NISTIR 4588

A General Routine for Analysis of Stack Effect

U.S. Department of Commerce
National Institute of Standards and Technology
Building and Fire Research Laboratory
Gaithersburg, MD 20899

Prepared for:
General Services Administration
Fire Protection Engineering Branch
Washington, DC 20405

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Table of Contents

List of Figures

List of Tables

A GENERAL ROUTINE FOR ANALYSIS OF STACK EFFECT

John H. Klote

Abstract

Stack effect is a major driving force of smoke movement in buildings. This paper presents a general method for evaluation of the location of the neutral plane for a space connected to its surroundings by any number of openings. A computer program, STACK, for analysis of the location of the neutral plane and resulting flows is presented along with example analyses. The examples show that the location of the neutral plane between a space and its surroundings is a weak function of temperature and a strong function of the size of openings. Further, the mass flow rate leaving a space due to stack effect is a strong function of temperature.

Nomenclature

A	area, m^2 (ft^2)
C	flow coefficient for flow opening, dimensionless
g	acceleration of gravity, m/s^2 (ft/s^2) [g is approximatly 9.80 m/s^2 (32.2 ft/s^2)]
H	height above the bottom of space, m (ft)
Hc	height of space (bottom to top), m (ft)
Hn	height of neutral plane above the bottom of space, m (ft)
h	height above neutral plane, m (ft)
K_o	constant, 1.00 (12.9)
K_p	constant, 1.00 (0.00598)
m	mass flow rate, kg/s (lb/s)
p	absolute pressure, Pa (in H_2O) [standard atmospheric pressure is 101,325 Pa (407.255 in H_2O)]
R	gas constant, 287.0 J/kg K (10.27 in H_2O ft^3 lb^{-1} $°R^{-1}$)
S	sign that determines direction of mass flow
T	absolute temperature, K (°R)
W	width of opening, m (ft)
Δp	pressure difference, Pa (in H_2O)
ρ	air density, kg/m^3 (lb/ft^3)
n	number of openings between space c and the outside

Subscripts

c	space
b	bottom
t	top
∞	outside

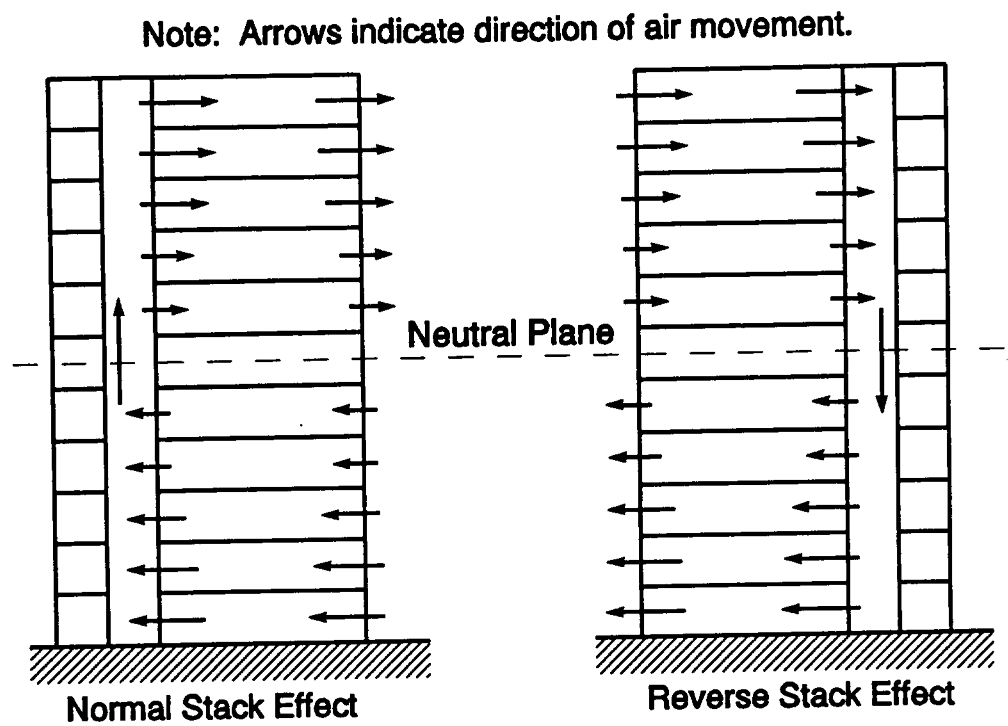

Figure 1. Air movement due to normal and reverse stack effect

1.0 Introduction

Frequently when it is cold outside, there is an upward movement of air within building shafts, such as stairwells, elevator shafts, dumbwaiter shafts, mechanical shafts, and mail chutes. Air in the building has a buoyant force because it is warmer and therefore less dense than outside air. The buoyant force causes air to rise within building shafts. This phenomenon is called by various names such as stack effect, stack action, and chimney effect. These names come from the comparison with the upward flow of gases in a smoke stack or chimney. However, a downward flow of air can occur in air conditioned buildings when it is hot outside. For this paper, the upward flow is called normal stack effect, and the downward flow is called reverse stack effect as illustrated in figure 1.

Stack effect is of concern in fire situations, because it can have a significant effect on smoke movement. The methods of analysis presented in this paper are part of a project to study the concept of staging areas for the physically disabled funded by the General Services Administration. Stack effect is also important for an understanding of the building air flows involved with energy conservation and indoor air quality. Stack effect also applies to the buoyancy driven flows between a room on fire and its surroundings. The methods of analysis of this paper can also be used for analysis of airflow in buildings for energy conservation or indoor air quality.

There is a horizontal plane at which the pressure inside a building or other space equals that outside. There is no pressure difference between the space and its surroundings at this *neutral plane*, and there is no horizontal flow at this plane. Determination of the location of the neutral plane is essential to evaluation of flow due to stack effect. Analytic equations have been developed for the location of the neutral plane for a few simple cases of leakage openings. However, the combinations of leakage openings in building shafts and compartments can be very complex.

A number of computer programs have been developed that allow analysis of air and smoke movement in buildings. Said (1988) provides an overview of such models that are intended for analysis of smoke movement or for design analysis of smoke control systems. While such programs can be used to analyze stack effect, they do not calculate the location of the neutral plane. Because of the general treatment of openings, the computer program presented in this paper can be used to evaluate some of the simplifying flow assumptions used in many other programs.

This paper presents a general method for evaluation of the location of the neutral plane for a space connected to its surroundings by any number of openings. A computer program, STACK, for analysis of the location of the neutral plane and resulting flows is presented along with example analyses. This computer program is intended to be a tool for analysis of stack effect and to help engineers develop insight into relationships between stack effect, building openings and temperatures.

The discussion in this paper and the STACK program both consider temperature to be uniform throughout the space and temperature uniform throughout the surroundings. The STACK model is applicable to fire spaces for which the vertical temperature is not significant. The discussion in this paper is limited to stack effect for one space, however, the concept of effective flow areas (Klote and Fothergill 1983) can be used to extend this analysis to complex systems of flow paths like those in many buildings. Another paper is planned concerning the application of effective flow area concept to stack effect analysis.

As background material, analytic equations are derived and discussed for the location of the neutral plane for a space with a continuous opening and a space with two openings. This information sets the stage for the presentation of the general approach and equations used in the STACK program. This is followed by example applications.

2.0 Space With A Continuous Opening

The following analysis is based on one by McGuire and Tamura (1975), and it is specifically for normal stack effect. The flow due to normal stack effect for a space connected to the outside by a continuous opening of constant width from the top to the bottom of the space is illustrated in figure 2. The opening extends from the bottom to the top of the space. Reverse stack effect is discussed later. The pressure difference from the space to the outside is expressed by

$$\Delta p_{c,\infty} = K_p g h(\rho_\infty - \rho_c) \tag{1}$$

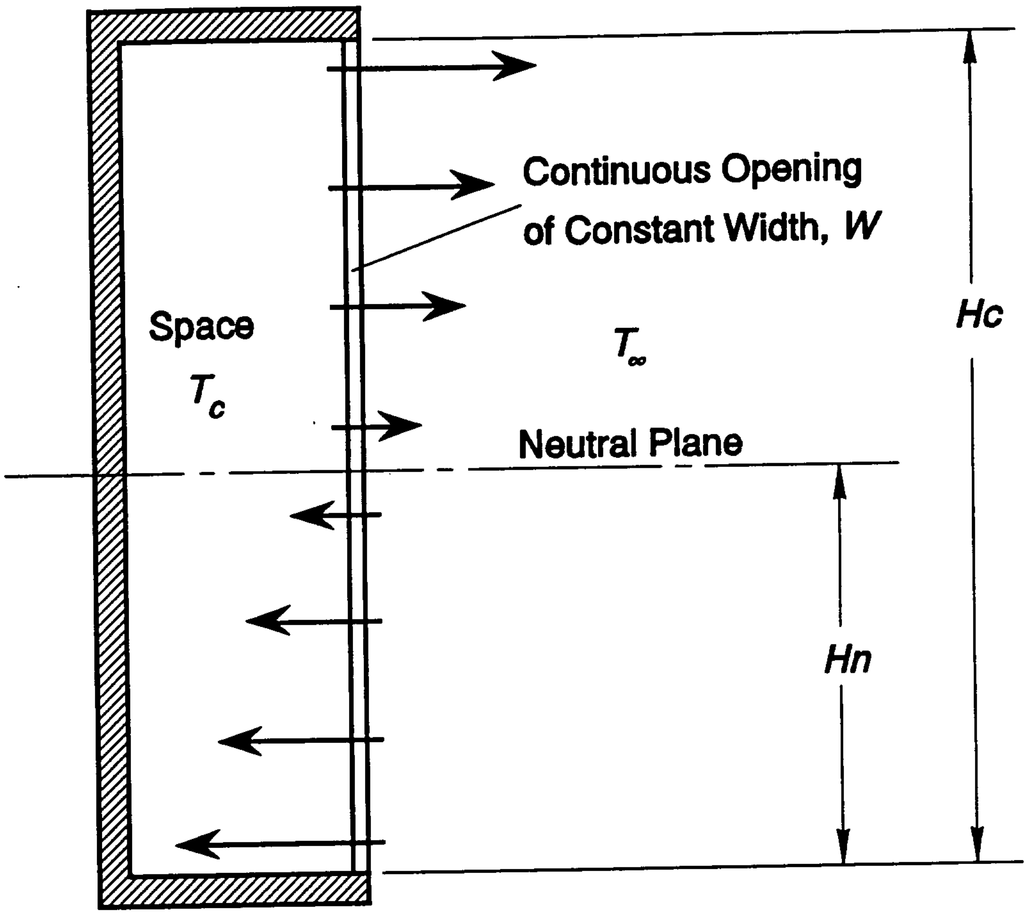

Figure 2. Normal stack effect for a space connected to the outside by a continuous vertical opening

where ρ_∞ is the density of the outside air, ρ_c is the density inside the space, and h is elevation above the neutral plane. The mass flow rate, dm_{out}, through a differential section, dh, of the opening above the neutral plane is

$$dm_{out} = K_o C\, W \sqrt{2 \rho_c\, \Delta p_{c,\infty}}\; dh = K_o C W \sqrt{2 \rho_c g h K_p (\rho_\infty - \rho_c)}\; dh \tag{2}$$

where C, W, and $\Delta p_{c,\infty}$ are the flow coefficient, width of opening, and the pressure difference from the space to the surroundings. The flow coefficient is dimensionless and is generally in the range of 0.6 to 0.7 for most flow paths in buildings. To obtain the mass flow rate from the space, equation (2) is integrated from the neutral plane (h = 0) to the top of the opening (h = Hc - Hn, where Hc is the height of the space, and Hn is the height of the neutral plane).

$$m_{out} = \frac{2}{3} K_o C W (Hc - Hn)^{3/2} \sqrt{2 \rho_c g K_p (\rho_\infty - \rho_c)} \tag{3}$$

In a similar manner an expression for the mass flow rate into the space can be developed.

$$m_{in} = \frac{2}{3} K_o C W Hn^{3/2} \sqrt{2 \rho_\infty g K_p (\rho_\infty - \rho_c)} \tag{4}$$

For steady flow, the mass flow rate leaving the space equals that entering the space. Equating equations (3) and (4), substituting the perfect gas equation ($\rho = p/RT$), and canceling like terms yields

$$\frac{Hn}{Hc} = \frac{1}{1 + (T_c/T_\infty)^{1/3}} \tag{5}$$

For an inside temperature of 22°C (72°F) and an outside temperature of -18°C (0°F), the neutral plane is located 48.8% of *Hc* above the floor of the space which is slightly different from the generally accepted approximation of halfway up the space. By the definition of normal stack effect, the ratio of the space temperature to the outside temperature is always greater than one ($T_c/T_\infty > 1$). Thus inspection of equation (5) shows that *Hn/Hc* is always less than one half. This means that, for this case, the neutral plane is below the mid-height of the space. The higher density air flowing through the lower portion of the opening needs less area than the lower density air flowing through the upper portion of the opening.

3.0 Shaft With Two Openings

The flow due to normal stack effect for a space connected to the outside by two vents is illustrated in figure 3 for horizontal and vertical openings. Analysis is simpler for horizontal openings, because the pressure difference across the opening does not very with elevation. The analysis of this section is for horizontal openings. However, the flow through vertical openings can be approximated by that through horizontal openings as is discussed later in an example. The two openings must be at different elevations in order for there to be mass flow due to stack effect. For normal stack effect, the flow out of the higher opening is

$$m_{out} = K_o C A_a \sqrt{2 \rho_c \Delta p_{c,\infty}} = K_o C A_a \sqrt{2 \rho_c g K_p (Hc - Hn)(\rho_\infty - \rho_c)} \tag{6}$$

where A_a is the area of the higher opening. The flow into the lower vent is

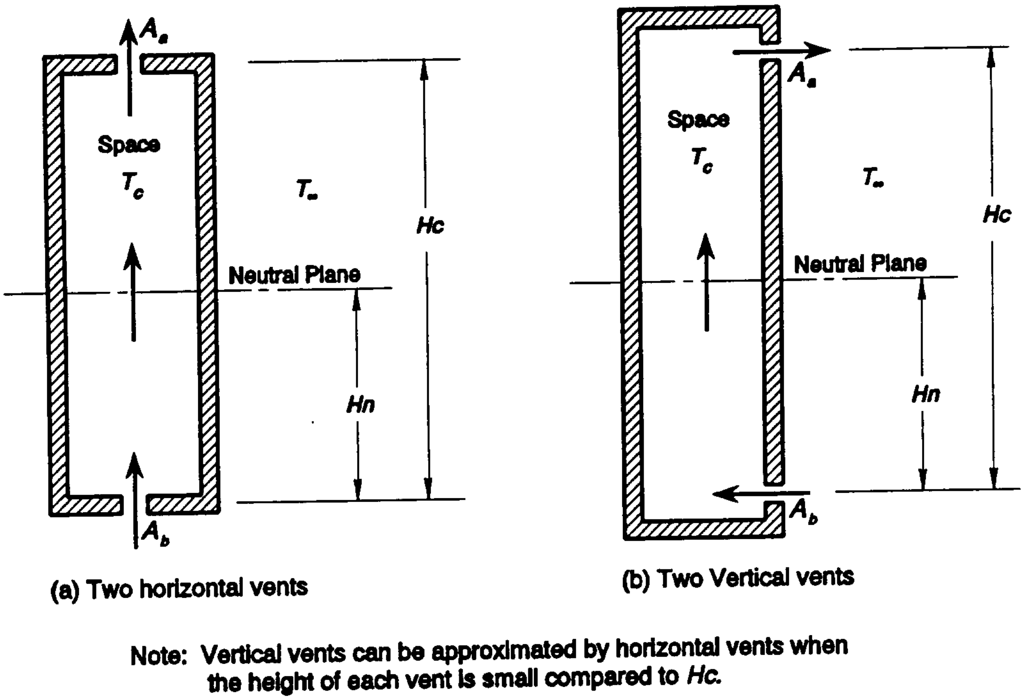

Figure 3. Normal stack effect for a space connected to the outside by two openings

$$m_{in} = K_o C A_b \sqrt{2\rho_\infty \Delta p_{\infty,c}} = K_o C A_b \sqrt{2\rho_\infty g Hn K_p (\rho_\infty - \rho_c)} \tag{7}$$

where A_b is the area of the lower opening. Equations (6) and (7) are combined in a similar manner as before and an expression is developed for the location of the neutral plane.

$$\frac{Hn}{Hc} = \frac{1}{1 + (T_c/T_\infty)(A_b/A_a)^2} \tag{8}$$

For an inside temperature of 22°C (72°F), an outside temperature of -18°C (0°F), and equal areas ($A_a = A_b$), the neutral plane is located 46.4% of Hc above the floor of the space which is a little less than the case of the continuous opening (48.8%).

3.0 Reverse Stack Effect

The above analyses were for normal stack effect. For reverse stack effect, the location of the neutral plane can be evaluated in the same manner as for normal stack effect. For a space connected to the outside by a continuous opening, the location of the neutral plane during reverse stack effect is

$$\frac{Hn}{Hc} = \frac{1}{1 + (T_o/T_c)^{1/3}} \tag{9}$$

For an inside temperature of 22° (72°F) and an outside temperature of 34°C (94°F), the neutral plane is located 49.7% of *Hc* above the floor of the space. As with the example for a continuous opening during normal stack effect, the neutral plane is below the mid-height of the space. For both normal and reverse stack effect, the higher density air flows through the lower portion of the opening, and the neutral plane is below the mid-height of the space. It can be observed from equations (5) and (9), that the neutral plane approaches the mid-height as the outside temperature approaches that of the space.

For a space connected to the outside by two horizontal openings, the location of the neutral plane during reverse stack effect is

$$\frac{Hn}{Hc} = \frac{1}{1 + (T_o/T_c)(A_b/A_a)^2} \tag{10}$$

For an inside temperature of 22°C (72°F), an outside temperature of 34°C (94°F), and equal areas ($A_a = A_b$), the neutral plane is located 49.9% of *Hc* above the floor of the space. It can be observed from equations (8) and (10), that the neutral plane will be below the mid-height when $A_a = A_b$ for both normal and reverse stack effect.

4.0 General Approach To Location Of Neutral Plane

The approach and equations presented in this section are those used in the STACK program. This program written in the QuickBASIC language is listed in appendix B.

A space is connected to the outside by a number of horizontal and vertical openings. For any orientation and location, the mass flow rate from the space through opening, *i*, can be expressed as a function of the height of the neutral plane,

$$m_i = f_i(Hn) \tag{11}$$

Equations for mass flow rate for specific orientations and locations are presented later. For steady flow, the sum of the mass flow rates from the space is zero:

$$\sum_{i=1}^{n} f_i(Hn) = 0 \tag{12}$$

where n is the number of openings between the space and the outside. Various numerical root finding techniques (Press, et al. 1986) can be used to find the location of the neutral plane, Hn, which satisfies equation (12). To find this root, STACK uses the method of bisection, and the mass flow rates are calculated from the equations presented in the following sections.

4.1 Vertical Openings

In the earlier derivations, the mass flow equations were developed for a specific direction of flow. The flow equations used in this section and the following sections are generalizations of the earlier equations, applicable to flow both into and out of the space. Because of the similarity to earlier equations, derivations are not presented.

The direction of flow through a vertical opening depends on the location of the opening with respect to the neutral plane and the relative magnitudes of the inside and outside temperatures. If the inside temperature is the same as the outside temperature, there is no flow. The six different conditions of flow direction for vertical openings are illustrated in figure 4. The flow for these six conditions is completely described by two generalized cases: the opening away from the neutral plane and the opening at the neutral plane.

4.1.1 Opening away from the neutral plane

For a vertical opening away from the neutral plane, the mass flow rate is

$$m = S \frac{2}{3} K_o C W_i \left| |h_{ti}|^{3/2} - |h_{bi}|^{3/2} \right| \sqrt{2 \rho_i g K_o |\rho_\infty - \rho_c|} \tag{13}$$

where S is the sign of $h_{bi}(\rho_\infty - \rho_c)$, h_{bi} is the elevation of the bottom of the opening above the neutral plane, h_{ti} is the elevation of the top of the opening above the neutral plane, and ρ_i is the density in the opening. The convention for the density in the opening is the same as before.

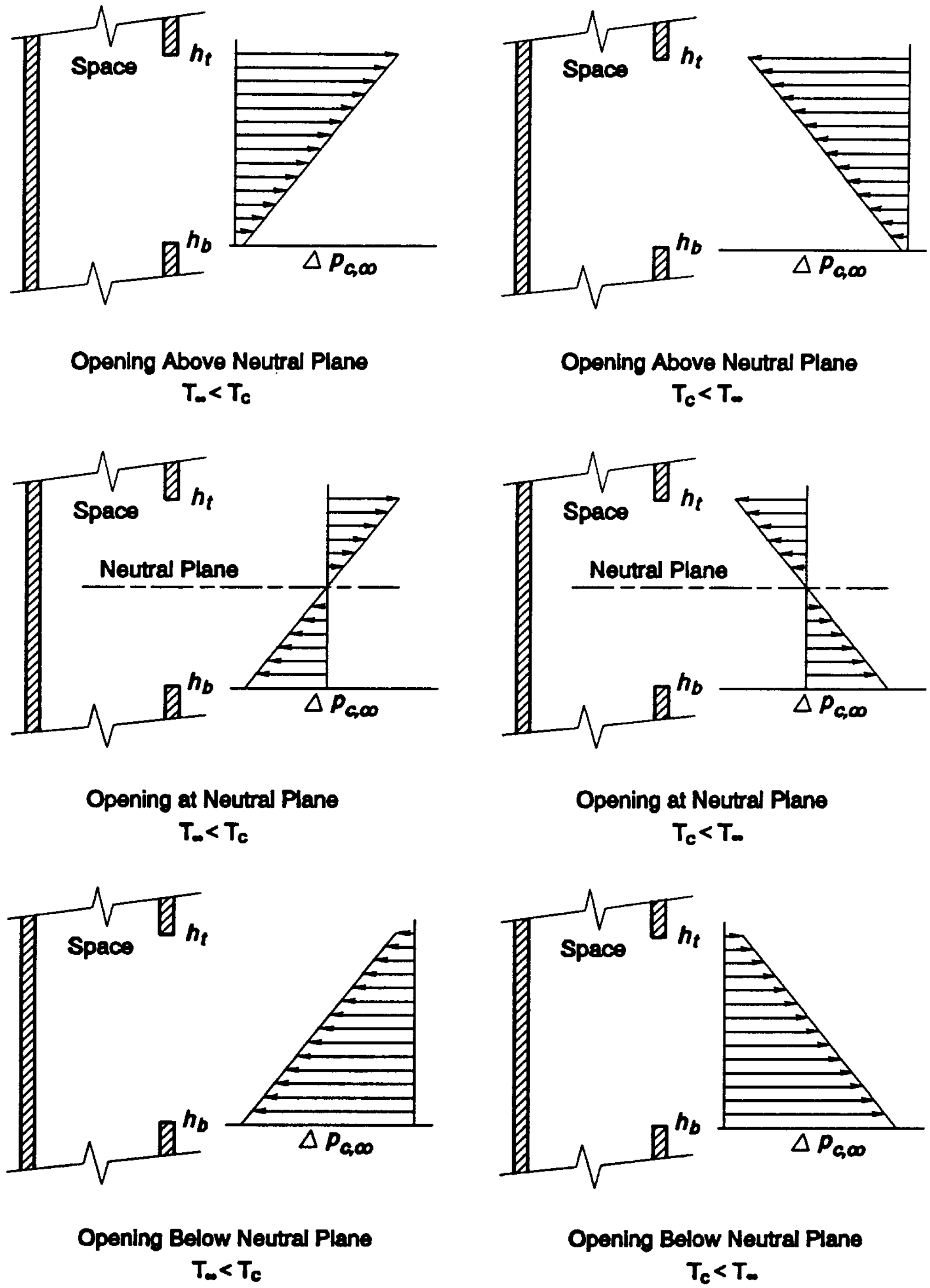

Figure 4. Flow directions for vertical openings

4.1.2 Opening at the neutral plane

For an opening at the neutral plane, two flow calculations are needed, because the flow is bi-directional. The flow above the neutral plane is

$$m = S\frac{2}{3}K_o C W_i \, |h_{ti}|^{3/2} \sqrt{2\,\rho_i g K_p \, |\rho_\infty - \rho_c|} \tag{14}$$

where S is the sign of $h_{ti}(\rho_\infty - \rho_c)$. The flow rate below the neutral plane is

$$m = S\frac{2}{3}K_o C W_i \, |h_{bi}|^{3/2} \sqrt{2\,\rho_i g K_p \, |\rho_\infty - \rho_c|} \tag{15}$$

where S is the sign of $h_{bi}(\rho_\infty - \rho_c)$.

4.2 Horizontal Openings

As with the vertical opening, the flow direction through horizontal openings depends on the location of the opening and the inside and outside temperatures. For the purposes of this paper it is assumed that the mass flow is zero when the opening is at the neutral plane. As previously stated, the pressure difference across the opening does not vary with elevation. Thus, the flow through a horizontal opening can only be in or out as illustrated in figure 5. The mass flow rate through a horizontal opening is

$$m = S K_o C A_i \sqrt{2\,\rho_i g K_p \, |h_i\,(\rho_\infty - \rho_c)|} \tag{16}$$

where S is the sign of $h_i(\rho_\infty - \rho_c)$, h_i is the elevation of the opening above the neutral plane, A_i is the opening area, and ρ_i is the density in the opening. If S is positive, the flow is from the space. The flow is to the space when S is negative. The density in the opening is approximated by that of the location from which the flow is coming. Thus, ρ_i is ρ_c for positive S, and ρ_i is ρ_∞ for negative S.

5.0 Example 1 - Room Fire

A room is fully involved in fire, and it is connected to the outside by an open door, open window, and leakage in the ceiling as shown in figure 6. At a room temperature of 590°C (1100°F) and an outside temperature of 21°C (70°F), STACK calculates *Hn/Hc* at 0.49 and the mass flow rate from the room at 2.74 kg/s (6.03 lb/s). The height of the neutral plane in this example is a weak function

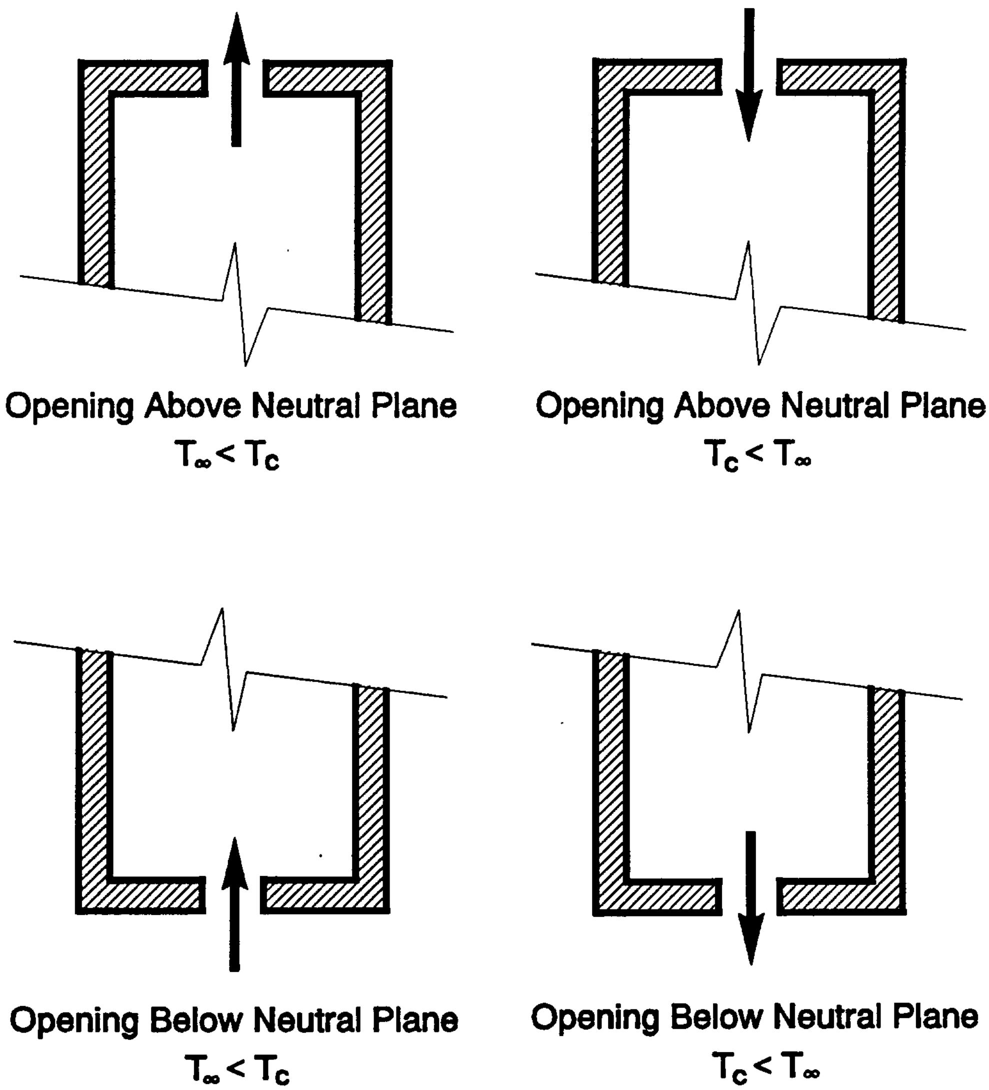

Figure 5. Flow directions for horizontal openings

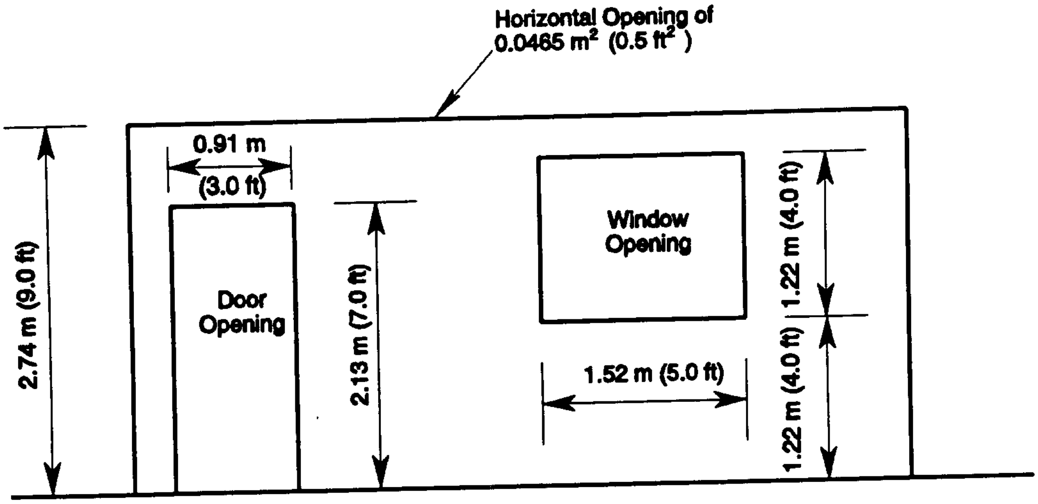

Figure 6. Fire room of example 1

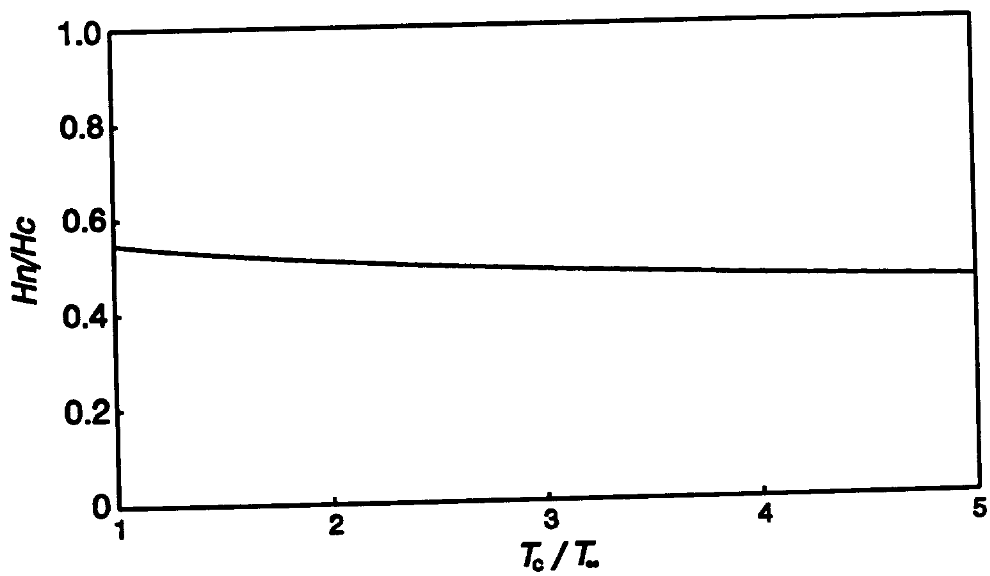

Figure 7. Height of neutral plane for example 1 for different room temperatures

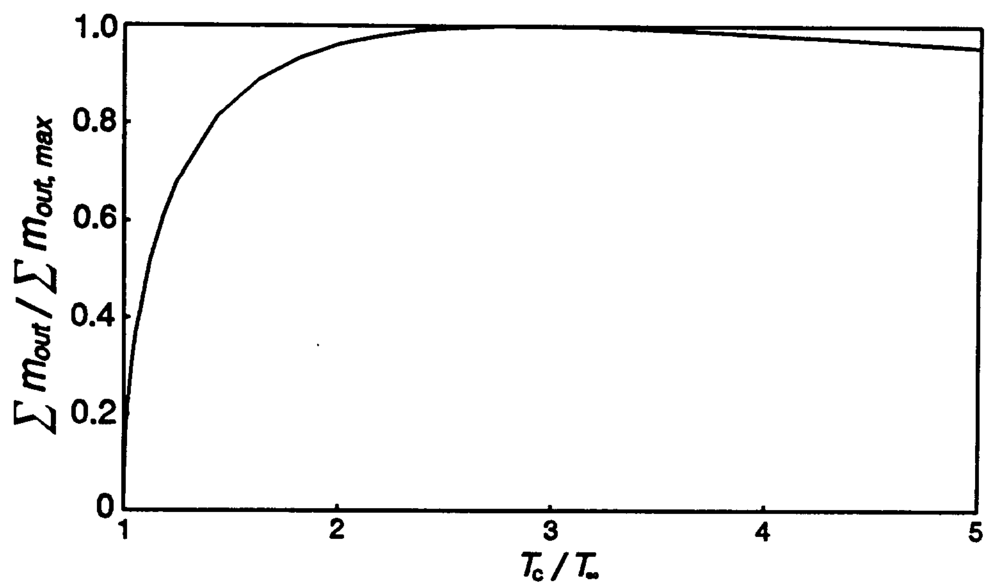

Figure 8. Mass flow rate leaving the room of example 1 for different room temperatures

of room temperature as shown in figure 7. However, the mass flow rate leaving the room is a strong function of temperature as illustrated in figure 8. For this example, the height of the neutral plane is a weak function of temperature, but the mass flow rate is a strong function of temperature. The functional relation for the space with a continuous opening and for a space with two openings is similar as can be observed from the equations developed for these two cases.

6.0 Example 2 - Top Vented Shaft

A shaft is connected to the outside by a continuous opening and is top vented as illustrated in figure 9. The height and width of the vertical opening, and temperatures are shown on the figure. For a vent area of 0.37 m^2 (4.0 ft^2), *Hn/Hc* is 0.91 and the mass flow rate out of the vent is 0.839 kg/s (1.85 lb/s). From figure 10 it is observed that the height of the neutral plane increases as the size of the top vent increases. In example 1 the location of the neutral plane was not a strong function of temperature, but it is observed in this example that the neutral plane location is a strong function of the areas of the openings. The mass flow out of the vent for different vent areas is shown in figure 11. This mass flow rate is a strong function of the area of the vent.

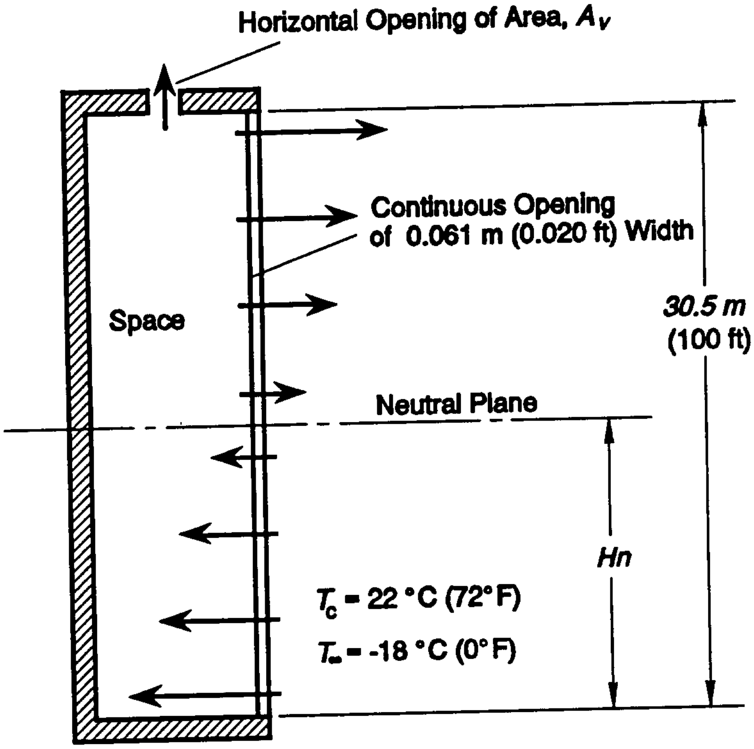

Figure 9. Top vented shaft of example 2

7.0 Example 3 - Approximation Of Vertical Openings

As previously stated the flow through vertical openings can be approximated by that through horizontal openings. The elevation of the horizontal opening is the arithmetic average of the bottom and top elevations of the vertical opening. This approximation is how all flows are dealt with in some smoke control and smoke movement programs (Klote and Fothergill 1983, Wakamatsu 1977, and Yoshida 1979). This example is intended to provide insight into the applicability and limitations of this approximation. Consider a shaft with the following vertical openings:

Opening 1 from 0 m (0 ft) to 30.5 m (100 ft) and 0.061 m (0.020 ft) wide,
Opening 2 from 6.10 m (20 ft) to 9.14 m (30 ft) and 0.305 m (1.00 ft) wide, and
Opening 3 from 0 m (0 ft) to 3.05 m (10 ft) and 0.305 m (1.00 ft) wide.

The shaft and the temperatures are shown in figure 12. STACK was used to calculate the location of the neutral plane under the following conditions:

Run 1 with all flow paths modeled exactly as vertical openings,
Run 2 with the two lower paths (openings 2 and 3) approximated by horizontal openings, and

Run 3 with all three paths approximated by horizontal openings.

The locations of the neutral plane and the flows for these runs are listed in table 1. Run 2 deviates from run 1 by only 0.4% for the location of the neutral plane and by less than 1.5% for the flows. Considering that the leakage values in most buildings are only roughly approximated, this error is not significant for most applications.

The deviation of run 3 from run 1 is 4.4% for the location of the neutral plane, and less than 4% for the flow through openings 2 and 3. However, all the flow through opening 1 is out for run 3, but it is bidirectional for the other runs. The major shortcoming of this approximation is that bidirectional flow is not included.

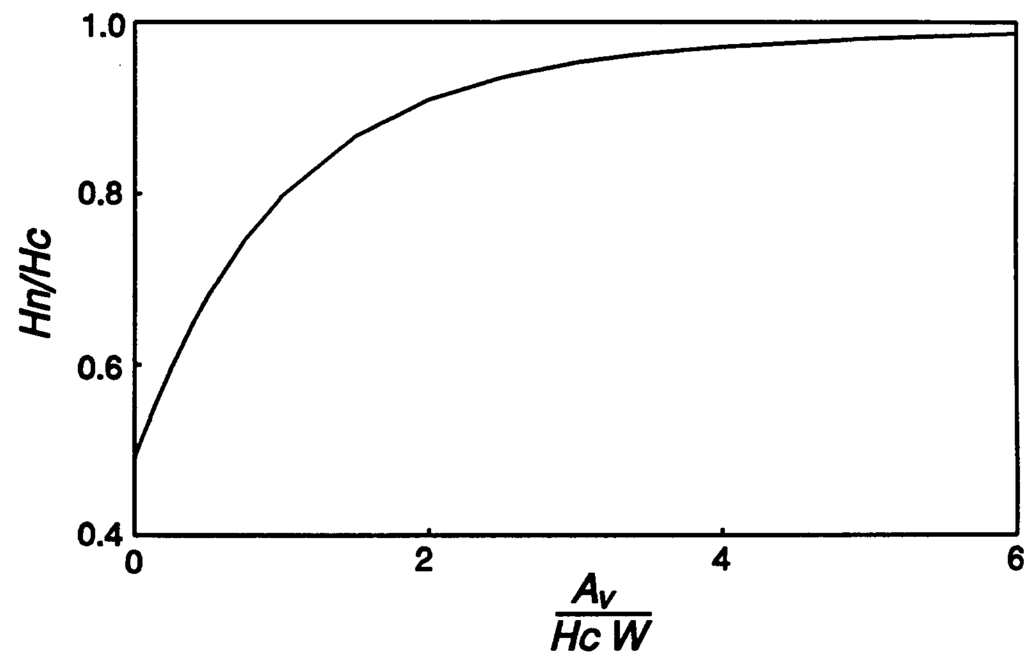

Figure 10. Height of neutral plane for example 2 for different vent areas

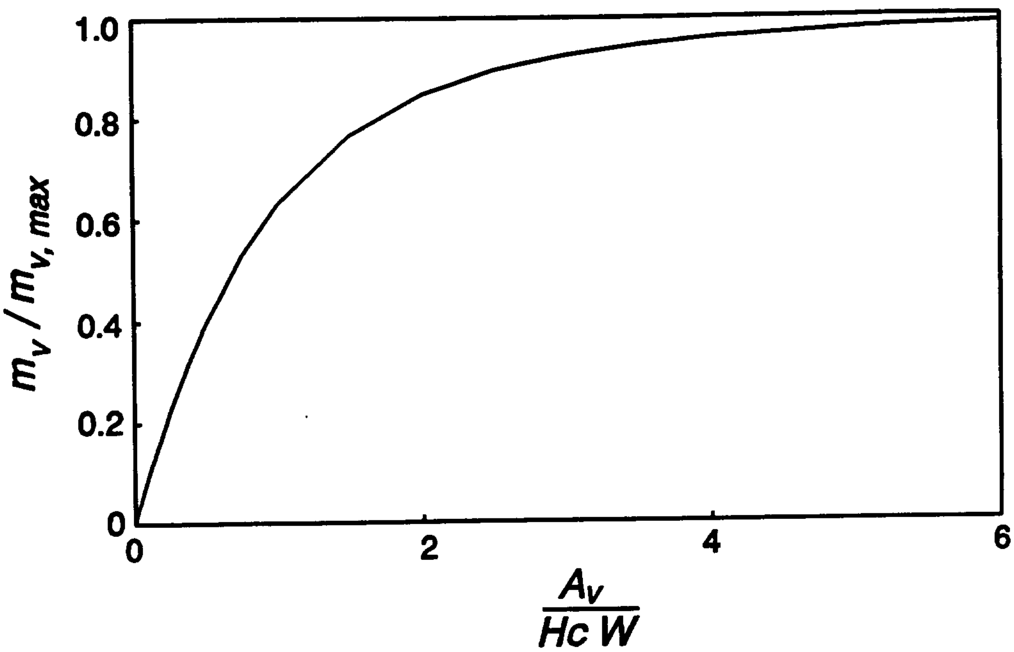

Figure 11. Mass flow rate leaving the vent of example 2 for different vent areas

8.0 Conclusions

1. The STACK program can be used to determine the location of the neutral plane and the flows due to stack effect.

2. The location of the neutral plane between a space and its surroundings is a weak function of temperature and a strong one of the size of openings.

3. Mass flow rate leaving a space due to stack effect is a strong function of temperature.

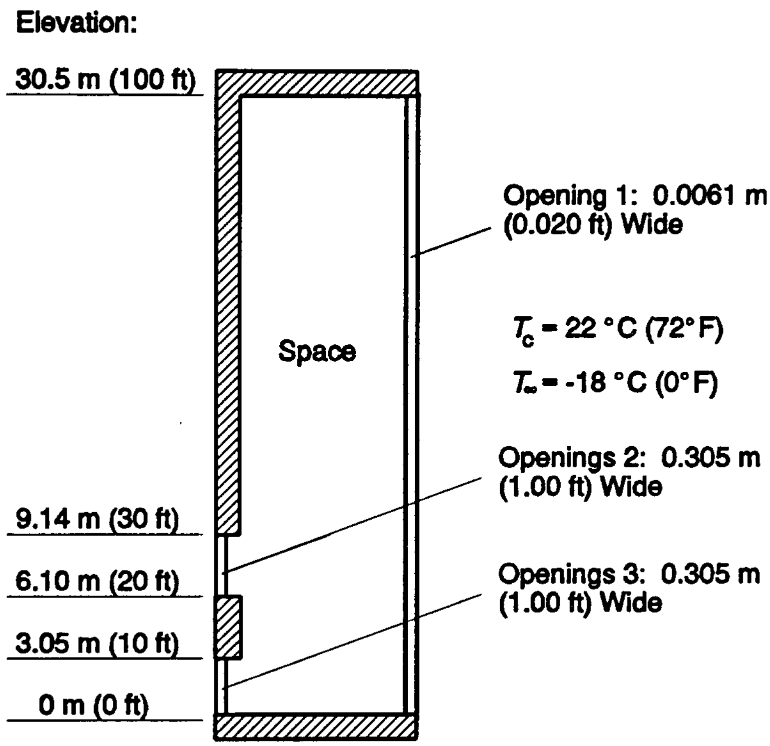

Figure 12. Shaft with three openings of example 3

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Table 1. Location of neutral plane and flows for example 3

	Hn/Hc	kg/s	lb/s
Run 1	0.1697		
Flow out of opening 1 above neutral plane		0.7044	1.553
Flow into opening 1 below neutral plane		0.0699	0.154
Flow out of opening 2		1.944	4.286
Flow into opening 3		2.579	5.685
Run 2	0.1703		
Flow out of opening 1 above neutral plane		0.7035	1.551
Flow into opening 1 below neutral plane		0.0703	0.155
Flow out of opening 2		1.972	4.347
Flow into opening 3		2.605	5.743
Run 3	0.1772		
Flow out of opening 1		0.794	1.750
Flow out of opening 2		1.885	4.155
Flow into opening 3		2.679	5.905

Appendix A Computer Program For Analysis Of Stack Effect

```
'******************************
' P R O G R A M    S T A C K *
'**********************************************
'STACK PROGRAM FOR EVALUATION OF STACK EFFECT DUE *
'TO HORIZONTAL AND VERTICAL OPENINGS. THIS PROGRAM*
'IS WRITTEN IN MICROSOFT QUICKBASIC.           *
'**********************************************
'
'*************************************************************************
'                   VARIABLES:
' ACCUR        ACCURACY CRITERION USED IN NEUTRAL PLANE CALCULATION.
' Ai(I)        AREA OF iTH HORIZONTAL OPENING.
' C            FLOW COEFFICIENT.
' COPIES       1 IF ONLY SCREEN OUTPUT IS DESIRED, 2 IF PRINTER OR FILE
'               OUTPUT IS ALSO DESIRED.
' DENcomp      DENSITY OF THE SPACE(COMPARTMENT) AIR.
' DENout       DENSITY OF OUTSIDE AIR.
' DIR$         DIRECTION OF MASS FLOW: EITHER "IN" OR "OUT" OF AN OPENING.
' ENGTc        TEMPERATURE OF THE SPACE IN DEGREES F IF ENGLISH UNITS ARE USED.
' ENGTout      TEMPERATURE OF OUTSIDE IN DEGREES F IF ENGLISH UNITS ARE USED.
' FLAGHOR$     CHARACTER FLAG INDICATING IF ANY HORIZONTAL OPENINGS ARE INPUT.
' FLAGVERT$    CHARACTER FLAG SHOWING IF ANY VERTICAL OPENINGS ARE USED.
' G            GRAVITATIONAL CONSTANT.
' Hbi(I)       HEIGHT OF BOTTOM OF iTH VERTICAL OPENING FROM THE FLOOR.
' Hti(I)       HEIGHT OF TOP OF iTH VERTICAL OPENING FROM THE FLOOR.
' Hi(I)        HEIGHT OF iTH HORIZONTAL OPENING.
' Hmax         MAXIMUM HEIGHT OF ANY OPENING ABOVE THE FLOOR.
' HORSTR$      CHARACTER LINE SERVING AS OUTPUT HEADER LINE FOR HOR. OPENINGS.
' MFLOW(I,J)   MASS FLOW RATE THROUGH OPENING I. USUALLY J=1 AND THERE
'               IS ONLY 1 MASS FLOW. SOMETIMES J=1 OR 2 AND THERE ARE 2
'               OPPOSING MASS FLOWS THROUGH A VERTICAL OPENING.
' N            NUMBER OF OPENINGS IN THE SPACE.
' P            ATMOSPHERIC PRESSURE.
' PATHSEL$     CHARACTER VARIABLE CONTAINING "N" IF THE USER ONLY WANTS THE
'               RESULTS SENT TO THE SCREEN, "PRN" IF A COPY OF THE RESULTS
'               IS TO BE SENT TO A PRINTER, OR A DOS FILENAME FOR OUTPUT TO
'               A FILE.
' PATHTYPE(I) 1 IF iTH OPENING IS HORIZONTAL, 2 IF IT IS VERTICAL.
' R            GAS CONSTANT.
' SECFLOW(I)   ARRAY CONTAINING MASS FLOW IN EITHER S LITERS/S OR SCFM
'               (DEPENDING ON UNITS CHOSEN).
' SOL          COMPUTED VALUE FOR NEUTRAL PLANE HEIGHT.
' Tc           TEMPERATURE OF SPACE IN DEGREES C IF SI DIMENSIONS ARE USED.
' TOTout       TOTAL MASS FLOW OUT OF THE SPACE.
' Tout         TEMPERATURE OF OUTSIDE IN DEGREES C IF SI UNITS ARE USED.
' UNITS        1 IF SI UNITS ARE TO BE USED, 2 IF UNITS ARE ENGLISH.
' VERTSTR$     CHARACTER LINE SERVING AS OUTPUT HEADER LINE FOR VERT. OPENINGS.
' Wi(I)        WIDTH OF iTH VERTICAL OPENING.
```

```
'
'             VARIABLES SHARED WITH OTHER ROUTINES:
'  Ai(),C,DENcomp,DENout,G,Hbi(),Hi(),Hti(),MFLOW(,),N,PATHTYPE(),Wi()
'******************************************************************************
'      FIRST, DECLARE THE MASS-FLOW FUNCTION CALLED BY THE ALGORITHM
'      AND SPECIFY THE VARIABLES SHARED BETWEEN IT AND THE MAIN PROGRAM.
'      ALSO, DECLARE THE ROOT-FINDING FUNCTION.
   DECLARE FUNCTION FUNET# (X#)
   DECLARE FUNCTION RTBIS# (LLIM#, UPLIM#, ACCUR#)
   DEFDBL A-Z
   DIM SECFLOW(25, 2)
   DIM SHARED DENout, DENcomp, C, G, N
   DIM SHARED Hbi(25), Hti(25), Hi(25), Wi(25), Ai(25), PATHTYPE(25)
   DIM SHARED MFLOW(25, 2)

'      PERFORM INITIALIZATIONS, ASCERTAIN IF THE USER WANTS SI OR ENGLISH
'      UNITS, INITIALIZE THE OUTPUT HEADINGS ACCORDINGLY, AND THEN READ IN
'      THE OUTSIDE AND SPACE TEMPERATURES. CHECK TO MAKE SURE THAT THE
'      TWO TEMPERATURES ARE NOT IDENTICAL. ALSO, AFTER THE UNITS ARE CHOSEN,
'      DETERMINE IF THE USER DESIRES A COPY OF PROGRAM RESULTS SENT TO A
'      PRINTER OR A FILE.
   CLS
   C = .65#
   G = 9.805#
   P = 101325#
   R = 287#
   FLAGHOR$ = " *NONE*"
   FLAGVERT$ = " *NONE*"
   INPUT "Enter 1 for SI Units or 2 for English Units: ", UNITS
   PRINT ""
   PRINT "Program output is always sent to the screen. If you wish"
   PRINT "to send an identical copy of the output to your printer or"
   PRINT "a file do the following:"
   PRINT "      For printer output enter PRN"
   PRINT "      For output to a file enter the DOS filename."
   PRINT ""
   INPUT "Output destination? (press enter for no file)  ", PATHSEL$
   IF PATHSEL$ = "" THEN PATHSEL$ = "N"
   PATHSEL$ = UCASE$(PATHSEL$)
   PRINT ""
   IF UNITS = 1 THEN
      HORSTR$ = "     " + "Height(m)    Area(Sq Meter)" + STRING$(23, " ")
      HORSTR$ = HORSTR$ + "Flow(kg/s)   Flow(sL/s)*"
      VERTSTR$ = "      " + "Height(m)      Height(m)       Width(m)"
      VERTSTR$ = VERTSTR$ + STRING$(10, " ") + "Flow(kg/s)   Flow(sL/s)*"
      DO
         INPUT "Outside Temperature (C) ?  ", Tout
         INPUT "Inside Temperature (C) ?  ", Tc
         IF Tout = Tc THEN
            PRINT " ERROR - OUTSIDE AND INSIDE TEMPERATURES ARE IDENTICAL. "
            PRINT " REENTER THESE VALUES.   "
```

```
         END IF
      LOOP UNTIL Tout <> Tc
      Tout = Tout + 273.15
      Tc = Tc + 273.15
   ELSE
      HORSTR$ = "      " + "Height(ft)     Area(Sq Feet)" + STRING$(23, " ")
      HORSTR$ = HORSTR$ + "Flow(lb/s)     Flow(scfm)*"
      VERTSTR$ = "      " + "Height(ft)     Height(ft)      Width(ft)"
      VERTSTR$ = VERTSTR$ + STRING$(10, " ") + "Flow(lb/s)     Flow(scfm)*"
      DO
         INPUT "Outside Temperature (F) ?  ", ENGTout
         INPUT "Inside Temperature (F) ?  ", ENGTc
         IF ENGTout = ENGTc THEN
            PRINT " ERROR - OUTSIDE AND INSIDE TEMPERATURES ARE IDENTICAL. "
            PRINT " REENTER THESE VALUES.    "
         END IF
      LOOP UNTIL ENGTout <> ENGTc
   END IF
   PRINT ""

'     READ IN THE NUMBER OF HORIZONTAL AND VERTICAL OPENINGS.
   INPUT "Number of Openings ?  ", N

'     INPUT INFORMATION FOR EACH HORIZONTAL AND VERTICAL OPENING.
'     THE ARRAY PATHTYPE IS USED TO DETERMINE WHETHER OPENING I
'     IS VERTICAL OR HORIZONTAL. SPECIFY THE APPROPRIATE DIMENSIONS
'     DEPENDING ON THE VALUE OF THE UNITS FLAG.
   PRINT ""
   FOR I = 1 TO N
      INPUT "Opening Type (Horizontal=1, Vertical=2) ?  ", PATHTYPE(I)
      IF PATHTYPE(I) = 1 THEN
         FLAGHOR$ = " "
         IF UNITS = 1 THEN
            INPUT "  Elevation of Opening (m) ?  ", Hi(I)
            INPUT "  Opening Area (Sq m) ?  ", Ai(I)
         ELSE
            INPUT "  Elevation of Opening (ft) ?  ", Hi(I)
            INPUT "  Opening Area (Sq ft) ?  ", Ai(I)
         END IF
      ELSEIF PATHTYPE(I) = 2 THEN
         FLAGVERT$ = " "
         IF UNITS = 1 THEN
            DO
               INPUT "  Elevation of Bottom (m) ?  ", Hbi(I)
               INPUT "  Elevation of Top (m) ?  ", Hti(I)
               IF Hbi(I) >= Hti(I) THEN
                  PRINT " BOTTOM HEIGHT OF VERTICAL OPENING IS GREATER THAN "
                  PRINT " OR EQUAL TO TOP HEIGHT. REENTER BOTH VALUES. "
               END IF
            LOOP UNTIL Hbi(I) < Hti(I)
            INPUT "  Width (m) ?  ", Wi(I)
```

```
      ELSE
         DO
            INPUT "  Elevation of Bottom (ft) ?  ", Hbi(I)
            INPUT "  Elevation of Top (ft) ?  ", Hti(I)
            IF Hbi(I) >= Hti(I) THEN
               PRINT " BOTTOM HEIGHT OF VERTICAL OPENING IS GREATER THAN "
               PRINT " OR EQUAL TO TOP HEIGHT. REENTER BOTH VALUES. "
            END IF
         LOOP UNTIL Hbi(I) < Hti(I)
         INPUT "  Width(ft) ?  ", Wi(I)
      END IF
   END IF
NEXT I

'     DETERMINE THE MAXIMUM HEIGHT OF THE OPENINGS.
Hmax = 0#
FOR I = 1 TO N
   IF PATHTYPE(I) = 1 AND Hi(I) > Hmax THEN Hmax = Hi(I)
   IF PATHTYPE(I) = 2 AND Hti(I) > Hmax THEN Hmax = Hti(I)
NEXT I

'     IF NUMBER OF OPENINGS IS 1, AND IT IS A HORIZONTAL OPENING, THEN
'     THE PROBLEM IS TRIVIAL.
IF N = 1 AND PATHTYPE(1) = 1 THEN
   PRINT "": PRINT ""
   PRINT USING " Neutral Plane is at Height ####.##: "; Hi(1)
   PRINT " No Mass Flow Due to Stack Effect Occurs."
   INPUT " Enter any Keystroke to Terminate Execution.", ANYKEY$
   STOP
END IF

'     IF ENGLISH UNITS ARE BEING USED, PERFORM CONVERSIONS FROM ENGLISH
'     TO METRIC SINCE THE MASS-FLOW CALCULATIONS REQUIRE METRIC VALUES.
IF UNITS <> 1 THEN
   FOR I = 1 TO N
      Hi(I) = Hi(I) * .3048
      Ai(I) = Ai(I) * .092903
      Hbi(I) = Hbi(I) * .3048
      Hti(I) = Hti(I) * .3048
      Wi(I) = Wi(I) * .3048
   NEXT I
   Hmax = Hmax * .3048
   Tc = ((ENGTc - 32!) * 5! / 9!) + 273.15
   Tout = ((ENGTout - 32!) * 5! / 9!) + 273.15
END IF

'     DETERMINE THE AIR DENSITY WITHIN THE SPACE AND OUTSIDE.
DENcomp = P / (R * Tc)
DENout = P / (R * Tout)

'     CALL THE ROOT-FINDING ROUTINE TO FIND HEIGHT OF NEUTRAL PLANE AS
```

```
'      WELL AS MASS-FLOW RATES DUE TO INDIVIDUAL OPENINGS.
    ACCUR# = .0000001# * Hmax#
    SOL = RTBIS(0#, Hmax#, ACCUR#)
    SOLFLOW = FUNET(SOL#)

'      IF ENGLISH UNITS ARE BEING USED, THEN IT IS NOW APPROPRIATE TO
'      CONVERT METRIC VALUES BACK TO ENGLISH UNITS, SINCE MASS-FLOW
'      CALCULATIONS ARE FINISHED.
    IF UNITS <> 1 THEN
       FOR I = 1 TO N
          Hi(I) = Hi(I) / .3048
          Ai(I) = Ai(I) / .092903
          Hbi(I) = Hbi(I) / .3048
          Hti(I) = Hti(I) / .3048
          Wi(I) = Wi(I) / .3048
          MFLOW(I, 1) = MFLOW(I, 1) * 2.2046
          MFLOW(I, 2) = MFLOW(I, 2) * 2.2046
       NEXT I
       SOL = SOL / .3048
       Tout = ((Tout - 273.15) * 9! / 5) + 32!
       Tc = ((Tc - 273.15) * 9! / 5) + 32!
    END IF

'      IF METRIC VALUES ARE DESIRED, CONVERT kg/s TO S LITERS/s.
    IF UNITS = 1 THEN
       FOR I = 1 TO N
          SECFLOW(I, 1) = 833! * MFLOW(I, 1)
          IF MFLOW(I, 2) <> 0! THEN SECFLOW(I, 2) = 833! * MFLOW(I, 2)
       NEXT I
    END IF

'      IF ENGLISH UNITS ARE BEING USED, CONVERT lbs/s TO scfm.
    IF UNITS <> 1 THEN
       FOR I = 1 TO N
          SECFLOW(I, 1) = 800! * MFLOW(I, 1)
          IF MFLOW(I, 2) <> 0! THEN SECFLOW(I, 2) = 800! * MFLOW(I, 2)
       NEXT I
    END IF

'      COMPUTE THE TOTAL MASS FLOW OUT OF THE SPACE.
    TOTout = 0!
    FOR I = 1 TO N
       IF MFLOW(I, 1) > 0! THEN TOTout = TOTout + MFLOW(I, 1)
       IF MFLOW(I, 2) > 0! THEN TOTout = TOTout + MFLOW(I, 2)
    NEXT I

'      NOW FOLLOWS THE SECTION OF THE PROGRAM THAT PRINTS OUT THE
'      OUTPUTS TO THE SCREEN, AND SENDS A COPY OF THE OUTPUT TO A PRINTER
'      OR A DOS FILE IF THE USER DESIRES. THIS SECTION IS ALWAYS EXECUTED
'      AT LEAST ONCE TO SEND THE RESULTS TO THE SCREEN, AND TWICE IF THE
'      USER WANTS A COPY OF THE RESULTS ON HIS PRINTER OR SENT TO
```

```
'      A DOS FILE. IN THIS LOOP, FIRST THE OUTSIDE TEMPERATURE, SPACE
'      TEMPERATURE, AND COMPUTED NEUTRAL-PLANE HEIGHT ARE PRINTED.
'      NEXT, INFORMATION CONCERNING THE HORIZONTAL OPENINGS(IF ANY)
'      IS OUTPUT. AFTER THIS, INFORMATION ABOUT THE VERTICAL OPENINGS
'      (IF ANY) APPEARS. IN THIS CASE, SPECIAL CARE IS TAKEN TO PROVIDE
'      FOR VERTICAL OPENINGS WHICH CROSS THE NEUTRAL PLANE, AND THUS
'      REQUIRE TWO MASS FLOW CALCULATIONS. FINALLY, THE NET MASS FLOW
'      AT THE NEUTRAL PLANE IS GIVEN.

OPEN "SCRN:" FOR OUTPUT AS #1
IF PATHSEL$ = "N" THEN COPIES = 1:  ELSE COPIES = 2

FOR Z = 1 TO COPIES


IF Z = 1 THEN CLS
IF UNITS = 1 THEN
   PRINT #1, USING "Outside temp. is #####.# C "; Tout - 273.15;
   PRINT #1, USING "       Space temp. is #####.# C "; Tc - 273.15
   PRINT #1, USING "Height of neutral plane is ####.### m "; SOL
ELSE
   PRINT #1, USING "Outside temp. is #####.# F "; Tout;
   PRINT #1, USING "       Space temp. is #####.# F "; Tc
   PRINT #1, USING "Height of neutral plane is ####.### ft "; SOL
END IF
IF FLAGHOR$ = " " THEN
   PRINT #1, "Horizontal Openings:"
   PRINT #1, HORSTR$
   FOR I = 1 TO N
      IF PATHTYPE(I) = 1 THEN
         IF MFLOW(I, 1) < 0! THEN DIR$ = "in " ELSE DIR$ = "out"
         PRINT #1, USING "    ####.###        ####.###"; Hi(I); Ai(I); TAB(48);
         PRINT #1, USING "\ \      #####.###"; DIR$; MFLOW(I, 1);
         PRINT #1, USING "    ########.#"; SECFLOW(I, 1)
      END IF
   NEXT I
END IF
IF FLAGVERT$ = " " THEN
   PRINT #1, "Vertical Openings:"
   PRINT #1, SPC(6); "Bottom"; SPC(10); "Top"
   PRINT #1, VERTSTR$
   FOR I = 1 TO N
      IF PATHTYPE(I) = 2 THEN
         IF MFLOW(I, 1) < 0! THEN DIR$ = "in " ELSE DIR$ = "out"
         PRINT #1, USING "     ####.###       ####.###           "; Hbi(I); Hti(I);
         PRINT #1, USING "###.###      \ \"; Wi(I); DIR$;
         PRINT #1, USING "     #####.###"; MFLOW(I, 1);
         PRINT #1, USING "   ########.#"; SECFLOW(I, 1)
         IF MFLOW(I, 2) <> 0! THEN
            IF MFLOW(I, 2) < 0! THEN DIR$ = "in " ELSE DIR$ = "out"
            PRINT #1, USING "\ \      #####.###   "; TAB(48); DIR$; MFLOW(I, 2);
```

```
                PRINT #1, USING "########.#"; SECFLOW(I, 2)
             END IF
          END IF
       NEXT I
    END IF
    PRINT #1, USING "Net mass flow is #####.### "; TAB(39); SOLFLOW
    PRINT #1, USING "Total mass flow out is #####.### "; TAB(33); TOTout
    IF UNITS = 1 THEN
       PRINT #1, "* sL/s is standard liters per second at 21 C and 1 atmosphere."
    ELSE
       PRINT #1, "* scfm is standard cubic ft per minute at 70 F and 1 atmosphere."
    END IF

'      IF THE USER DESIRES A COPY OF THE RESULTS SENT TO THE PRINTER OR
'      A FILE, THE OUTPUT DESTINATION IS OPENED FOR OUTPUT.

    IF Z = 1 AND PATHSEL$ <> "N" THEN
       CLOSE #1
       OPEN PATHSEL$ FOR OUTPUT AS #1
    END IF


    NEXT Z


    END

DEFSNG A-Z
'**********************************************************
'    FUNCTION FOR CALCULATION OF MASS-FLOW AT AN ASSUMED *
'    NEUTRAL PLANE HEIGHT IN THE SPACE. IF THE NET        *
'    MASS-FLOW IS 0, THEN THE HEIGHT IS INDEED THE        *
'    NEUTRAL PLANE HEIGHT. THE FUNCTION ALSO COMPUTES     *
'    MASS-FLOW RATES DUE TO INDIVIDUAL OPENINGS IN THE    *
'    SPACE.                                               *
'**********************************************************
'
'            LOCAL VARIABLES:
'
' DENi    DENSITY OF AIR PASSING THROUGH OPENING I.
' LHbi(I) HEIGHT OF BOTTOM OF VERTICAL OPENING I ABOVE X.
' LHi(I)  HEIGHT OF HORIZONTAL OPENING I ABOVE X.
' LHti(I) HEIGHT OF TOP OF VERTICAL OPENING I ABOVE X.
' S       -1 OR 1, INDICATES DIRECTION OF FLOW.
' SS      NET MASS FLOW.
' STO     INTERMEDIATE STORAGE VARIABLE FOR EQUATION CALCULATION.
' X       HEIGHT INPUT TO FUNET AS AN ARGUMENT.
'*********************************************************************
    FUNCTION FUNET# (X#)

    DEFDBL A-Z
```

```
'     DIMENSION THE LOCAL ARRAYS. LHbi IS LITTLE H SUB bi, ETC.
   DIM LHbi(25), LHti(25), LHi(25)

'     SET TOTAL AND INDIVIDUAL MASS FLOW TERMS TO 0.
   SS = 0#
   FOR II = 1 TO 25
      FOR J = 1 TO 2
         MFLOW(II, J) = 0!
      NEXT J
   NEXT II

'     CALCULATE THE NET MASS FLOW TERM FOR THE SPACE FOR I = 1 TO N,
'     WHERE N IS THE TOTAL NUMBER OF OPENINGS. MASS-FLOW RATES TO/FROM
'     INDIVIDUAL OPENINGS ARE ALSO COMPUTED.

   FOR I = 1 TO N

'           IF THE iTH OPENING IS HORIZONTAL, THEN DO THE FOLLOWING.
      IF PATHTYPE(I) = 1 THEN

         LHi = Hi(I) - X
         S = SGN(LHi * (DENout - DENcomp))
         IF S = -1 THEN DENi = DENout
         IF S = 1 THEN DENi = DENcomp
         STO = S * C * Ai(I)
         MFLOW(I, 1) = STO * SQR(2! * DENi * G * ABS(LHi * (DENout - DENcomp)))
         SS = SS + MFLOW(I, 1)

'           IF THE iTH OPENING IS VERTICAL, THEN EXECUTE THE ELSE BLOCK.
      ELSE

         LHbi = Hbi(I) - X
         LHti = Hti(I) - X

'           IF THE HEIGHTS OF THE TOP AND BOTTOM OF THE OPENING ARE
'           BOTH ABOVE OR BOTH BELOW THE CHOSEN HEIGHT, THEN THE
'           CURRENT OPENING DOES NOT SPAN THE CHOSEN HEIGHT.
         IF LHbi * LHti > 0 THEN

            S = SGN(LHbi * (DENout - DENcomp))
            IF S = -1 THEN DENi = DENout
            IF S = 1 THEN DENi = DENcomp
            STO = S * (2! / 3!) * C * Wi(I)
            STO = STO * ABS(((ABS(LHti)) ^ 1.5 - (ABS(LHbi)) ^ 1.5))
            MFLOW(I, 1) = STO * SQR(2! * DENi * G * ABS(DENout - DENcomp))
            SS = SS + MFLOW(I, 1)

'           THE CURRENT VERTICAL OPENING SPANS THE CHOSEN HEIGHT.
         ELSE
```

```
'                 CALCULATE MASS FLOW TERM FOR THE PORTION OF THE OPENING
'                 ABOVE THE CHOSEN HEIGHT. ADD IT TO NET MASS-FLOW.
              S = SGN(LHti * (DENout - DENcomp))
              IF S = -1 THEN DENi = DENout
              IF S = 1 THEN DENi = DENcomp
              STO = S * (2! / 3!) * C * Wi(I) * (ABS(LHti)) ^ 1.5
              MFLOW(I, 1) = STO * SQR(2 * DENi * G * ABS(DENout - DENcomp))
              SS = SS + MFLOW(I, 1)

'                 CALCULATE MASS FLOW TERM FOR THE PORTION OF THE OPENING
'                 BELOW THE CHOSEN HEIGHT. ADD IT TO NET MASS-FLOW.
              S = SGN(LHbi * (DENout - DENcomp))
              IF S = -1 THEN DENi = DENout
              IF S = 1 THEN DENi = DENcomp
              STO = S * (2! / 3!) * C * Wi(I) * (ABS(LHbi)) ^ 1.5
              MFLOW(I, 2) = STO * SQR(2! * DENi * G * ABS(DENout - DENcomp))
              SS = SS + MFLOW(I, 2)

           END IF

        END IF

     NEXT I


'       SET THE FUNCTION VALUE TO THE COMPUTED TOTAL MASS-FLOW RATE.
     FUNET = SS

     END FUNCTION

DEFSNG A-Z
'******************************************************************************
'    FUNCTION RTBIS IS USED TO FIND THE ROOT OF FUNET, I.E., WHERE NET
'    MASS FLOW IS 0. THE BISECTION ALGORITHM IS USED TO FIND THE ROOT.
'    X1# AND X2# ARE THE LOWER AND UPPER BOUNDS BETWEEN WHICH THE ROOT
'    LIES, WHILE XACC# IS THE DESIRED ACCURACY OF THE ROOT.
'******************************************************************************
'
'

     FUNCTION RTBIS# (X1#, X2#, XACC#)

     DEFDBL A-Z

     JMAX = 40

     FMID = FUNET(X2#)
     F = FUNET(X1#)
     IF F * FMID >= 0! THEN
        PRINT "ROOT MUST BE BRACKETED FOR BISECTION."
        STOP
     END IF
```

```
IF F < 0! THEN
   ROOT = X1
   DX = X2 - X1
ELSE
   ROOT = X2
   DX = X1 - X2
END IF

FOR J = 1 TO JMAX
   DX = DX * .5
   XMID = ROOT + DX
   FMID = FUNET(XMID#)
   IF FMID < 0! THEN ROOT = XMID
   IF ABS(DX) < XACC OR FMID = 0! THEN EXIT FOR
NEXT J

RTBIS = ROOT

END FUNCTION
```

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Stack effect is a major driving force of smoke movement in buildings. This paper presents a general method for evaluation of the location of the neutral plane for a space connected to its surroundings by any number of openings. A computer program, STACK, for analysis of the location of the neutral plane and resulting flows is presented along with example analyses. The examples show that the location of the neutral plane between a space and its surroundings is a weak function of temperature and a strong function of the size of openings. Further, the mass flow rate leaving a space due to stack effect is a strong function of temperature.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
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