Table of the negative average differential surface pressures as a function of the height of the neutral level for that face.

$\frac{\Delta P_j^-}{P_s}$	$\beta_j^0 < 0$	$0 \leq \beta_j^0 \leq 1$	$1 < \beta_j^0$
ceiling	$1 - \beta_j^0$	$1 - \beta_j^0$	0
walls	$\frac{1}{2} - \beta_j^0$	$\frac{1}{2}(1 - \beta_j^0)^2$	0
floor	$-\beta_j^0$	0	0

TABLE 2

Table of measured neutral levels for research house.

TIME	β_j^0	$\delta\beta_j^0$
22:00	.49	.46
23:15	.49	.46
00:30	.48	.44
01:45	.57	.43
03:00	.53	.43
04:15	.58	.42
05:30	.71	.42
06:45	.73	.43
mean	.57	.10

FIGURE CAPTIONS

1) Figure 1 is a graph of the surfaced averaged differential pressures. ΔP^{+} is the average of the positive differential surface pressure, and ΔP^{-} is the average of the negative differential surface pressure. The pressures are graphed as a function of the height of the neutral level, β^{0}, for that face. $\beta^{0}=0$ is the floor of the structure and $\beta^{0}=1$ is the ceiling of the structure.

2) Figure 2 is a depiction of the experimental set-up used in the determination of the neutral level. The boxes labelled 1 and 2 are the inside and outside differential pressure transducers respectively. The normalized heights, β, of the various elements are indicated on the left wall of the structure. The pressures, P, at various points in the system are shown.

3) Figure 3 is a copy of the chart recording made during the experimental determination of the neutral level.

   The left most scale corresponds to the differential pressure measured by one of the pressure sensors (cf. Fig. 2). The cyclic behavior is induced by the changing temperature inside the house which effected the pressure inside the helium filled line connecting the references of the two sensors.

   The middle scale corresponds to the relatively steady curve in the middle. This is the difference in differential pressures between the two pressure sensors. Notice that this difference is not affected by the cyclic behavior of either of the sensors. The periods of increased noise on this curve correspond to the periods of increased wind speed.

   The rightmost scale is the inside-outside temperature difference and corresponds to the upper relatively steady curve. The temperature difference shows some cyclic behavior induced by the heating system of the test structure.

The latter two curves were used to calculate the neutral level in the structure as a function of time.

4) Figure 4 is a drawing of the neutral levels and differential pressures induced by a combination of the stack and wind effects in a structure having no vent or other large openings.

   a) (bottom) No wind — Stack dominated.
   b) (middle) Light wind — intermediate case.
   c) (top) Heavy wind — Wind dominated.

   The arrows indicate the direction and magnitude of the differential pressure (and hence the infiltration) across the envelope.

5) Figure 5 is a theoretical plot of the infiltration caused by the stack effect as a function of the height of the neutral level. Q^+ is the infiltration (into the structure), Q^- is the exfiltration (out of the structure), and β^0 is the height of the neutral level divided by the height of the structure. The solid line is the actual infiltration as would be measured in the structure and the difference between the solid line and the dashed line is that part of the actual infiltration that is attributable to vents.

6) Figure 6 divides the weather parameters into two regimes: one dominated by the wind and the other dominated by the stack effect. The horizontal axis is the inside-outside temperature difference times the number of stories of the structure. The vertical axis is the effective wind speed; that is, the wind speed felt in the local environment around the structure. If the effective wind speed is equal to the actual wind speed then the curve is that when the wind strength parameter, σ, is equal to unity.

7) Figure 7 is a drawing of the neutral levels and differential pressures induced by a combination of the stack and wind effects in a structure having a vent in the ceiling.

a) (bottom) No wind -- Stack dominated.

b) (top) Light wind -- Intermediate case.

Because of the rather large flows that would be induced through a vent in the heavy wind case, it is not shown. The arrows indicate the direction and magnitude of the differential pressure (and hence the infiltration) across the envelope.

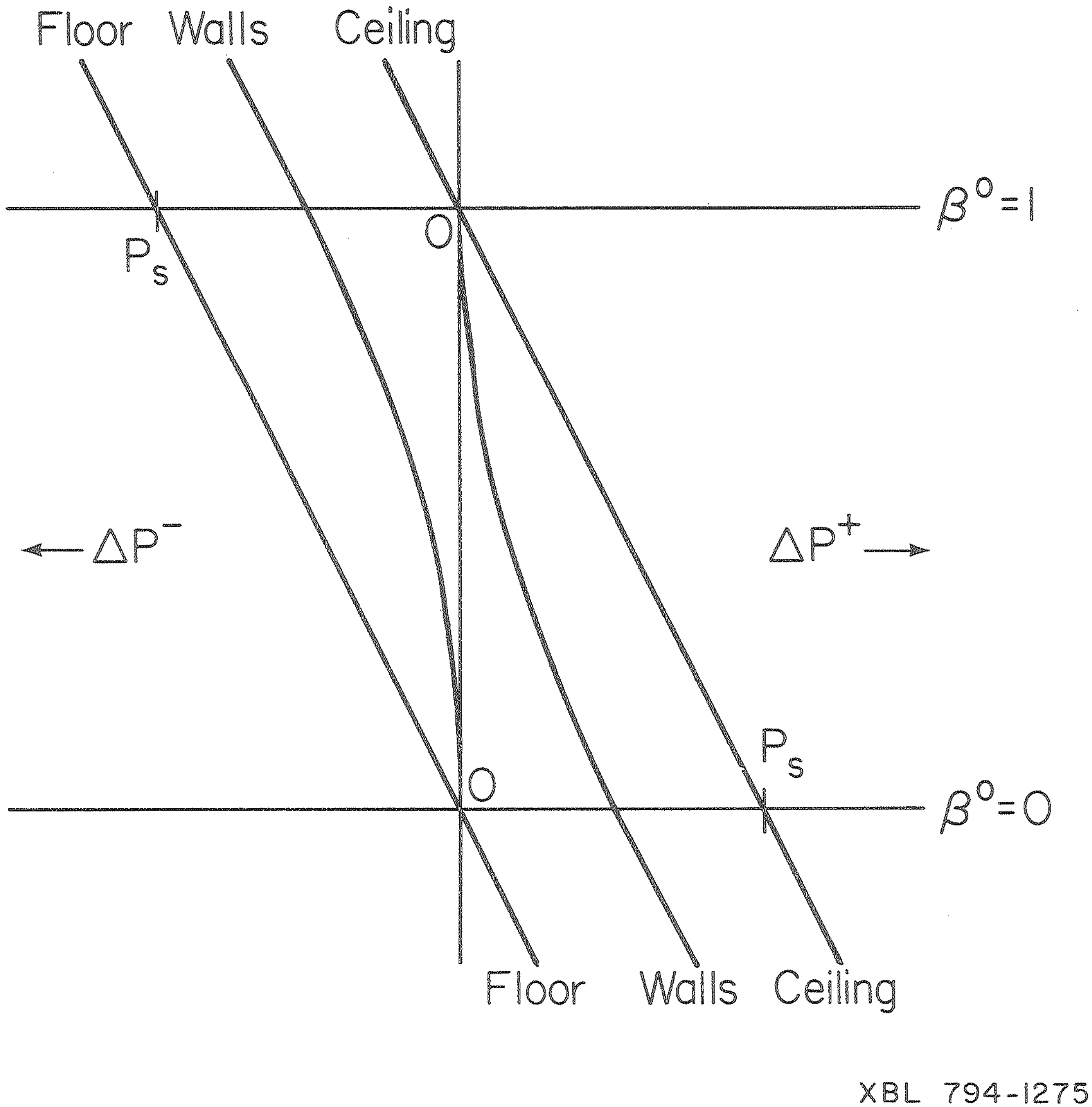
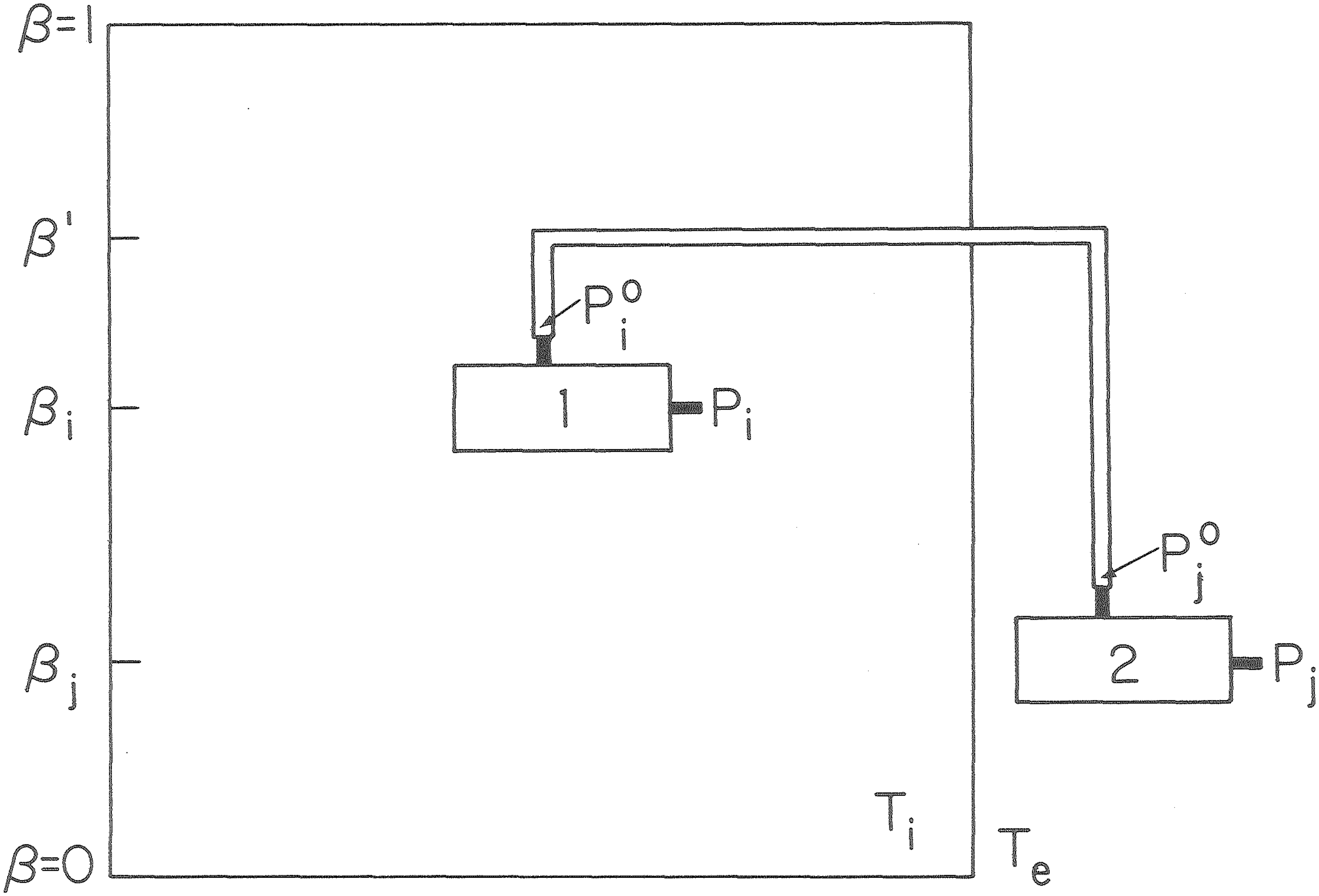

Floor
Walls
Ceiling
$\beta^o=1$
P_s
O
$\leftarrow \Delta P^-$
$\Delta P^+ \rightarrow$
P_s
O
$\beta^o=0$
Floor
Walls
Ceiling
XBL 794-1275

Figure 1



XBL 794-1274

Figure 2

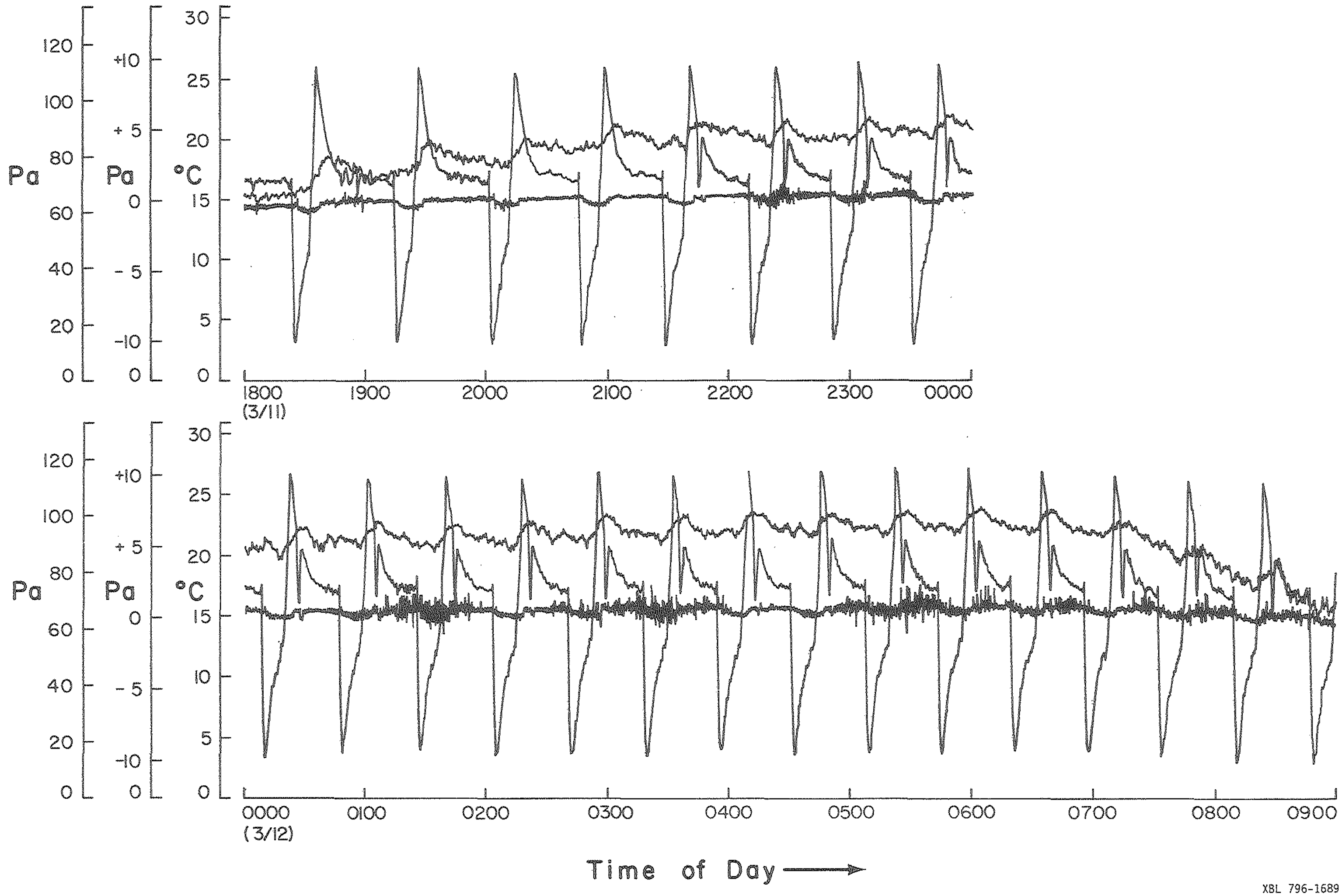

Pa
Pa
°C
120
100
80
60
40
20
0
+10
+ 5
0
- 5
-10
0
30
25
20
15
10
5
0
1800
(3/11)
1900
2000
2100
2200
2300
0000
0000
(3/12)
0100
0200
0300
0400
0500
0600
0700
0800
0900
Time of Day
XBL 796-1689

Figure 3

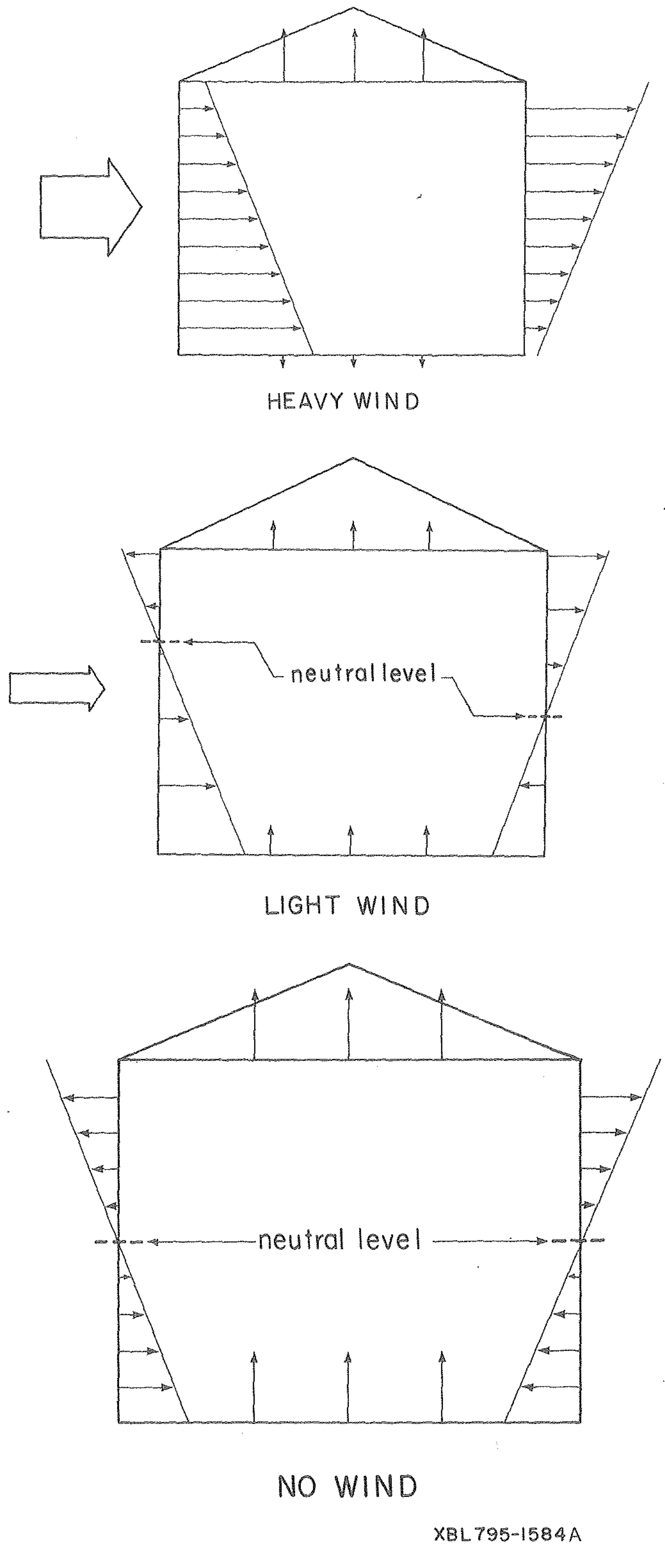
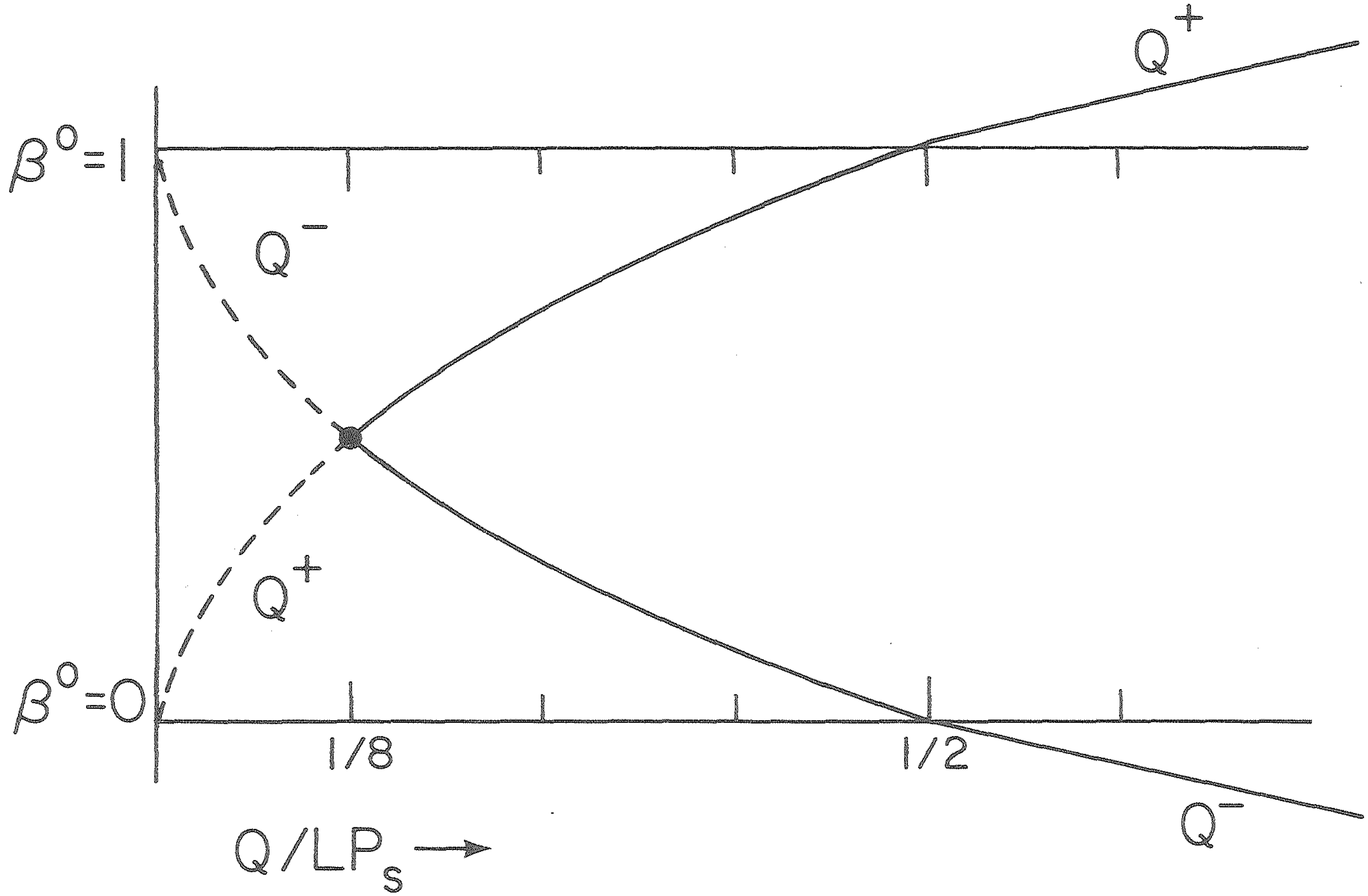

HEAVY WIND
neutral level
LIGHT WIND
neutral level
NO WIND
XBL795-1584A

Figure 4



XBL 794-1273

Figure 5

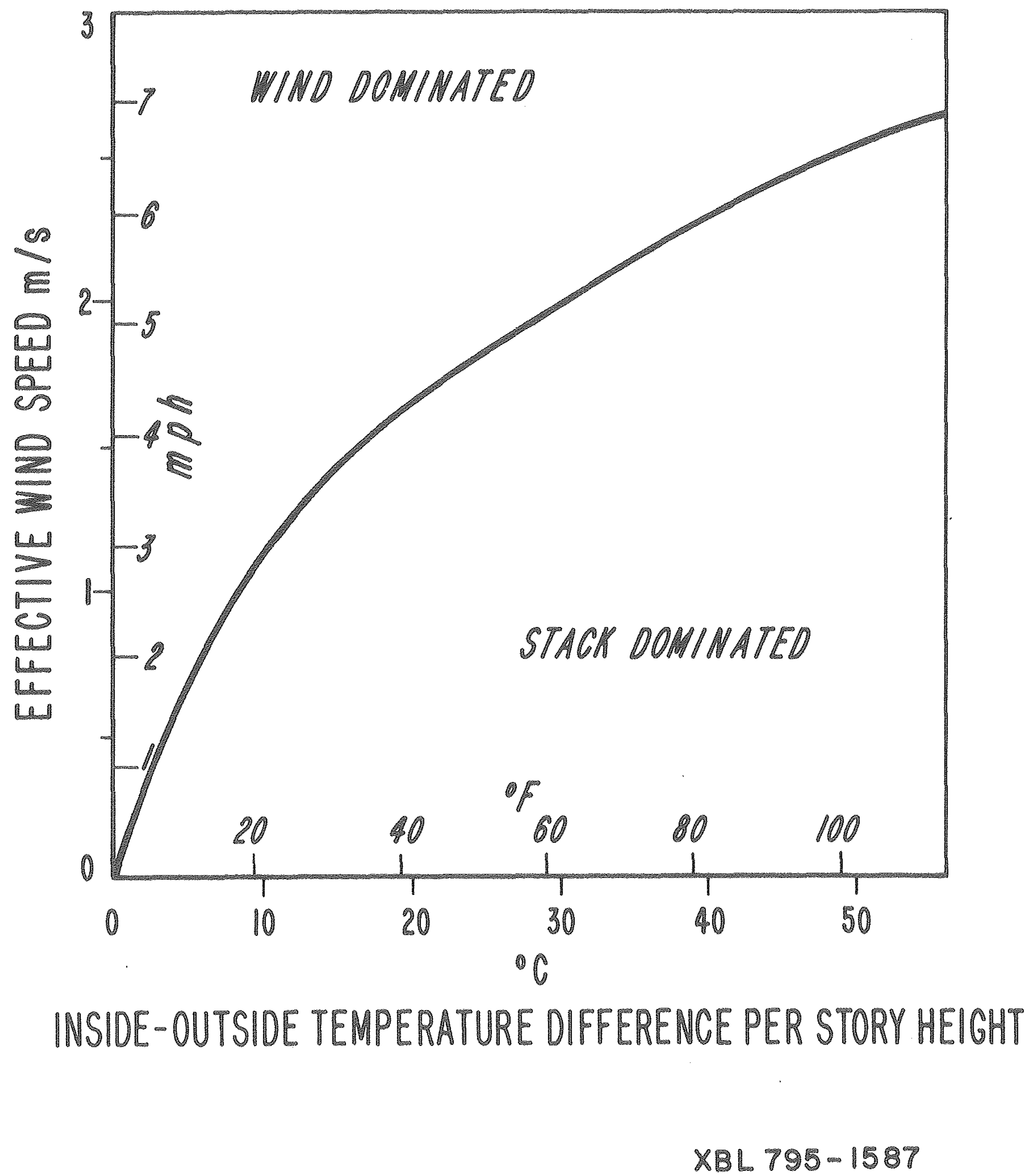

WIND DOMINATED
STACK DOMINATED
EFFECTIVE WIND SPEED m/s
mph
0
1
2
3
1
2
3
4
5
6
7
°F
20
40
60
80
100
0
10
20
30
40
50
°C
INSIDE-OUTSIDE TEMPERATURE DIFFERENCE PER STORY HEIGHT
XBL 795-1587

Figure 6

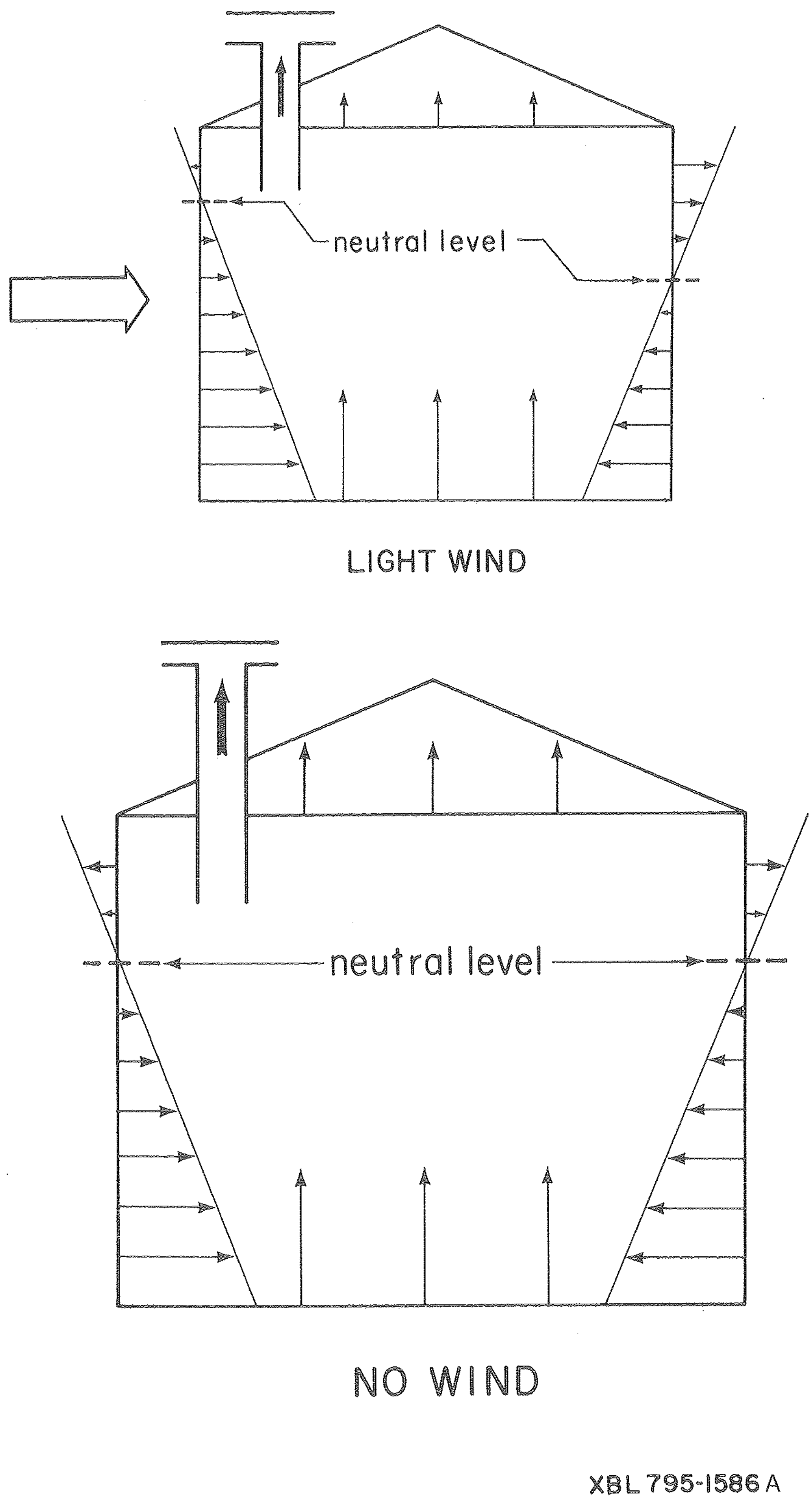

neutral level
LIGHT WIND
neutral level
NO WIND
XBL 795-1586 A

Figure 7

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