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A COMPUTER MODEL FOR FLUID DYNAMIC ASPECTS OF A TRANSIENT FIRE IN A TWO ROOM STRUCTURE

(SECOND EDITION)

by

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ABSTRACT

A computer model which treats the fluid dynamic aspects of a transient fire in a two-room structure is described. In the model, the gas in each room is divided into two regions of uniform density: A ceiling layer which contains hot products of combustion, and a layer next to the floor which contains uncontaminated air. The fire plume entrains this fresh air, mixes it with hot combustion products and transports it to the ceiling layer. Flow through openings is described by a calculation similar to that used for orifice flows.

Fire growth, heat transfer to the walls, and other important features of a fire are described by ad hoc selection of parameters.

The thickness and temperature of the ceiling layers and the rate of flow of hot and cold air through opening are calculated as a function of the time by numerical integration of ordinary differential equations derived from the conservation laws of mass and energy.

A number of examples are presented to illustrate the use of the program and some general scaling rules for the initial stages of a room fire.

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List of Symbols

b	width of opening (door or window)
Cmp	coefficient of plume mass flux
C_{oc}	orifice coefficient for cold flow
C_{oh}	orifice coefficient for hot flow
C_h	distance from floor to fire source
C_ℓ	constant for length scale in fire plume
C_{LS}	heat-loss coefficient
C_p	specific heat at constant pressure
C_v	constant for velocity in fire plume
g	gravitational acceleration
h	floor-to-ceiling height
ℓ_v	length scale for velocity distribution in fire plume
ℓ_T	length scale for temperature distribution in fire plume
$\mathcal{L}$	line-fire length
$\dot{m}(i, j)$	mass flow rate into j-th room through i-th opening from outdoors
$\dot{m}_E$	plume mass flow rate
$\dot{m}_f$	mass flow rate of fuel
$\dot{m}_j$	mass flow rate entrained by door jet
$\dot{m}_h(i, j)$	mass flow rate from j-th room ceiling layer to outdoors through i-th opening
$\dot{m}_{12}$	mass flow rate of fresh air from room 2 to room 1
$\dot{m}_{hij}$	mass flow rate of hot gas from room i to room j
$\dot{m}$	total cold-air flow into room
$\dot{m}_h$	total hot-gas flow out of room

p	pressure
Q	heat input from fire
Q_R	reference heat input
Q_W	heat transfered to ceiling and walls
$\dot{q}$	total heat and enthalpy flux into lower layer
$\dot{q}_h$	total heat and enthalpy flux out of ceiling layer
r	radial distance from plume center
S	floor area
t	time
T	temperature
y_{iu}	floor-to-soffit height of opening between two rooms
$y_{i\ell}$	floor-to-sill height of opening between two rooms
$y_u(i, j)$	soffit height for i-th opening in j-th room
$y_\ell(i, j)$	sill height for i-th opening in j-th room
y	distance from floor to ceiling-layer bottom
V	velocity
W	upward component of velocity in fire plume
Z	vertical distance from fire source
ρ	density
ΔT	temperature difference, $(T - T_\infty)$

Subscripts

1	room 1
2	room 2
∞	outdoors

Superscript

Dimensionless quantities are defined on the following page.

Reference Quantities for Dimensionless Variables

length	h_1
area	S_1
time	$S_1/(h_1\sqrt{gh_1})$
density	ρ_∞
pressure	$\rho_\infty g h_1$
temperature	T_∞
mass flux	$\rho_\infty h_1^2\sqrt{gh_1}$
heat or enthalpy flux	$\rho_\infty C_p T_\infty h_1^2\sqrt{gh_1}$

Dimensionless Variables

$\overline{m}_i = \dot{m}_i/(\rho_\infty h_1^2\sqrt{gh_1})$

$\overline{m}_{hi} = \dot{m}_{hi}/(\rho_\infty h_1^2\sqrt{gh_1})$

$\overline{q}_i = \dot{q}_i/(\rho_\infty C_p T_\infty h_1^2\sqrt{gh_1})$

$\overline{q}_{hi} = \dot{q}_{hi}/(\rho_\infty C_p T_\infty h_1^2\sqrt{gh_1})$

$\overline{y}_i = y_i/h_1$

$\overline{\rho}_{hi} = \rho_{hi}/\rho_\infty$

$p_i^* = (p_i - p_\infty)/(\rho_\infty g h_1)$

$\rho_i^* = \overline{\rho}_{hi} - 1$

$\overline{m}_E = \dot{m}_E/(\rho_\infty h_1^2\sqrt{gh_1})$

$\overline{m}_f = \dot{m}_f C_p T_\infty/Q$

$\overline{m}_J = \dot{m}_J/(\rho_\infty h_1^2\sqrt{gh_1})$

$\overline{Q} = Q/(\rho_\infty C_p T_\infty h_1^2\sqrt{gh_1})$

$\overline{S}_2 = S_2/S_1$

Note That:

$i = 1$ for room 1

$i = 2$ for room 2

Dimensionless Variables (Cont.)

$\bar{t} = h_1 \sqrt{g h_1}\; t / S_1$

$Q_R{}^* = Q_R / (\rho_\infty C_p T_\infty h_1{}^2 \sqrt{g h_1})$

$t^* = \bar{t}\, Q_R{}^{*1/3}$

Changes Made in Room Fire Model Program

1. Some errors in "FLOW 2" subroutine are corrected.

2. Some changes were made in "PRESS" subroutine to insure iterative convergence.

3. Subroutine "ADMASS" was added. See paragraph 9.

4. Different outdoor pressures may be specified for different openings through PAMB(M,N). M is for opening and N for room; e.g. PAMB(2,1) is the value for pressure outside opening 2 in room 1. If values for PAMB(M,N) are not assigned through the namelist "NAM 1", 0. is assigned (default value).

5. Flag FLPRT is changed to NFLPRT, an integer variable. Flags FPLOT 1 and FPLOT 2 are combined to NPLOT:

   NPLOT = 0 no plotting

   NPLOT = 1 plot y_1 and ρ_{h1}

   NPLOT = 2 plot y_1, ρ_{h1}, y_2 and ρ_{h2}.

6. Integration may be started with arbitrary initial condition, specified by the initial values: TI, for time; Y1I, Y2I for ceiling layer heights; ROH1I, ROH2I for ceiling-layer densities ρ_2* and ρ_1*; P1I, P2I for room pressures p_1* and p_2*. Default values are unchanged.

7. Integration step size may be changed by specifying TM 1, TM2, DT1, DT2, DT3 through namelist "NAM 1".

8. Output format is changed so that (i) heat-input Q is printed in the first table, (ii) MH21, hot-gas mass flow from room 2 to room 1, is added in the second table, which is printed when NFLPRT = 1.

9. SUBROUTINE ADMASS provides means for adding mass into room 1 and/or 2 which simulates mass addition (positive) or mass subtraction (negative) through heating and air-conditioning ducts or by forced ventilation. FORTRAN variables used for this purpose are:

Dimensionless mass addition rates through Vent M in Room N,

CMADD(M, N) into fresh-air zone

HMADD(M, N) into ceiling layer

Temperature of air added into the fresh-air zone is assumed to equal the ambient temperature (.0 in the program). When HMADD(M, N) is positive (mass flow into the ceiling layer), dimensionless enthalpy flux QADD(M, N) must also be specified (default values is .0). When HMADD(M, N) is negative, the program assumes that the temperature of outflow is equal to the appropriate ceiling-layer temperature.

The above variables are dimensioned as CMADD(5, 2), HMADD(5, 2) and QADD(5, 2) in the program. Default values are all zero.

ICMAD(N), IHMAD(N) are total number of fresh-air vents and hot-air vents, respectively, of room N.

CMADD, HMADD, QADD, ICMAD and IHMAD are added in the namelist "NAM1".

Example: Consider a room with a ceiling level air-conditioning duct. Let the air flow into the room be enough to replace the air in the room N times in an hour. The flow rate is then $\dot{w}_a$ = $\rho_\infty N(SH/3600) m^3/sec$ and the dimensionless flow rate is:

$$\text{HMADD}(1, 1) = w_a/\rho_\infty H^2 \sqrt{gH}$$

$$= \frac{N}{3600} \left(\frac{S_1}{H^2}\right) \sqrt{\frac{H}{g}}$$

Thus, if a room $S = 3 \times 6\ m^2$, $H = 3m$ and $N = 3$:

$$HMADD(1, 1) \approx 10^{-3}$$

If we consider a 60 kw fire in a room with a ceiling layer at 2 meters, $Q^* \simeq 0.01$ and the dimensionless plume entrainment rate is about .02. This flow rate is twenty times that of the vent and hence the vent flow will not be very important. If we examine very small fires, say 60 w, then the vent flow will be 1/2 of the plume entrainment flow and hence will be very important.

Note that in its present form air is added or removed from one layer or the other and the location of the vent is not specified.

1. INTRODUCTION

A fire starts in a room of a multiroom structure. Hot gas rises from the fire, entrains fresh air from the room as it rises toward the ceiling in a plume and forms a layer of hot gas under the ceiling. This ceiling layer of hot gas gradually becomes thicker and finally starts to flow out under the door soffit into the next room. Under the influence of heat transfer from the fire and ceiling layer gas, the fire heat input grows exponentially and combustible material surrounding the fire is gradually heated. Finally some minutes after ignition, these uninvolved fuel elements begin to pyrolize rapidly, fire spreads through the combustible products of pyrolysis and room flashover occurs.

During the early stages of the fires, the heat released by the fire is large enough to keep the pressure in the room above that in adjoining rooms, and both hot and ambient gas flows out of the door. Later on, the pressure falls below the ambient value. Then, fresh air enters the room through the bottom of the door, to replace that entrained in the plume, and hot gas flows out of the top of the door.

The hot gas flowing out of the fire room forms a ceiling layer in the adjoining room which thickens until hot gas can flow on into rooms further from the fire.

The spread of fire described above is complicated by processes such as radiant and convective heat transfer, the growth of the fire area and heat input rate, and the ignition and remote burning of products of pyrolysis. In the present paper we have chosen to examine some of the fluid dynamic aspects of the overall fire spread problem involving two rooms with arbitrary openings to the outside and a single opening connecting the two rooms. In addition, we assume that the gas in each room is divided into a hot region near the ceiling, the ceiling layer, and a cooler layer near the floor. This two-layer model is a rough approximation of the actual temperature profiles observed in real fire situations and its use greatly simplifies the calculations.

We do not attempt to calculate some important processes. For example, we will treat as given functions of the time, the fire heat input rate and the heat transfer rates from various regions of the gas. We have ignored the spreading process of the thin hot gas layer along the ceiling immediately following the inpingement of the fire plume or the door plume in the adjacent room. Instead, in keeping with the two layer model, we assumed that the hot gas spreads instantaneously over the ceiling as soon as the plume hits it. Therefore, our model is not appropriate for describing the ceiling layer in a long corridor without obstructions. However, long corridors with sizable obstructions across the ceiling may be treated by our model as a series of rooms with large openings.

The model described here will be used with other more detailed models of a room fire to develop a multiroom fire spread model.

A description of the physical bases of the mathematical model is given in Section 2 and a brief explanation of the numerical techniques, in Section 3. A number of examples are presented in Section 4. These results illustrate the use of the program, the sensitivity of the solutions to several of the modeling parameters and suggest some general ideas concerning time scales for room fires.

The Appendix contains a detailed description of the numerical program and a numerical example.

This report revises and extends material presented in a previous report dated January 1978.

2. PHYSICAL BASES FOR MODELING

The elements of the present model are presented in this section. These are: a fire of given, time dependent, heat input rate; a turbulent buoyant plume in which cool air is entrained, heated, and transported to the ceiling layer; the flow through openings under the influence of a hydrostatic pressure field; and entrainment by the gas flowing through the opening. Given a mathematic model for these elements and equations for conservation of mass and energy applied to each layer, we can develop a numerical calculation for the pressure, temperature, density and height of each layer in the multiroom model. The work described here concerns a two room situation. Generalization to more rooms is possible but does lead to algebraic complexities.

In the following paragraphs we describe the physical bases for the various subprograms of the calculation and give a brief derivation of the conservation laws.

I. Entrainment

The primary source of entrainment is the fire plume which acts as a pump to move air up into the ceiling layer. The fire plume is well enough understood that the plume produced by weak and physically small fires can be described adequately; larger fires can not be treated yet with any confidence. We use the conventional Boussinesq treatment, described below in Section A, for all fires regardless of size.

Entrainment at an opening is even less well understood. We describe two entrainment mechanisms and discuss the ad hoc entrainment model used in the present computer subprogram in Section B.

(A) Fire Plume.

The model used to describe the fire plume is based on that described by Turner, Taylor and Morton (Ref. 1) and it makes use of the Boussinesq approximation that density differences are small enough that they can be ignored everywhere except in the buoyancy terms of the momentum equation. The fundamental assumption concerns the rate of entrainment of fresh air by the plume.

When the results of Yokoi (Ref. 2) are used to determine the constant that appears in the entrainment assumptions, the turbulent fire plume can be characterized by the following equations:

$$\frac{\Delta T_m}{T_\infty} = \frac{\Delta\rho_m}{\rho_\infty} = C_T(Q^*)^{2/3} \qquad C_T \approx 9.1 \tag{1a}$$

$$\frac{w_m}{\sqrt{gZ}} = C_v(Q^*)^{1/3} \qquad C_v \approx 3.8 \tag{1b}$$

$$\frac{\ell v}{Z} = C_\ell \qquad C_\ell = 0.125 \tag{1c}$$

$$\frac{\ell_T}{Z} = C_{\ell_t} \qquad \frac{C_{\ell_t}}{C_\ell} = 1.15 \tag{1d}$$

and

$$\frac{\Delta T}{\Delta T_m} = \exp\{-(r/\ell_t)^2\}\ , \tag{1e}$$

$$\frac{w}{w_m} = \exp\{-(r/\ell_v)^2\}\ . \tag{1f}$$

Here the subscript (m) refers to conditions on the centerline of a plume with Gaussion distribution of velocity w, temperature and density T and ρ. Length scales for the radial distribution of temperature differences $\Delta T \equiv T-T_\infty$ and velocity are ℓ_t and ℓ_v. The parameter Q^* is a dimensionless measure of the rate of heat input from the fire and is given by

$$Q* = Q/\rho_\infty \sqrt{gZ}\, C_p\ T_\infty\ Z^2$$

The height above the fire is Z.

Measurements made far above the fire, where Z is large compared with the diameter of the fire D and density differences are small, are in good agreement with the predictions made from this representation.

Given these approximations, we can show that the mass-averaged temperature and density in the plume are:

$$\frac{\overline{\Delta T}}{T_\infty} = \frac{\overline{\Delta \rho}}{\rho_\infty} = \left[\frac{1}{\pi C_v C_\ell^2}\right] (Q*)^{2/3} = \frac{Q}{\dot{m}_E C_p T_\infty} \tag{2a}$$

and mass flow in the plume at height Z is

$$\dot{m}_E = \rho_\infty w_{max} \pi \ell_v^2$$

$$= \rho_\infty \sqrt{g \frac{\overline{\Delta \rho}}{\rho_1}} \left[(\pi C_v C_\ell^2)^{3/2}\right] (Z)^{5/2} ,$$

or

$$\dot{m}_E = \rho_\infty \sqrt{gZ}\ (Q*)^{1/3}\ Z^2\ (\pi C_v C_\ell^2) \quad . \tag{2b}$$

A development similar to that outlined above for the axisymmetric plume can be carried out for the plume above a line fire. The only new parameter is the fire length $\mathcal{L}$ and we again use a dimensionless heat addition parameter Q_2* which is based on the total heat released by the fire:

$$Q_2* = \frac{Q}{\rho C_p\ T_\infty \sqrt{gZ}\ \mathcal{L} Z} \quad ,$$

Q = total heat addition rate.

The plume equations are based on the assumption of a Gaussian distribution for velocity and temperature with a scale ℓ_v. The model equations are:

$$\frac{\Delta T_{m2}}{T_\infty} = C_{T2}\ (Q_2^*)^{2/3} \qquad C_{T2} = 2.6 \tag{3a}$$

$$\frac{W_{m2}}{\sqrt{gz}} = C_{v2}\ (Q_2^*)^{1/3} \qquad C_{v2} = 2 \tag{3b}$$

$$\frac{\ell_v}{Z} = C_{\ell 2} \qquad C_{\ell 2} = 0.14 \tag{3c}$$

$$m_{E2} = \rho_\infty \sqrt{\frac{\overline{\Delta\rho}}{\rho_\infty}\ g}\ (\sqrt{\pi}\ C_{v2} C_{\ell 2})^{3/2}\ (Z^{3/2}\mathcal{L}) \tag{4a}$$

$$\frac{\overline{\Delta T}}{T_\infty} = \left[\frac{1}{\sqrt{\pi}\ C_{v2} C_{\ell 2}}\right] (Q_2^*)^{2/3} = \frac{\overline{\Delta\rho}}{\rho_\infty} \tag{4b}$$

The values of constants are much less certain here than for the axisymmetric case, and again, the Boussinesq approximation has been used.

(B) Door Jet

The two situations in which strong entrainment was observed by a stream flowing through an opening are illustrated in Figure 1. In Figure 1a, a hot jet flows under the soffit of an opening and impinges on the ceiling layer of an adjacent room. The jet entrains gas from the cooler region of this room during this process and under some conditions the entrained flow will be larger than the flow through the door. Entrainment by this jet is modeled in the RJET Subroutine and the notation is described in the figure.

Insufficient data is available now to permit an accurate estimate to be made of this entrainment rate. Hence, the algorithm used here is viewed as a first very crude model which is useful to us in the development of the program, but which must be improved substantially.

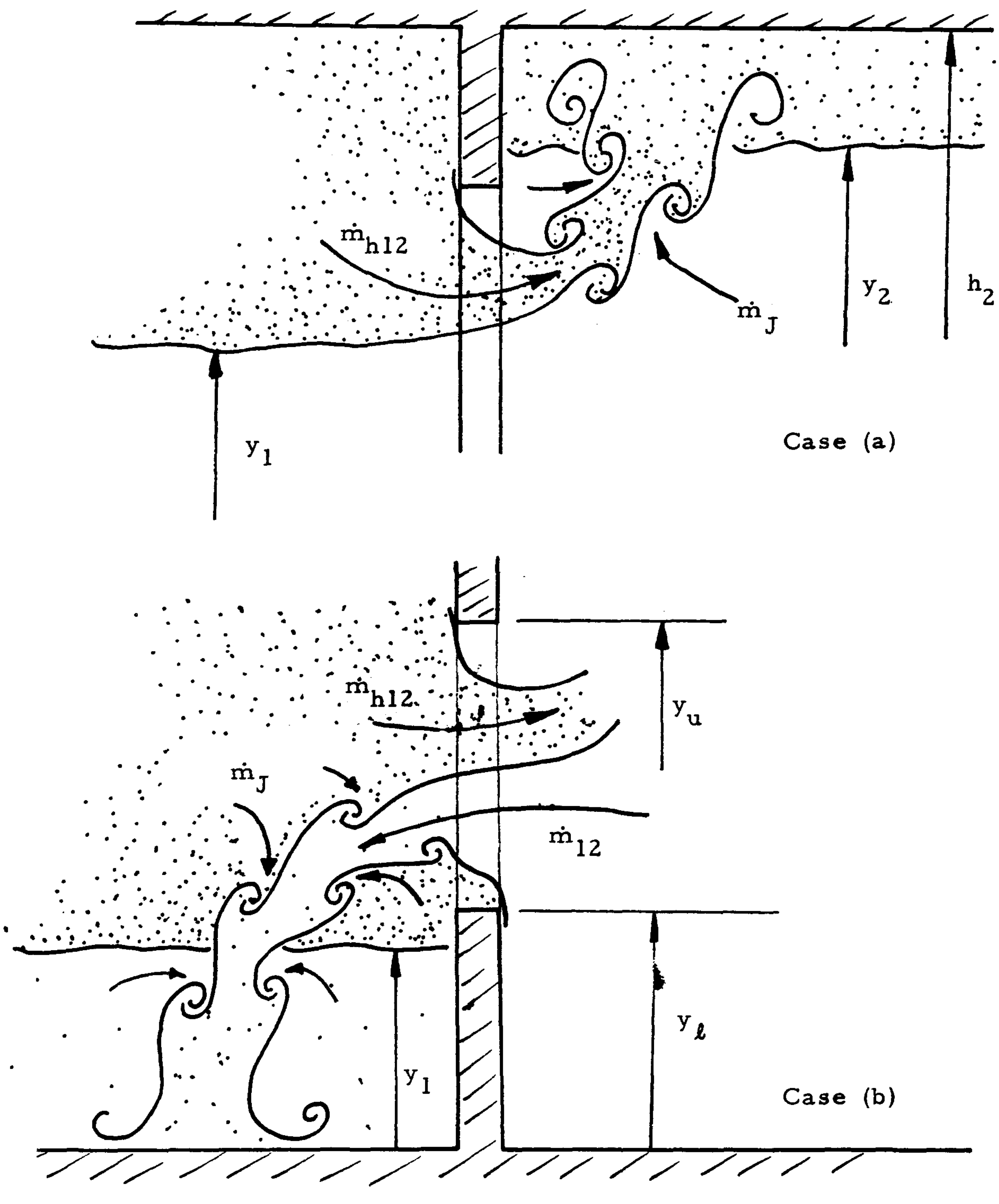


Figure 1. Mixing in the Opening

We have observed in salt-water/water modeling experiments that the entrainment rate increases as the distance $(y_2 - y_1)$ increases. In the model we normalize this distance by $(y_u - y_1)$ which corresponds roughly to the initial scale of the doorjet. In addition, we found in the salt-water/water model work that entrainment stopped when y_2 approached the average of y_1 and y_u. We have arbitrarily chosen to normalize the length $y_j \equiv \left[y_2 - \frac{1}{2}(y_u + y_1)\right]$ by the distance $(h_2 - y_1)$. Here h_2 is the height of room two. The resulting equation for the entrained flow is:

$$R_{jet} \equiv \frac{\dot{m}_J}{m_{h12}} = C_J\left(\frac{y_2 - y_1}{y_u - y_1}\right)\left[\frac{y_2 - \frac{1}{2}(y_u + y_1)}{h_2 - y_1}\right]^2 \tag{5}$$

The constant C_J has been taken to be 1, and R_{jet} is the ratio of entrained mass flow rate to the rate of mass flow out of the opening.

By analogy, the entrainment rate for the flow shown in Figure 1b can be written as

$$R_{jet} = C_J\left(\frac{y_u + y_\ell - 2y_1}{y_u + y_\ell - 2y}\right)\left[\frac{y_u + 3y_\ell - 4y_1}{y_1}\right]^2 \tag{6}$$

The neutral buoyancy point is close to $(y_u + y_1)/2$ for this case, which is only of interest when $y_1 < y_\ell$. This flow program has not yet been included in the subroutine.

II. Flow Through an Opening

Calculation of flows through an opening connecting spaces with differing static pressures is approached in the same manner as that used to calculate orifice flow. Consider the situation shown below in Figure 2. We assume that $P_i > P_k$, that the flow from (i) to (k) separates from the walls

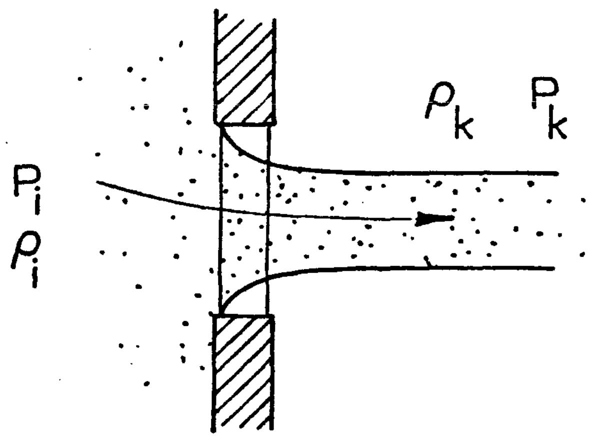


Figure 2. Flow Through on Opening

to form a jet, and that the pressure at the vena contracta in the jet is P_k. The dynamic pressure in the jet can be found from the Bernoulli equation for an incompressible flow from a stagnation pressure of magnitude P_i to a static pressure P_k:

$$\frac{1}{2} \rho_i V_i^2 + P_k = P_i \tag{7}$$

Given V_i from equation (7), the mass flux from (i) to (k) through an opening of area A is:

$$\dot{m}_{ik} = \rho_i V_i C_{oi} A = C_{oi} \sqrt{2 (P_i - P_k) \rho_i} A$$

The coefficient C_{oi} is the flow coefficient which is most simply understood as the ratio of the cross section area at the vena contracta to the area of the opening. However, it is also used to take into account errors in this simple calculation due to viscous effects and geometric effects.

If the pressures P_i and P_k are functions of position, as they are in our problem due to hydrostatic effects, we must use an integral over the opening area. The pressure difference can be written as a function of elevation y as

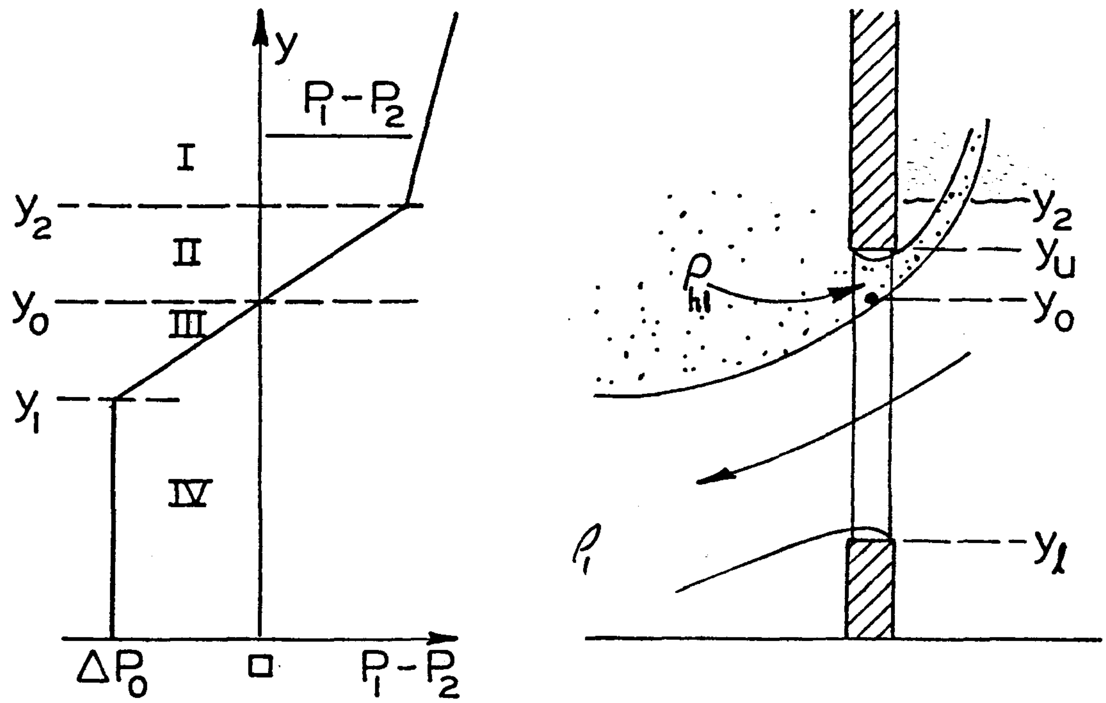
$$P_i - P_k = (P_{io} - P_{ko}) - \int_o^y (\rho_i - \rho_k)\, g\, dy = \Delta P_{ik} \tag{8}$$

and the corresponding mass flow rate as

$$m_{ik} = C_{oi} \int_{y_\ell}^{y_u} \sqrt{2\,|\Delta P_{ik}\ (y)|\,\rho_i}\ \mathrm{sgn}\ (\Delta P_{ik})\ \ b(y)\ dy \tag{9}$$

Here, b(y) is the width of the opening, y is the vertical coordinate and g the gravitational constant. The integral is taken over the region between the highest (or upper) extent of the door y_u, and the lowest extent y_ℓ.

The pressure difference across the wall separating two rooms can change in sign as we move from the floor to the ceiling for physically reasonable flow situations. For example, consider the example shown in Figure 3B. Here each room is assumed to be divided into two regions, the densities of the gas in the lower regions are ρ_∞, and in the upper regions are ρ_{h1} and ρ_{h2} respectively. In addition, we assume that for this case $\rho_\infty > \rho_{h2} > \rho_{h1}$. The pressure difference across the wall which is produced by hydrostatic effects when the value at the floor is negative is shown in Figure 3A. Between the floor and y_1, the density difference is zero and we see from equation (8) that the pressure difference must be constant. Between y_1 and y_2, the density difference $(\rho_{h1} - \rho_\infty)$ is negative and consequently the pressure difference must increase. The position of zero difference is at y_o which is called the neutral buoyancy point. Above y_2, the density difference, $(\rho_{h1} - \rho_{h2})$, is still



(3A) (3B)

Case 1.1

y_u / y_ℓ	I	II	III	IV
I	1.1.1.4			
II	1.1.1.3	1.1.2.3		
III	1.1.1.2	1.1.2.2	1.1.3.2	
IV	1.1.1.1	1.1.2.1	1.1.3.1	1.1.4.1

Figure 3. Opening Flow Calculation Scheme

negative but we have assumed it to be less so and hence the slope is larger in this region.

The direction of mass flow through an opening in the situation described in Figures 3A and 3B will be from room (2) to room (1) if the opening is below y_o and in the opposite direction if it is above y_o. Both flows can be calculated from equation (8) but choice of subscripts (i) and (k) and the direction of the flow will be fixed according to the sign of the pressure difference.

Rather than carrying out numerical integration of terms such as those in equations (8) and (9) for each opening and each time step, we have chosen to carry out the integrals analytically for a number of special cases and for three general families of density/pressure distributions. Because of our use of the two layer model for the density distribution in a room, the density differences which appear in equation (8) take on various constant values over the room height. For the example, in Figure 3 the pressure and derivative of mass flux are:

(a) For $0 \leq y \leq y_1$, Region IV:

$$\left.\begin{aligned} &\rho_i - \rho_\infty = 0 \\ &P_2 - P_1 = P_{o2} - P_{o1} = \Delta P_o \\ \text{and} \quad &\frac{dm_{21}}{dy} = C_{o2}\sqrt{2\Delta P_o \rho_\infty}\, b(y) \end{aligned}\right\} \quad (10)$$

(b) For $y_1 < y \leq y_o$, Region III

$$\left.\begin{aligned} &\rho_i - \rho_k = -(\rho_\infty - \rho_{h1}) \\ &P_2 - P_1 = \Delta P_o + (\rho_\infty - \rho_{h1})(y - y_1)\, g \\ &y_o = y_1 - \Delta P_o / \left[(\rho_\infty - \rho_{h1}) g\right] \end{aligned}\right\} \quad (11)$$

and $$\frac{d\dot{m}_{21}}{dy} = C_{o2} \sqrt{2 \rho_\infty g \, (\rho_\infty - \rho_{h1}) (y_o - y)} \, b(y)$$

(c) For $y_o < y \leq y_2$, Region II

$$\left.\begin{aligned} \rho_i - \rho_k &= - (\rho_\infty - \rho_{h1}) \\ P_1 - P_2 &= (\rho_\infty - \rho_{h1}) (y - y_1) \, g - \Delta P_o \\ \text{and} \quad \frac{d\dot{m}_{12}}{dy} &= C_{o1} \sqrt{2\rho_1 \, g \, (\rho_\infty - \rho_{h1}) (y - y_o)} \, b \end{aligned}\right\} \qquad (12)$$

and finally

(d) For $y_2 \leq y$, Region I

$$\left.\begin{aligned} \rho_i - \rho_k &= - (\rho_{h1} - \rho_{h2}) \\ P_1 - P_2 &= \left[(\rho_\infty - \rho_{h1}) (y_2 - y_1) \, g - \Delta P_o\right] (\rho_{h2} - \rho_{h1}) g \, (y - y_2) \\ y_o' &\equiv y_2 - \left[(\rho_\infty - \rho_{h1})(y_2 - y_1) \, g - \Delta P_o\right] / \left[(\rho_{h2} - \rho_{h1}) g\right] \\ \text{and} \quad \frac{d\dot{m}_{12}}{dy} &= C_{o1} \sqrt{2\rho_1 \, g (\rho_{h2} - \rho_{h1})(y - y_o')} \, b(y) \end{aligned}\right\} \qquad (13)$$

Given an opening which includes any of the regions I to IV of Figure 3, the mass flux can be calculated from the appropriate equation given above. For example, consider the situation shown in Figure 3b where an opening has its upper bound in region II and lower in region I. The mass flux from lower (cool) region of room (2) into the lower region of room (1) is given by carrying out the integral of (3) from y_1 to y_o. If we assume that $b(y)$ is a constant b, the mass flux for the region $y_\ell \leq y < y_1$ is:

$$C_{o2} \sqrt{2 \, \Delta P_o \, \rho_\infty \, g} \; b \; (y_1 - y_\ell) \qquad (14a)$$

and that for $y_1 < y < y_o$ is

$$\frac{2\sqrt{2}}{3} \; C_{o2} \; b \; \sqrt{\rho_\infty g \; (\rho_\infty - \rho_{h1})} \; (y_o - y_1)^{3/2} \tag{14b}$$

The total mass flux from cooler region of room 2 into the cooler region of room 1 is the sum of the two terms in equation 14.

Similar algebraic relationships have been developed for the flow out of the hot region of room 1 into the hot region of room 2. For the special case considered here, the flow through the opening between y_o and y_u is

$$\frac{2\sqrt{2}}{3} \, C_{o1} \; b \; \sqrt{\rho_{1h} \; (\rho_\infty - \rho_{h1})} \; (y_u - y_o)^{3/2} \tag{14c}$$

Ten relationships of this form must be considered for the pressure/density distribution shown in Figure 3 and identified as Case 1.1.

These are defined in the table of Figure 3. Thus, when y_u is in Region I, y_1 may lie in Regions I, II, III, or IV; when y_u is in region II, y_1 may lie in regions II, III, or IV; and so on. In each of the 10 examples, algebraic expressions such as those given in equations 14a, 14b and 14c have been developed. They are identified by the code shown in Figure 3 and this code is also used in the computer program to identify the case in questions.

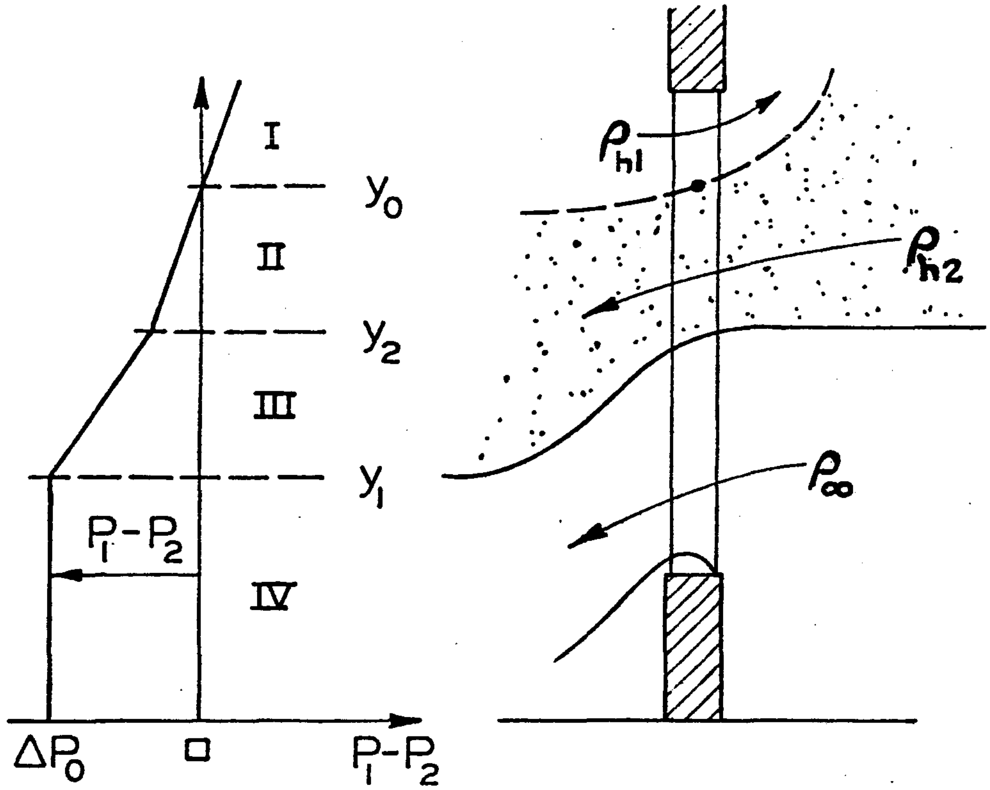
For cases in which the opening geometry includes the neutral buoyancy point, flow in both directions will be present. This situation is illustrated in Figure 3B for Case 1.1.2.1. The geometry of the flow near the door is complex and we expect that some dependence of the flow coefficient on opening geometry will occur to produce deviations from our simple model. Extensive measurements have demonstrated that the flow field sketched in Figure 3B is a reasonable model of real flows.

We have assumed in drawing the pressure versus elevation curve shown in Figure 3 that the density in the ceiling layer of room 2 is greater than that in room 1; i.e., that $\rho_{h1} \leq \rho_{h2}$. Two other variations of the pressure distribution are possible with this density distribution and these are shown in Figures 4A and 4B. In Case 1.2, Figure 4A, the neutral buoyancy point y_o lies above y_2 whereas in Case 1.1 it lies between y_1 and y_2. Case 2 shown in Figure 4B covers the situation for which the pressure difference at the floor level is positive.

Bookkeeping of a new type must be developed to account for the complex flow of Case 1.2. Here, hot gas flows out of hot region of room 1 into hot region of room 2 for $(y > y_o)$. However, we also have a hot flow from room 2 into room 1 for $y_o > y > y_2$. Finally, a cool flow moves from lower region of (2) to the cool region of (1) for $y_2 > y > y_\ell$. In our treatment of this flow, we arbitrarily assume that the flux of hot gas from room 2 into room 1 (for $y_o > y > y_2$), flows into and mixes instantaneously with the hot gas in the upper layer of room 1. Experimental work is required to check the validity of these flow field assumptions.

The flow field and calculations of the situation described in Figure 4B are relatively straight forward and approach closely to conventional orifice flows.

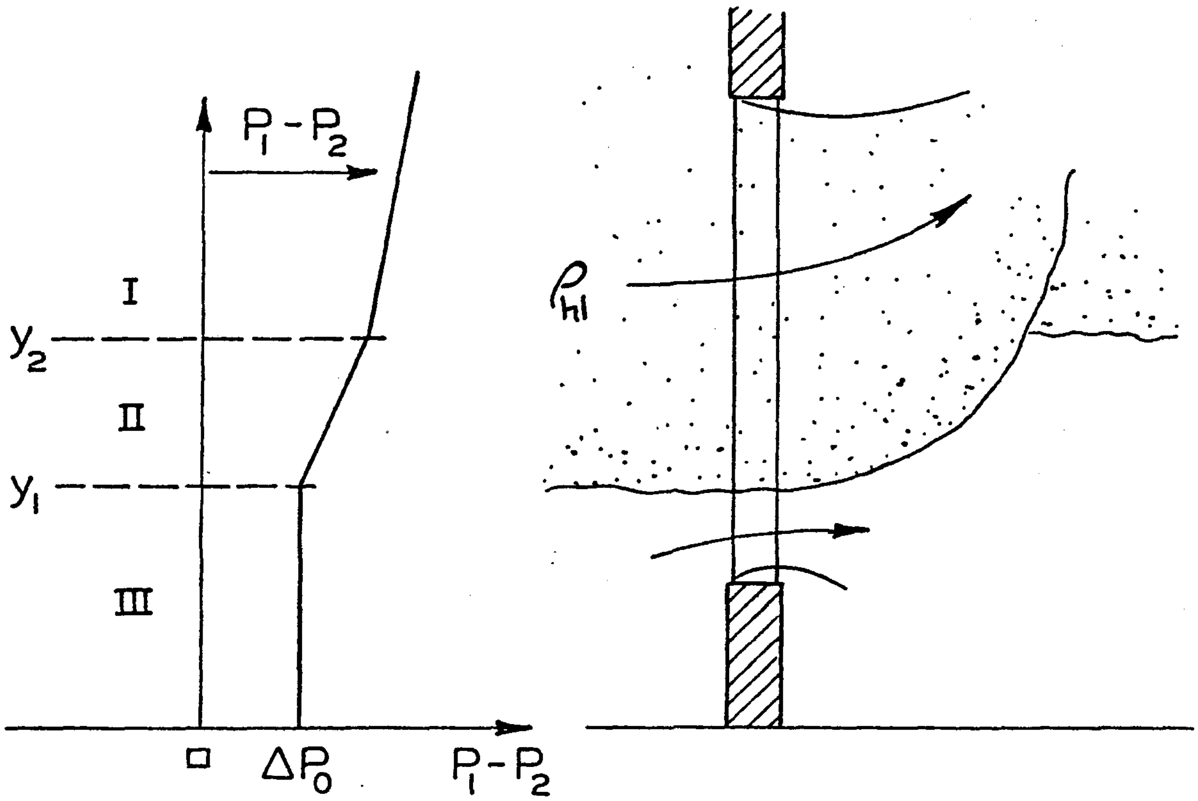
We must also deal with situations in which the density inequality is reversed, i.e., when $\rho_{h1} > \rho_{h2}$. This change in density distribution will primarily affect the sign of the slope of the pressure versus elevation curves for positions above y_2. Pressure distributions for the three



Case 1.2

y_ℓ \ y_u	I	II	III	IV
I	1.2.1.4			
II	1.2.1.3	1.2.2.3		
III	1.2.1.2	1.2.2.2	1.2.3.2	
IV	1.2.1.1	1.2.2.1	1.2.3.1	1.2.4.1

Figure 4A. Opening Flow Calculation Scheme



Case 2

y_ℓ \ y_u	I	II	III
I	2.1.3		
II	2.1.2	2.2.2	
III	2.1.1	2.2.1	2.3

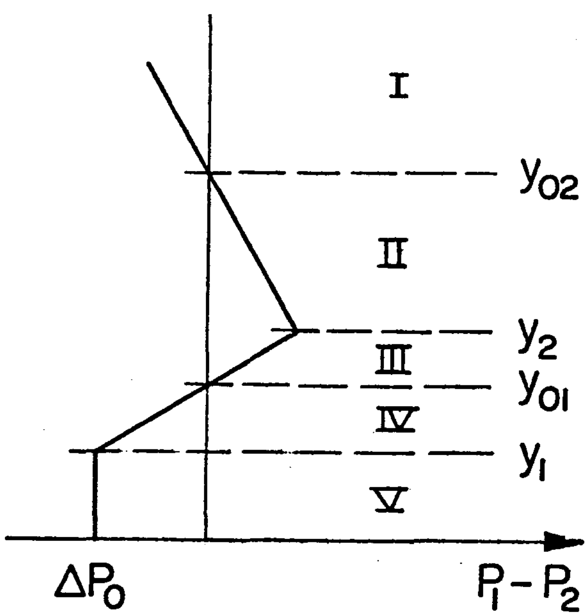
Figure 4B. Opening Flow Calculation Scheme cases we need to examine are shown in Figures 5A and 5B. Note that Case 1.1.0 corresponds to Case 1.1; Case 2.0, to 2; and Case 1.2.0, to Case 1.2.

Finally, we must consider situations in which the ceiling layer in room 2 is below that in room 1. For this situation, the computer has been instructed to reverse the indices 1 and 2, and calculate mass fluxes as before.

The mass flow rates corresponding to the conditions described by the pressure distribution shown in Figures 4 and 5 have been treated in the same manner as the example shown in Figure 3. Equations similar to equations 10 through 14 have been developed and are included in the computer program in the Flow 1 and Flow 2 sections.

III Equations of Conservation of Mass and Energy

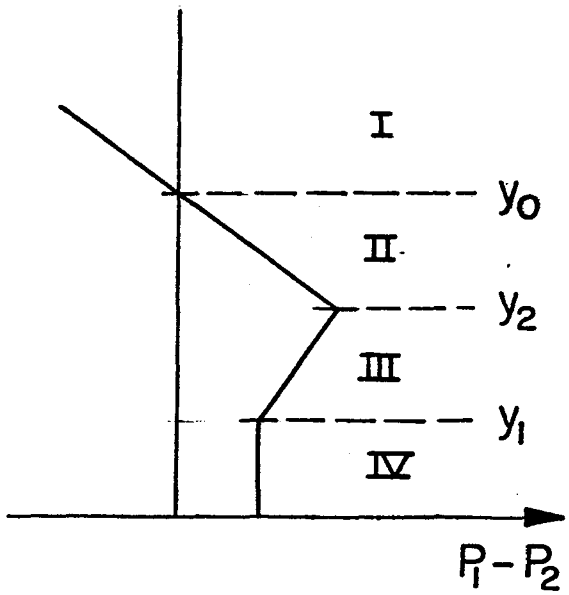
Suppose that a small fire is going in room 1 and room 2 is connected to room 1 through one opening. Rooms 1 and 2 may have other openings to outdoors. Symbols are also defined in Figure 6.



Case 1.1.0

y_ℓ \ y_u	I
I	1.1.0.1
II	1.1.0.2
III	1.1.0.3
IV	1.1.0.4
V	1.1.0.5

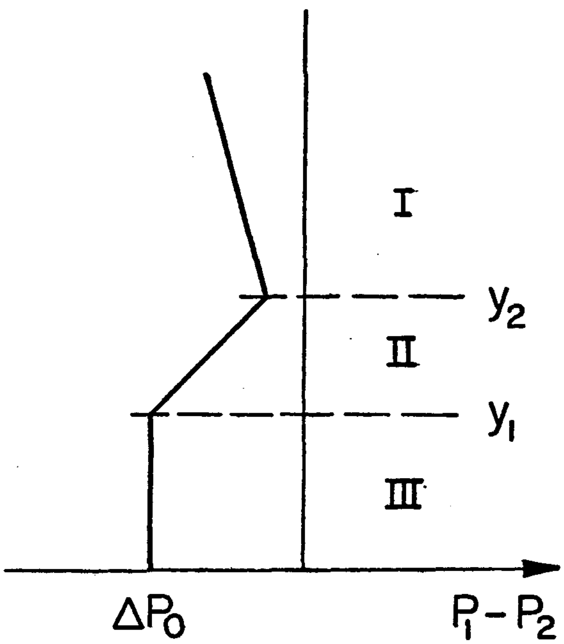
5A. Case 1.1.0: Modification of Case 1.1 with $\rho_{h1} > \rho_{h2}$



Case 2.0

y_ℓ \ y_u	I
I	2.0.1
II	2.0.2
III	2.0.3
IV	2.0.4

5B. Case 2.0: Modification of Case 2 with $\rho_{h1} > \rho_{h2}$



Case 1.3

y_ℓ \ y_u	I	II	III
I	1.3.1.3		
II	1.3.1.2	1.3.2.2	
III	1.3.1.1	1.3.2.1	1.3.3

5C. Case 1.3: Modification of Case 1.2 with $\rho_{h1} > \rho_{h2}$

Figure 5. Opening Flow Calculation Scheme for $\rho_{h1} > \rho_{h2}$.

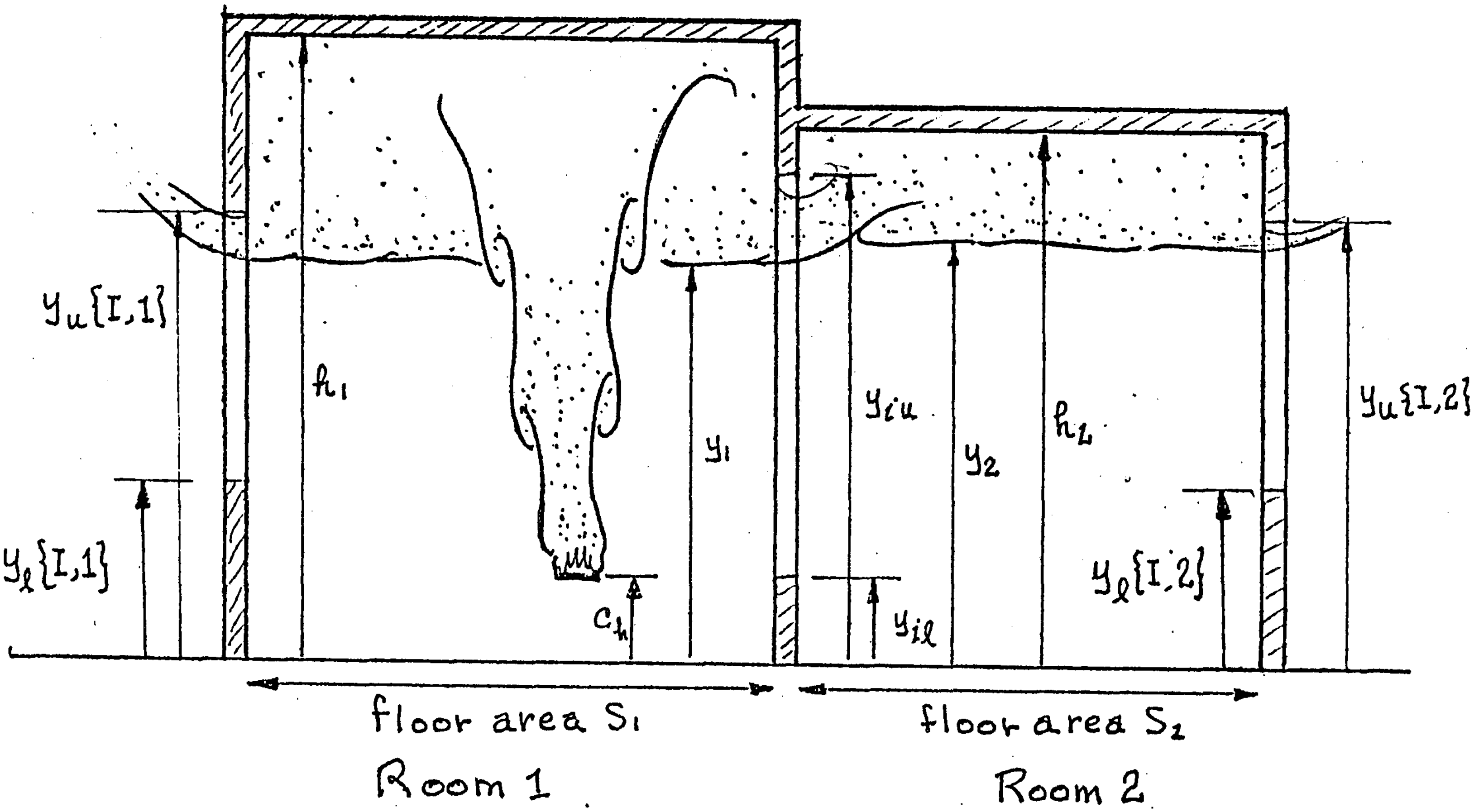


Figure 6. Schematic Diagram for Two Room Model to Illustrate Notation

The equations for mass and energy balance for the ceiling layer and the lower layer in room 1 are given below. Equations 15a and b are the continuity equations and 15c and d are equations for the internal energy of the gas in each layer. The dy_1/dt terms are included to account for the work done by pressure forces on the moving interface.

$$\frac{d}{dt}(\rho_1 y_1 S_1) = \dot{m}_1 - \dot{m}_E \tag{15a}$$

$$\frac{d}{dt}\left[\rho_{h1}\ (h_1 - y_1)\ S_1\right] = \dot{m}_E + \dot{m}_f - \dot{m}_{h1} \tag{15b}$$

$$\frac{d}{dt}\ (\rho_1 y_1 S_1 C_v T_1) + \rho_1 S_1 \frac{dy_1}{dt} = \dot{q}_1 - \dot{m}_E C_p T_1 \tag{15c}$$

$$\frac{d}{dt}\left[\rho_{h1}\ (h_1 - y_1)\ S_1\ C_v\ T_{h1}\right] - p_1\ S_1 \frac{dy_1}{dt} = \dot{m}_E\ C_p\ T_1 + Q - \dot{q}_{h1} \tag{15d}$$

Here $\dot{m}_1$ and $\dot{m}_{h1}$ are the algebraic sums of all mass flows through openings, and $\dot{q}_1$ and $\dot{q}_{h1}$ represent the sums of enthalpy fluxes through openings and heat transfer by convection and radiation into the respective regions.

The pressure within the room varies because of hydrostatic effects by terms of the order of ρgh and thus errors of the order of ρgh compared to a mean value p_1 are made if the hydrostatic terms are omitted. However,

$$\frac{\rho gh}{p_1} < \frac{\rho_\infty gh}{p_1} < \frac{\gamma gh}{\gamma RT} < 3 \times 10^{-4}$$

for h = 8 ft. Hence, we can neglect these hydrostatic effects here and in the equations of state, which may be written as

$$R \rho_l T_l = p_l$$

$$R \rho_{hl} T_{hl} = p_l$$

when we also assume that $R_h = R$. Replacing $\rho_l T_l$ and $\rho_{hl} T_{hl}$ by p_l/R in equations (15c) and (15d) and adding the resulting equations, we obtain an equation for p_l of the form:

$$\frac{dp_l}{dt} = \frac{R}{C_v S_l h_l} (\dot{q}_l - \dot{q}_{hl} + Q)$$

The temperature and hence the density in the lower region changes with pressure changes in the room and also because of heat transfer to the lower layer. The relative magnitude of the pressure variation is very small in most cases of practical interest. The heat transfer to the lower layer air is by mixing of hot outgoing gas and cold incoming air and by convective heat transfer from the floor and walls that are heated by radiation from the fire, the hot ceiling-layer gas and the walls and ceiling in contact with the ceiling layer gas. If all these effects are negligible, then T_l and ρ_l are equal to T_∞ and ρ_∞, respectively, of the ambient air. For simplicity, this is assumed to be the case in our numerical program. Then the system of differential equations (15) reduces to:

$$\rho_\infty S_l \frac{dy_l}{dt} = \dot{m}_l - \dot{m}_E \tag{16a}$$

$$S_1 \frac{d}{dt}\left[(h_1 - y_1)\,\rho_{h1}\right] = \dot{m}_E + \dot{m}_f - \dot{m}_{h1} \tag{16b}$$

$$\frac{dp_1}{dt} = \frac{R}{C_v S_1 h_1}\,(\dot{q}_1 - \dot{q}_{h1} + Q) \tag{16c}$$

For the purpose of subsequent discussion, we introduce the dimensionless variables defined in the list of symbols. Then the pressure equation may be written as

$$\frac{\rho_\infty g h_1}{\gamma p}\;\frac{dp_1{}^*}{d\bar{t}} = \bar{q}_1 - \bar{q}_{h1} + \bar{Q}$$

Here $\bar{q}_1$ and $\bar{q}_{h1}$ are functions of $\bar{y}_1$, $\bar{\rho}_{h1}$ and $p_1{}^*$. For any reasonable h_1, we get

$$\rho_\infty g h_1/(\gamma p_\infty) = g h_1/(\text{sound speed})^2 << 1$$

Hence, we can neglect the pressure term and this differential equation is reduced to the algebraic relationship:

$$\bar{q}_1 - \bar{q}_{h1} + \bar{Q} = 0 \quad .$$

Consequentally, at any time $p_1{}^*$ is determined such that this static equilibrium condition is satisfied. Thus the set of equations (16) that describes the time-evolution of the ceiling layer becomes

$$\frac{d\bar{y}_1}{d\bar{t}} = \bar{m}_1 - \bar{m}_E \tag{17a}$$

$$\frac{d}{dt}\left[(1 - \bar{y}_1)\,\bar{\rho}_{h1}\right] = \bar{m}_E - \bar{m}_{h1} + \bar{m}_f\,\bar{Q} \tag{17b}$$

$$\bar{q}_1 - \bar{q}_{h1} + \bar{Q} = 0 \tag{17c}$$

A similar set of equations is obtained from the conservation equations of mass and energy in the second room:

$$\frac{d\bar{y}_2}{d\bar{t}} = \frac{1}{\bar{S}_2} (\bar{m}_2 - \bar{m}_J) \tag{18a}$$

$$\frac{d}{d\bar{t}} \left[(\bar{h}_2 - \bar{y}_2) \rho_{h2} \right] = \frac{1}{\bar{S}_2} (\bar{m}_J - \bar{m}_{h2}) \tag{18b}$$

$$\bar{q}_2 - \bar{q}_{h2} = 0 \quad . \tag{18c}$$

Dimensionless variables for the second room are based on the same parameters as were used to normalize corresponding variables for room 1. The latter definitions are presented at the top of page 21. For example,

$$\bar{q}_2 \equiv \dot{q}_2 / (\rho_\infty C_p T_\infty h_1{}^2 \sqrt{g h_1})$$

and in addition

$$\bar{h}_2 \equiv h_2 / h_1$$

and

$$\bar{m}_J = \dot{m}_J / (\rho_\infty h_1{}^2 \sqrt{g h_1}) \quad .$$

3. DESCRIPTION OF COMPUTER PROGRAM

The equations 17 and 18 have been programed for numerical solution and are written below in terms of the dimensionless variables. They are listed without overbars for brevity and terms such as $\bar{m}_{h1}$ have been written in more detail than before.

$$\frac{dy_1}{dt^*} = [m_{12} + \sum_j m(j,1) - m_E] Q_R{^*}^{-1/3} \tag{19a}$$

$$\frac{d}{dt^*}[(1-y_1)\rho_1{^*}] = \Big\{m_{12} - m_{h12} + m_{h21} + \sum_j [m(j,1) - m_h(j,1)] + m_f Q\Big\} Q_R{^*}^{-1/3} \tag{19b}$$

$$\frac{dy_2}{dt^*} = \Big[-m_{12} + \sum_j m(j,2) - m_J\Big] Q_R{^*}^{-1/3}/S_2 \tag{19c}$$

$$\frac{d}{dt^*}[(h_2 - y_2)\rho_2{^*}] = \Big\{m_{12} - m_{h12} + m_{h21} + \sum_j [m(j,2) - m_h(j,2)]\Big\} Q_R{^*}^{-1/3}/S_2 \tag{19d}$$

$$m_{12} + \sum_j m(j,1) - \frac{1}{1+\rho_1{^*}}\Big[m_{h12} + \sum_j m_h(j,1)\Big] + m_{h21}\frac{1}{1+\rho_2{^*}} (1+m_f)Q - Q_{w1} = 0 \tag{20a}$$

$$m_{12} + \sum_j m(j,2) + \frac{1}{1+\rho_1{^*}} m_{h12} - \frac{1}{1+\rho_2{^*}} \sum_j m_h(j,2) + m_{h21} - Q_{w2} = 0 \tag{20b}$$

where

$$\rho_1{^*} \equiv \rho_{h1} - 1, \quad \rho_2{^*} \equiv \rho_{h2} - 1 \quad . \tag{21}$$

In the above equations, m_{12} is the flow of fresh air from room 2 to room 1, m_{h12} is the flow of hot gas from room 1 to room 2, $m(j,i)$ is the flow of fresh air from the outdoors into room i through j-th opening, and $m_h(j,i)$ is the flow of hot gas escaping from room i to the outdoors through j-th opening. The fuel mass parameter m_f is assumed to be a known parameter. The heat losses Q_{w1} and Q_{w2} are given in terms of specified constants C_{LS1} and C_{LS2} as:

$$Q_{w1} = C_{LS1} Q \tag{22a}$$

$$Q_{w2} = C_{LS2} m_{h12} \rho_1^*/(1+\rho_1^*) \tag{22b}$$

The mass flow entrained into the fire plume $\dot{m}_E$ is computed with the aid of the notation illustrated in Figure 6 in the following manner. The height of the fire above the floor is C_h, the height of the ceiling layer is y_1, and the difference $(y_1 - C_h)$ is the plume height y_p which corresponds to Z in the description of the plumes given earlier in the discussion of entrainment in Section B-I. Axisymmetric and line plumes are included in the plume subprogram. In terms of the parameters defined above, the equation for the axisymmetric case can be rewritten as:

$$m_E = C_{mp}\ Q^{1/3}\ y_p^{\ 5/3} \tag{23}$$

The mass flow rates m_{12}, m_{h12}, $m(i,j)$ are known functions of y_1, y_2, ρ_1^*, ρ_2^*, p_1^*, p_2^* when the dimensions of openings are given. Thus, at any time step, if y_1, y_2, ρ_1^*, ρ_2^* are known, then p_1^* and p_2^* and hence all mass flow rates are determined by solving the two algebraic equations (20a, b). Thereafter all derivatives are evaluated from equation (19a $\sim$ d).

Numerical solution of the four ordinary differential equations for ceiling-layer heights and densities, and the two nonlinear algebraic equations for pressures are coded in FORTRAN IV to be executed by an IBM 370/158 computer at the CIT Computing Center.

At each time step, the nonlinear algebraic equations are solved by a numerical Newtons method to obtain the pressures and hence the mass and energy fluxes through the openings, and then the differential equations are solved by a CIT library routine which incorporates the fourth-order Runge-Kutta-Gill method, the Adams-Moulton predictor-corrector formula, and a provision for automatic control of truncation error.

Details of the computer program are described in the Appendix and a detailed description is given of the calculation which leads to the first example discussed in the next section and presented in Figure 7. Numerical values of various parameters calculated for this example are presented in Appendix E.

4. DISCUSSION OF RESULTS

In this section, we will discuss the behavior of the ceiling layers in a number of one and two room configurations which are predicted by the program. Some results of general interest are obtained concerning the influence of several parameters and a number of examples are presented.

Consider first a two room example which illustrates some of the capabilities of the program. The first room has a height h and has a closed window opening to the outside, which is modeled by an opening with $0.4 \leq y/h \equiv \bar{y} \leq 0.8$ and a width $b = 0.0025\ h$. The door which connects the two rooms is almost closed at first; it starts to open at $t^* = 10$ and is completely opened at $t^* = 11.5$. The door height is $0.813\ H$ and for $0 \leq t^* \leq 10$ its width is $0.002\ h$. After $t^* = 11.5$, the door width is $0.375\ h$. Room 2 has the same area and height as room 1 and is connected to the outside by an open door with height $0.813\ h$ and width $0.375\ h$.

The fire grows linearly from a very small value at $\tau^* = 0$ to a value corresponding to $Q^* = 0.01$ at $\tau^* = 8$. Heat losses to the walls in room 1 are 25 percent of the fire heat input rate and in room 2, they are 20 percent of the enthalpy flux through the door from room 1.

The dimensionless ceiling layer interface heights y_i/h and density ratios ρ_{hi}/ρ_{∞} values are shown in Figure 7 and numerical values for 13 parameters are given in Section E of the Appendix as a function of t^*. The ceiling layer interface height and density in room 1 fall rapidly for $\tau^* > 0$ and continue to decrease until the door slowly opens. Small changes occur in the second room after $\tau^* = 2.4$ when the ceiling layer in room 1 falls below the soffit of the door connecting rooms one and two. As the door is opened, i.e., $10 \leq t^* \leq 11.5$, a

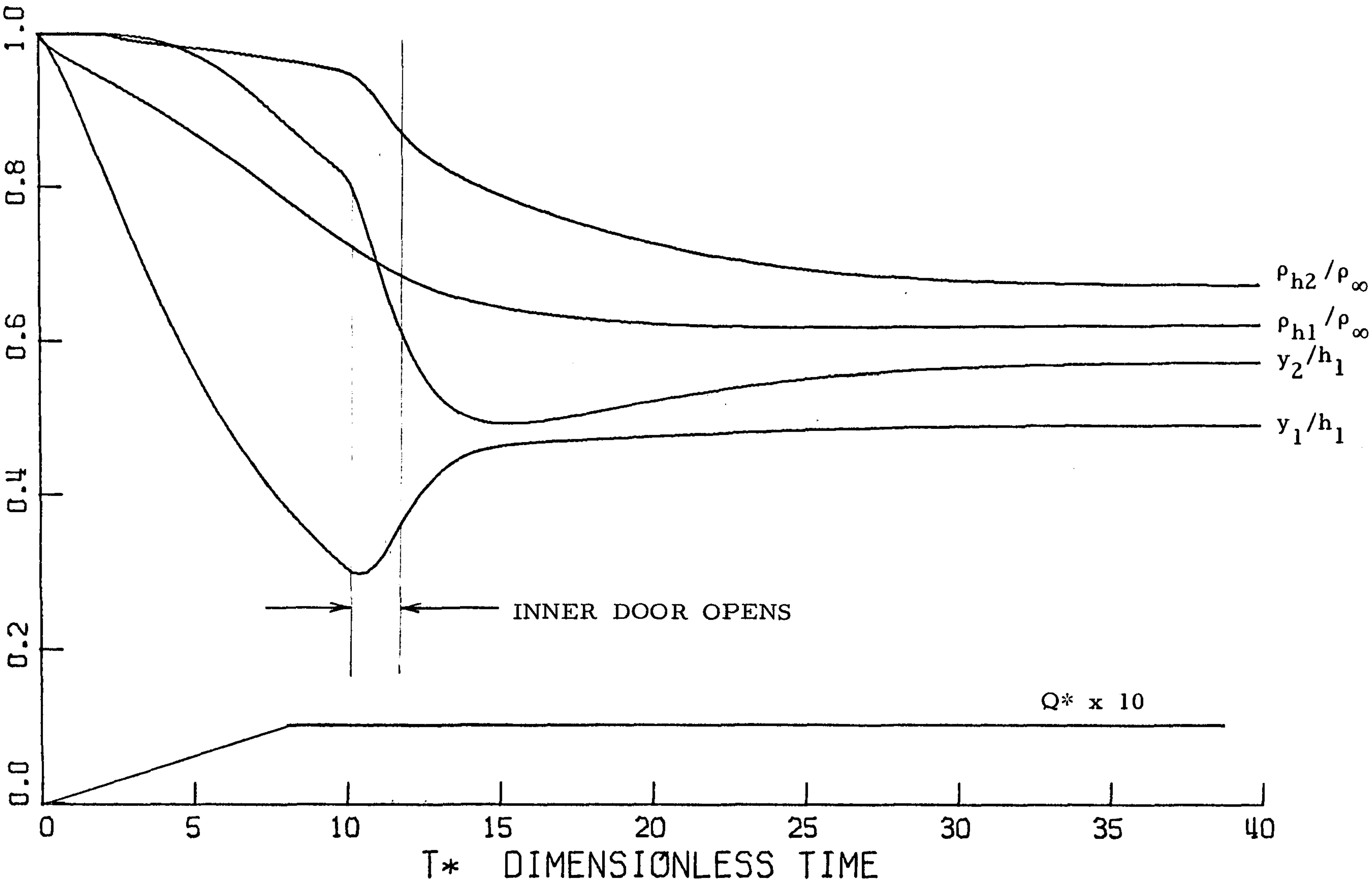


Figure 7. DOOR OPENING BETWEEN ROOMS

rapid flow of hot gas enters room 2 and the steady state values of the parameters are very nearly reached at $\tau^* = 20$.

In order to put these parameters in dimensional form we must assign values to room height and etc. When we pick: height = H = 2.5 m, floor area ≡ S = 20 m^2 and $T_\infty = 20^\circ$ C, then:

Heat Input = Q = Q*(1.11 x 10^4 kw), maximum value is 111 kw

Time = T = τ^*(7.52 sec)

For these values, note that when the door is opened at about 75 seconds after the start of the fire, the temperature in the ceiling layer of the first room is already about 90° C and that the interface of this layer is at about 0.8 m above the floor level. The time required after the door is opened for the excess hot gas in room 1 to flow into room 2 is about 40 seconds. Final ceiling layer temperatures are about 200° C.

In the following paragraphs we will first examine the effects of changing some of the parameters which appear in our program and then a number of examples.

Entrainment Parameters and Flow Coefficients. A number of constants appear in the fire plume and door flow modeling equations and it is of interest to compare the sensitivity of the ceiling layer depth and density to changes in these parameters. In particular we are concerned with the sensitivity of the solutions to the choice of flow coefficients for the flow through the openings and the entrainment parameters for the plume and the door jet. We will examine the influence of the first two parameters for a single room with a fire with a heat input parameter which grows from 0 at $\tau^* = 0$, to $Q^* = .01$ or 10^{-5} at $\tau^* = 1.0$, and a single door with a soffit at ZU = 0.813 a width of ZB = 0.375. Consider first the door flow coefficients C_{oh} and C_{oc}. Some unpublished experimental data suggest that the values for these coefficients should lie in the range 0.6 to 1.0 and that for many configurations of interest the value is close to 0.60.

The influence of the two orifice coefficients, C_{oc} and C_{oh} which appear in equations for the flow of cold air (i.e., the lower layer) and hot gas (the upper layer) through an opening is illustrated in table (I). Here, steady values of interface height and ceiling layer density are presented as a function of Q* and the flow coefficients. The steady values were obtained for dimensionless times of the order of 40 in all cases. Flow coefficients in the range 0.6 to 1.0 and for Q* values of 10^{-5} and 10^{-2} are considered.

Changing both coefficients simultaneously from 0.6 to 1.0 causes the ceiling layer interface height y_1 to increase by less than 10 percent. The density ratio (ρ_{h1}/ρ_∞) for the smaller value of Q* is very close to one and the quantity $(\rho_\infty - \rho_{h1})/(\rho_\infty)$ is used for both cases to make the changes easier to percieve. This density difference ratio decreases by less than 14 percent as the coefficients increase from 0.6 to 1.0 for both values of Q* and this change is a result of the increase in y_1 which increases the entrainment in the plume and hence decreases the plume mass-averaged temperature.

The last two columns of the table illustrate the changes produced when the coefficients are not of equal value.

The variations in the interface level y_1 and density of the ceiling layer produced by a wide range of values of flow coefficients are less than ± 6 percent for the conditions considered here. Hence, our solutions will not be critically dependent on the accuracy of the value used in our computations. We will use 0.60 for both coefficients.

Table I*

Effect of Changing Flow Coefficients for Flow Through Opening.

Q*							
	COH	0.6	0.7	0.8	1.0	0.6	1.0
	COC	0.6	0.7	0.8	1.0	1.0	0.6
10^{-5}	y_1/h	.585	.600	.612	.613	.590	.625
	$100\frac{(\rho_1 - \rho_{h1})}{\rho_1}$	.604	.578	.558	.520	.595	.530
10^{-2}	y_1/h	.560	.577	.591	.613	.566	.604
	$\frac{(\rho_1 - \rho_{h1})}{\rho_1}$	.396	.384	.374	.360	.391	.366

*Values for y_u/h = 0.813 and b/h = 0.375

The effects of changing the plume entrainment rate constant Cmp on the interface height and ceiling layer density are shown in Table II for the same room and fire uses in the above example and with $Q^* = .01$. Clearly, changing Cmp by factors of 2 produces appreciable changes in both parameters and hence Cmp must be known to within 10-20 percent to avoid serious errors. The value used in the other calculations described here is 0.1865 which is satisfactory for describing the far field of a point source of heat.

Finally, the influence of the constant C_J used in the tentative model for entrainment in the doorway by the ceiling layer jet was examined for $C_J = 1/4$, 1 and 4. Results were obtained for a two room model with identical doors (ZU = YU = 0.813 and BO = ZB = 0.375) and for $Q^* = 0.01$. The affect on y_1 and ρ_{h1}/ρ_1 of changing C_J was negligible and because the interface height in the second room fell below the critical value described in equation 5, Section 2IB, entrainment by the door jet was zero for the steady state and had no influence on the steady values of ρ_{h2}/ρ_2 and y_2. However, during the transient entrainment by the door jet was large and the influence of large changes in C_J were observable but were never important.

Table II*

Effect of Changing Entrainment Rate Parameter Cmp.

Cmp	.046	.093	.1865	.373	.746
y_1/h	.71	.65	.56	.45	.33
$\frac{\rho_1 - \rho_{h1}}{\rho_1}$	.64	.51	.40	.32	.29
$\frac{Cmp}{Cmps}$	$\frac{1}{4}$	$\frac{1}{2}$	1	2	4

*Values for $y_u/h = 0.813$, $b/h = 0.375$ and $Q^* = 0.01$ as in Table I.

Heat Input Rate, One Room. The influence of the dimensionless heat input parameter Q^* on the transient behavior of the ceiling layer interface level and the density is shown in Figure 8 for a single room with a single door. For purposes of comparison, the density is presented as the ratio $DR \equiv (\rho_{hl_o} - \rho_{hl})/(\rho_{hl_o} - \rho_{hl_s})$ where ρ_{hl_o} is the initial value and ρ_{hl} is the instantaneous value of ceiling layer density, and ρ_{hl_s} is the ceiling layer density after the steady state has been achieved. The time scale is the parameter $\tau(Q^*)^{1/3} = \tau^*$.

In this example, values of Q^* of 10^{-4}, 10^{-3}, 10^{-2} and 10^{-1} were examined. For the lowest three values of Q^*, the time scale used here τ^* does a reasonable job of reducing the three curves to a single curve. Curves not shown here, for smaller values of Q^* are indistinguishable from the $Q^* = 10^{-4}$ curves. Thus, τ^* is a useful scaling parameter for small fires. However, for $Q^* \geq 10^{-1}$, the simple scaling of the time is no longer satisfactory and large deviations occur.

The sharp break in the $y_1\{\tau^*\}$ curve for $Q^* = 0.1$ is a result of our use of a large time step in these calculations; however, a very rapid change in slope does occur when the pressure in the room changes sign and a smaller time step merely rounds off the sharp corner shown here.

The ceiling layer depth approaches to within a few percent of its final value at $\tau^* \approx 5$ for all four values of Q^* where as much larger times are required for the density ratios to reach their steady values for Q^* values below 10^{-2}.

Opening Geometry. The effects of room scale, both floor area S and room height h, are contained within the dimensionless ceiling layer height $y_1 = y_1/h$ and time scale

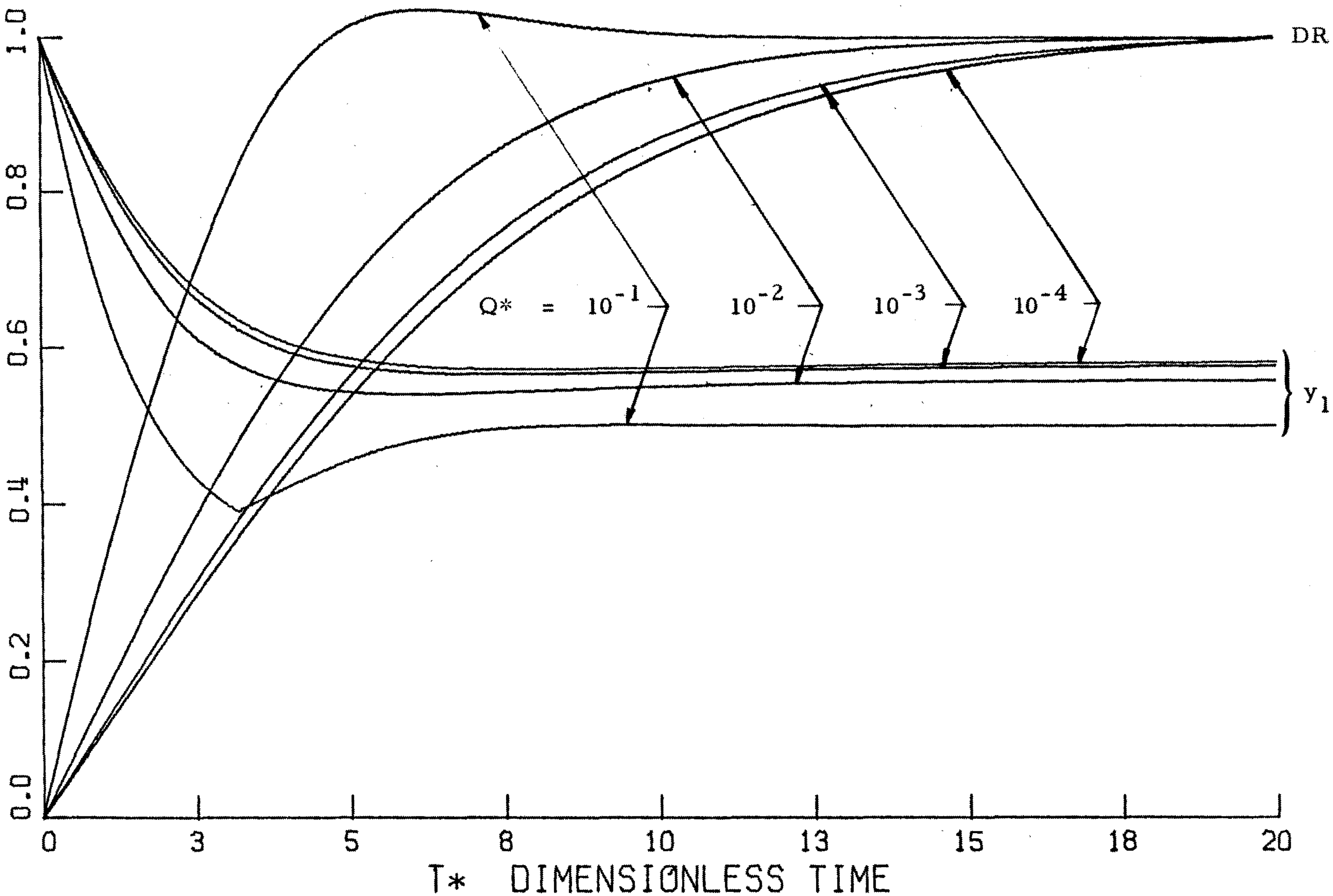


Figure 8. Effect of Q* on Density Ratio and Interface Height for a Single Room.

$$\tau^* = \left(\frac{\dot{Q}}{\rho_\infty C_p T_\infty \sqrt{gh}\ \ h^2} \right)^{1/3} t \sqrt{\frac{g}{h}} \left(\frac{h^2}{S} \right)$$

Hence, the results presented in Figure 8 are general with respect to these parameters. However, the door geometry which is described by its soffit height y_u and width b appear explicitly in the calculation and will affect the transient and steady state results. The curves shown in Figure 9 illustrate the effect of reducing the height to the soffit (i. e., the opening height) for $Q^* = .01$. The development of the ceiling layer interface height appears to follow a curve independent of soffit height, y_u, until a height close to the steady state level is reached. A rapid deviation from the universal curve then occurs which is followed by a slight undershoot and an asymptotic approach to the final value.

The density again takes much longer to reach the steady state value and the undershoot in y_1/h is a result of the density in the ceiling layer being much higher than its steady value when y_1 first passes its steady state value.

For all four of these examples, the ceiling layer interface heights vary from 70 to 75 percent of the opening height. In contrast when the door area is changed by changing the width $\bar{b}$, a smaller change in height is required. Several examples of the steady state values for the latter example are given in Table III.

Fire Geometry. The effects of changing the fire height from floor level to a point at h/4 is shown in Figure 10 for a dimensionless heat input parameter of $Q^* = .01$ and the standard door opening. The transient time is almost equal to that for the standard fire position. Changes in

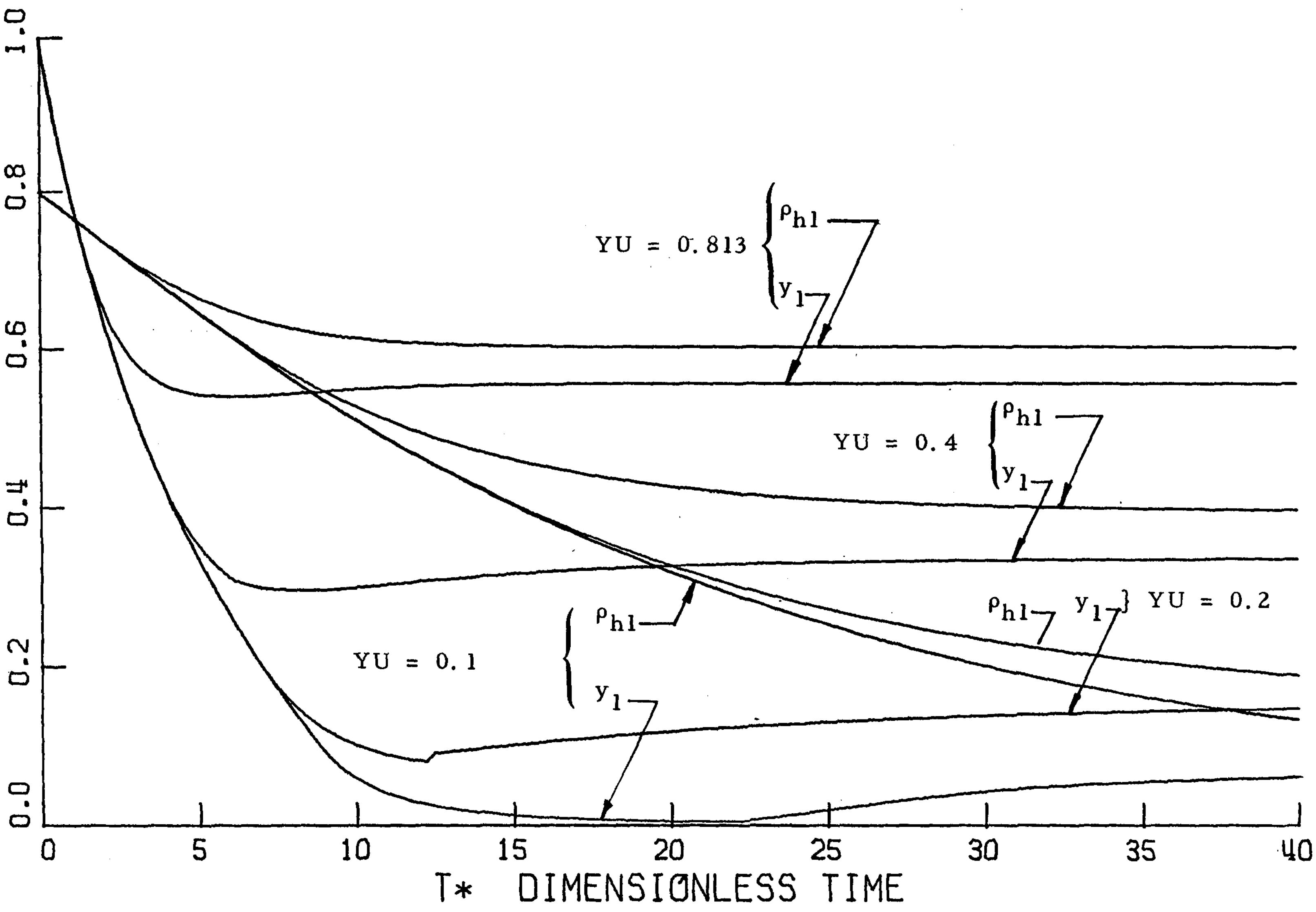


Figure 9. Effect of Reducing Soffit Height on ρ_{h1} and y_1.

Table III.

$\overline{b}$	$\overline{y}_l$	$\overline{\rho}_{hl}$	$\overline{y}_l / \overline{y}_u$
.094	.38	.44	.47
.188	.47	.54	.58
.375	.56	.60	.69
.750	.63	.65	.77
1.500	.69	.68	.85

Effect of Changing Opening Width in a One Room Case, YU = 0.813 H.

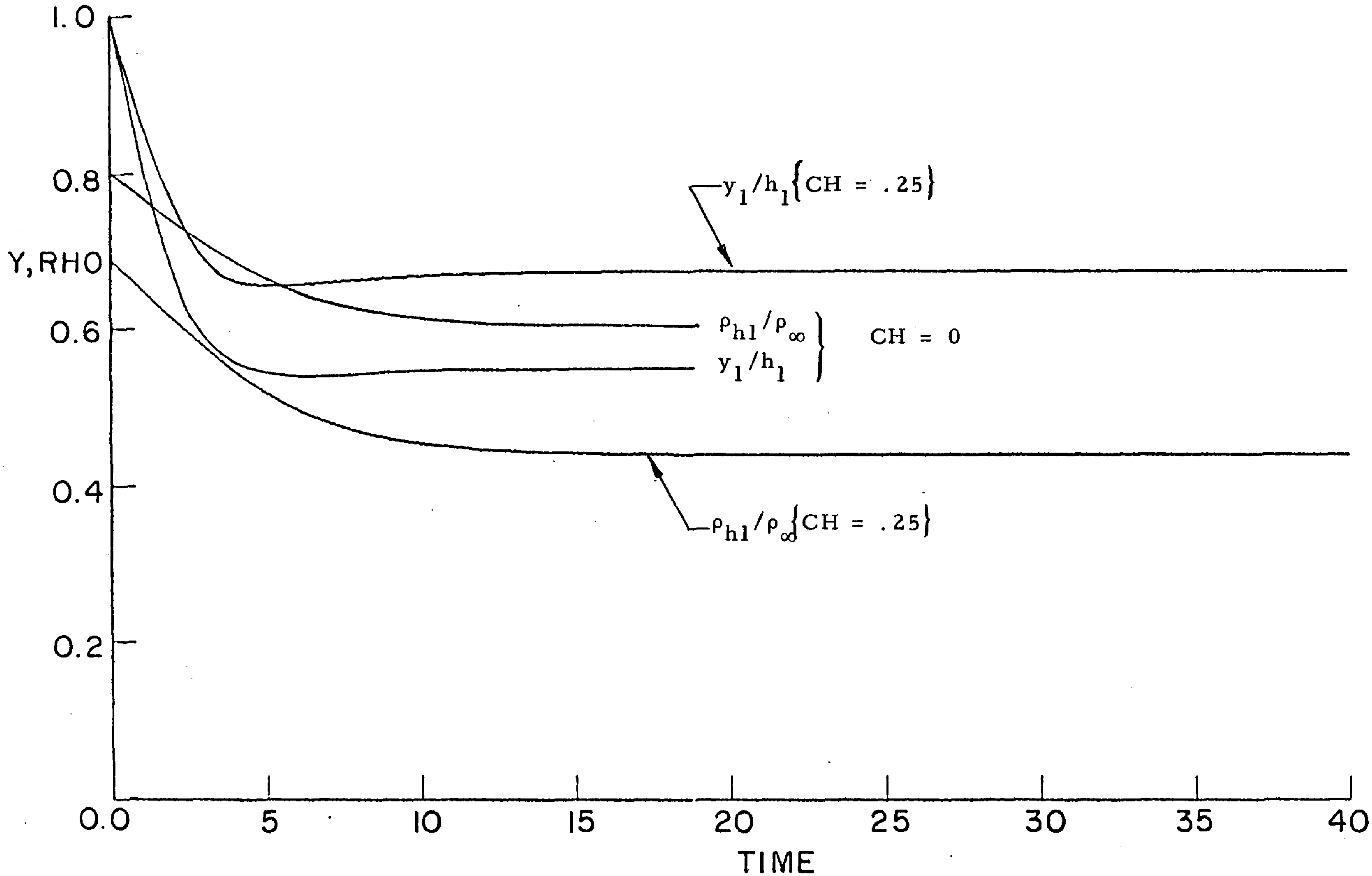


Figure 10. Effect of Changing Fire Elevation, CH.

y_1 and (ρ_{h1}/ρ_1) result from the decreased entrainment of the fire plume.

Similar results are shown in Figure 11 where a comparison is presented of calculations for the standard point source plume and for a line plume with some dimensionless heat addition rates. Time scales are still almost equal and gross differences in y_1 and ρ_{h1}/ρ_1 result from differences in plume entrainment.

As a final example of the transient calculations for a single room with a door opening, the effects of using a fire with a heat input rate which varied exponentially is shown in Figure 12. The heat input for the Exponential Fire is assumed to vary as $\dot{Q}* = Q*_{ref} \exp\{.01(t* - 64)\}$ for $0 < t* < 64$ where $Q*_{ref}$ is a constant equal to .01 in this example, and $\dot{Q}*$ and $t*$ are our usual dimensionless heat input parameter and time. For $t* > 64$, $Q* = 0.01$. The abrupt changes for $t* > 64$ result from the sudden change in the slope of $Q*\{t*\}$ at that time.

In this example, the ceiling layer interface height decreases to about 0.54 of the room height and reaches this value around $t* = 25$. This time appears to be about 5 times greater than that required for the corresponding times required for a fire with constant heat input. However, in the present case we have defined $t*$ in terms of $Q*_{ref}$ rather than the instantaneous value of $Q*$ given by the above equation. If we calculate values of $\tau*$ based on the instantaneous value of heat input; (i.e., $\tau_i* \equiv \tau(Q*)^{1/3}$) the time required for the ceiling layer depth to approach its steady value is again about 5.

<u>Two Rooms, Heat Loss</u>. The influence of heat loss to the walls on the steady values of interface heights and ceiling layer densities is illustrated

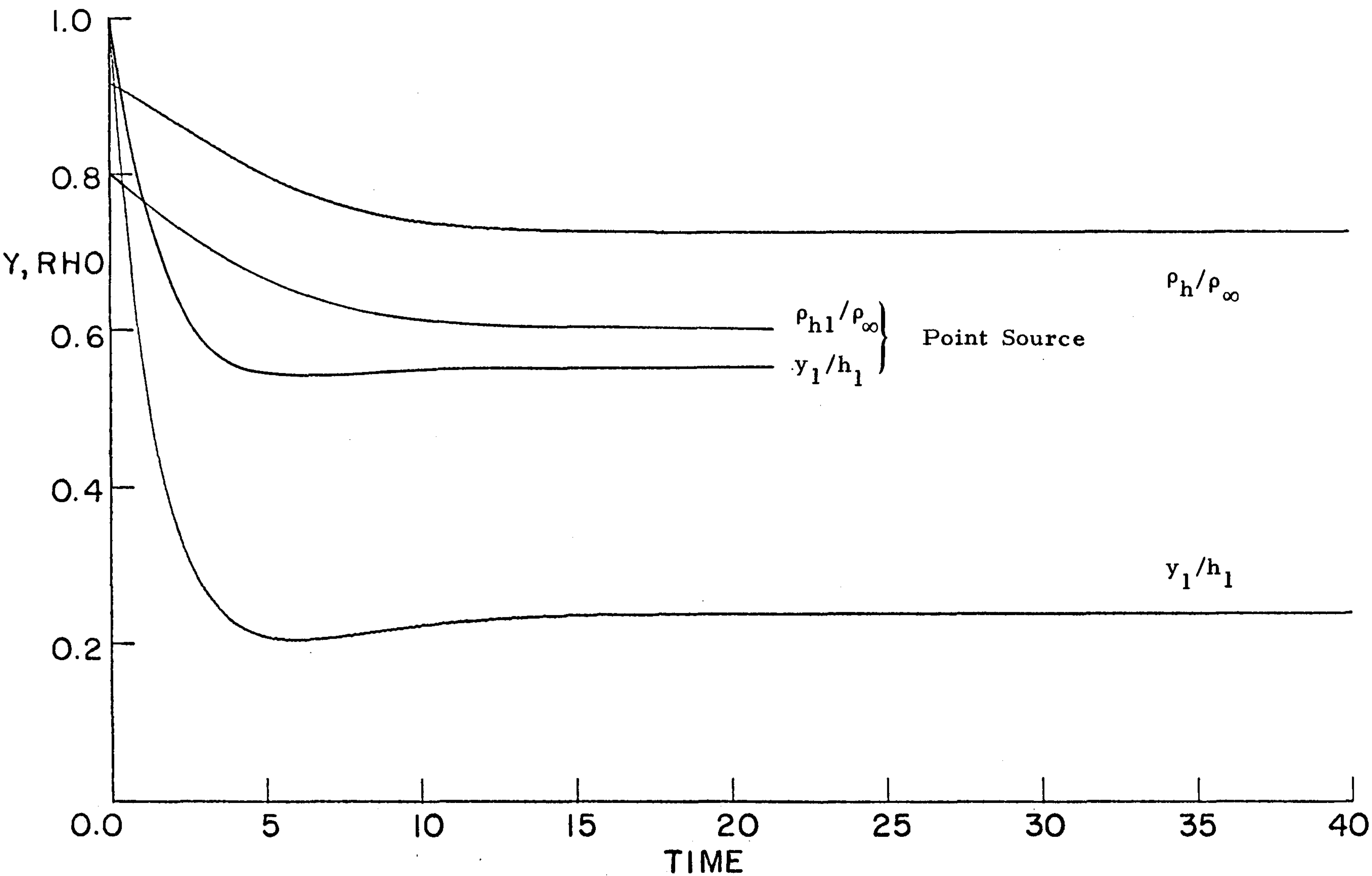


Figure 11. History for a Line Fire and the Standard Point Source Fire.

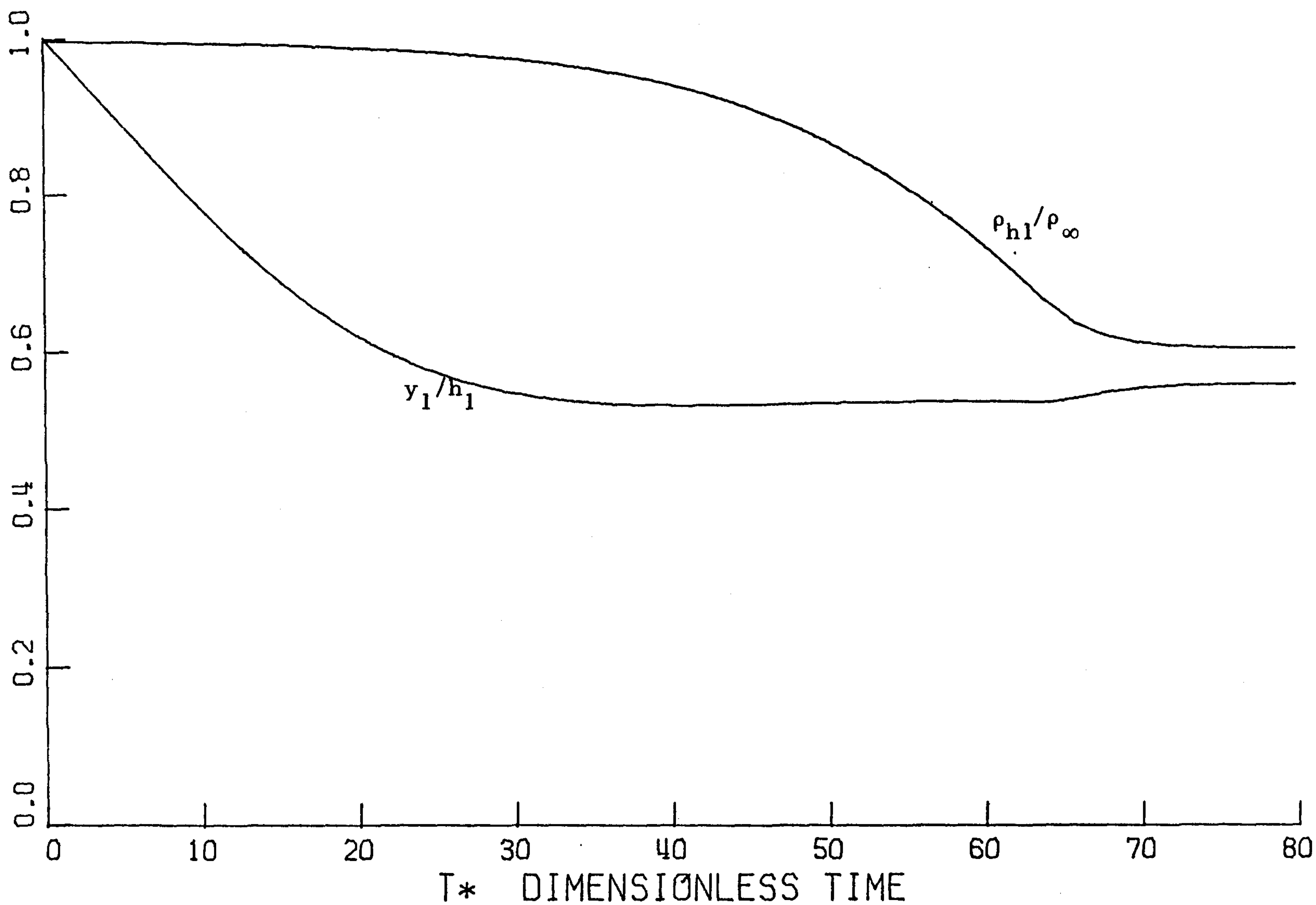


Figure 12. History of a Point Source Fire with Expnential Heat Input.

in Table IV for the standard two room example. The fraction of the heat input from the fire removed by convection from the ceiling layer of room 1 is C_{LS1} and the fraction of the heat carried by the hot gas into room 2 which is removed by convection from the ceiling layer in room 2 is C_{LS2}. (These terms appear in the energy equations for the two ceiling layers given in Equations 20 and 22.)

The effect on ceiling layer interface height of substantial convective losses is no more than 5 percent. For example, compare $\bar{y}_1$ values for lines (1), (4) and (5) or $\bar{y}_2$ values for lines (1); (6) and (7) for examples where losses from either room 1 or room 2 alone are increased. When losses in both rooms increase simultaneously, e.g., lines (1), (2) and (3) the net effect on interface height in room 2 is larger. This is to be expected since the total heat available to increase the gas temperature in room 2 decreases by a factor of 4 for line (3) and compared to line 1.

The effect on the density in the ceiling layer of either room is large for all the examples.

Table IV

Effect of Heat Transfer to Ceiling

	C_{LS1}	C_{LS2}	$\overline{y}_1$	$\overline{\rho}_{h1}$	$\overline{y}_2$	$\overline{\rho}_{h2}$
1)	0	0	.495	.554	.587	.554
2)	0.25	0.25	.491	.621	.566	.686
3)	0.50	0.50	.480	.702	.513	.827
4)	0.25	0	.489	.619	.582	.619
5)	0.50	0	.477	.700	.572	.701
6)	0	0.25	.479	.556	.575	.625
7)	0	0.50	.500	.558	.552	.717
8)	0.25	0.50	.493	.622	.537	.768
9)	0.50	0.25	.479	.702	.551	.760

$Q^* = 0.01$, $\overline{y}_u = 0.813$, $\overline{y}_\ell = 0$, $\overline{b} = 0.375$

Room 2: $\overline{Z}_u = 0.813$, $\overline{Z}_\ell = 0$, $\overline{Z}_b = 0.375$ $C_J = 1.0$

Hospital Corridor Case. As a final example, consider a two room configuration in which the fire room, room 1, is connected to a much larger room 2. The connection between the rooms is the standard door (ZU = 0.813 and ZB = 0.375), and room two is connected to the outside only through a small leak (e.g., under a closed door) with an area about 6-1/2 percent of the area of this door. We arbitrarily assume that 40 percent of the heat input from the fire is lost to the walls in the fire room and 20 percent of the enthalpy flux to the second room is transferred to the walls. The heat input from the fire grows linearly to a value of $Q* = 0.1$ at $\tau* = 100$ and remains constant thereafter. If the dimensions of the first room are a height $h_1 = 2.5$ m and an area $S_1 = 20\ m^2$ and, the dimensions of the second room are $h_2 = 2.5$ m and $S_1 = 200\ m^2$. Note that $S_2 = 10 S_1$. For this example, $t = 3.5\ \tau*$ seconds.

The ceiling layer interface heights and densities are shown in Figure 13. The interface height in the fire room (y_1) quickly falls to about 0.45 H and remains there until the interface height in room 2 overtakes it at about $\tau* = 75$. For larger times we have $y_2 < y_1$ and y_2 approaches zero at $105 = \tau*$.

When $\tau* > 75$, we have a situation in which $y_2 < y_1$ and $\rho_{h2} > \rho_{h1}$, and we must use the pressure diagrams described in Figure 5 with subscripts 1 and 2 interchanged to calculate the flows at the door between the rooms.

The behavior of y_1 and y_2 for $\tau^* > 100$ can be understood as follows. The plume entrains cool air and hence reduces y_1. However, y_1 will approach zero asymptotically because the entrainment rate is proportional to $y_1^{5/2}$. In contrast cool air is removed from room two both by flowing into room 1 and by flowing out through the leak.

The solutions are not reasonable when $y_1 < 0.1$ to 0.2 since the fire will extend into the ceiling layer and hence one would expect the heat input rate to be reduced. Also values of ρ_{h1} less than 0.1 to 0.2 are not reasonable. Hence, the solution for $\tau^* > 100$ is at best more qualitative than that for earlier times.

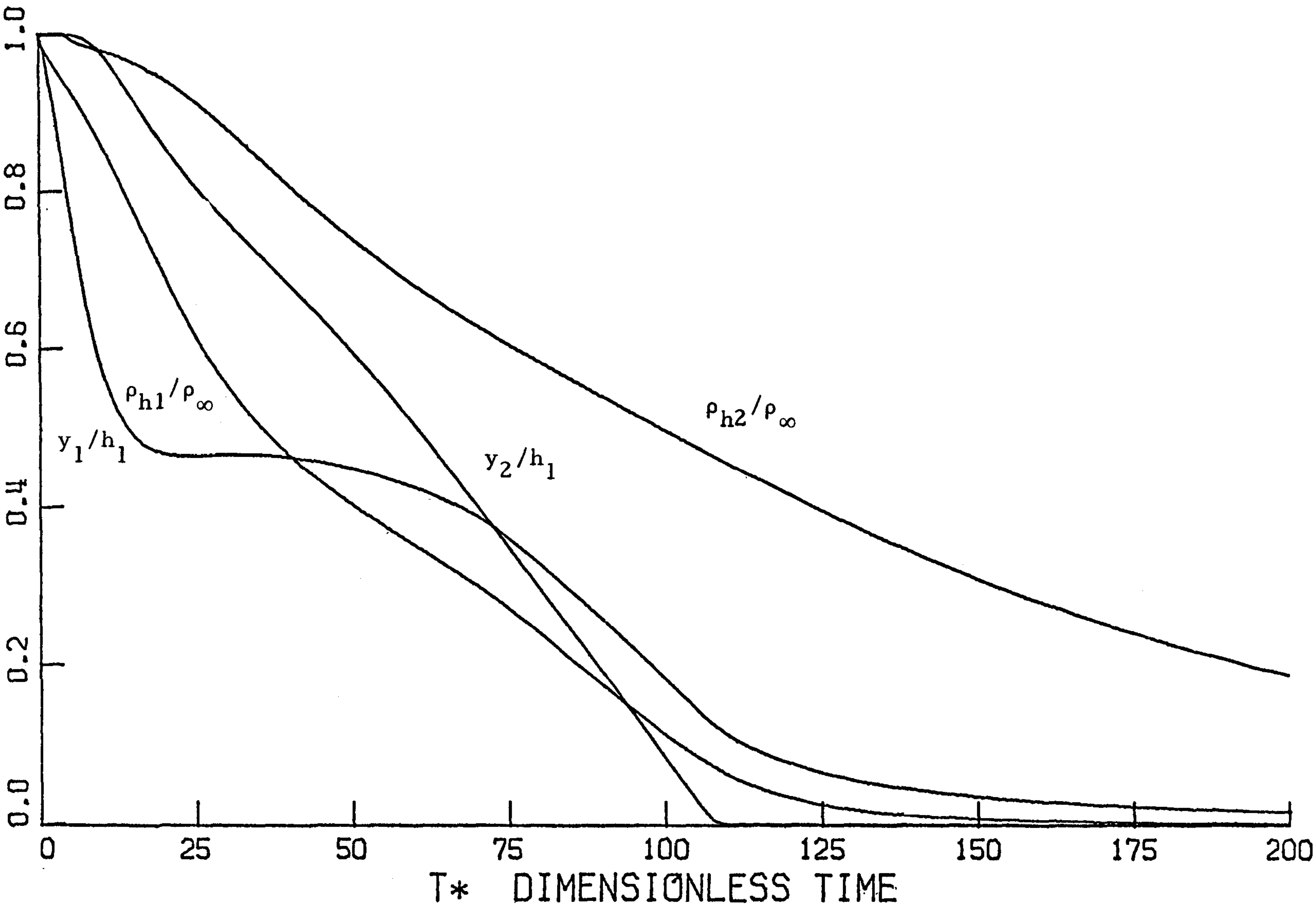


Figure 13. Hospital Corridor Example.

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2. Yokoi, S., "Study on the Prevention of Fire Spread Caused by Hot Upward Current," Report No. 34, Building Research Institute, Japanese Government, 1960.

3. Zukoski, E. E. and Kubota, T., "A Computer Model for Fluid Dynamic Aspects of a Transient Fire in a Two Room Structure", California Institute of Technology, Pasadena, California, January 1978.

APPENDIX

The Appendix contains four Sections. In the first two Sections, A and B, a more detailed description is given of the computer program organization and notation. The various subroutines are described and parameters used in this description are defined again.

The Fortran IV listing for the complete program, June 1978 realization, is listed in Section C.

Finally, a typical example is illustrated in Section D and detailed numerical values for 13 parameters are given in Section E as a function of t*.

A. DETAILED DESCRIPTION OF COMPUTER PROGRAM

Numerical solution of six equations derived from the conservation laws -- four ordintary differential equations for ceiling-layer heights and densities and two nonlinear algebraic equations for pressures -- are coded in FORTRAN IV to be executed by an IBM 370/158 computer at the CIT Computing Center.

At each time step, the nonlinear algebraic equations are solved by a numerical Newtons method to obtain the pressures and hence the mass and energy fluxes through the openings, and then the differential equations are solved by a CIT library routine which incorporates the fourth-order Runge-Kutta-Gill method, the Adams-Moulton predictor-corrector formula, and a provision for automatic control of truncation error.

The program, listed in Section D, consists of the following subprograms:

MAIN PROGRAM

SUBROUTINE DATAIN

SUBROUTINE DERIV

SUBROUTINE PRESS

SUBROUTINE F78

SUBROUTINE FLOW 1

SUBROUTINE FLOW 2

SUBROUTINE GRAPH

FUNCTION FIRE

FUNCTION PLUME

FUNCTION RJET

FUNCTION DRO

FUNCTION DRS

and CIT library subprograms, not included in the FORTRAN listing

SUBROUTINE MODDEQ

plotting routines

MAIN PROGRAM is the executive program that calls other subprograms and also prints input and output data. The input data are read by SUBROUTINE DATAIN through a title card and a name list named NAM1. The title card contains TITLE(10) which is 40 character alphanumeric data to identify the case. The dimensionless variables and parameters included in the name list NAM1 are:

YU, YL, BO	the heights to the soffit and sill and the width of the opening connecting two rooms.
H2B, S2B	the floor-to-ceiling height and the floor area of the second room.
QREF	reference heat input from the fire
C5	time constant used in SUBROUTINE FIRE
CFLS1, CFLS2	heat loss coefficients in the room 1 and 2
CMP	mass-entrainment coefficient used in SUBROUTINE PLUME
CH, CL	length data used in SUBROUTINE PLUME
	CH = height from the floor to the fire source
	CL = length of two-dimensional fire
COC, COH	flow coefficients at an opening for cold and hot flows
ICFD	flag used in SUBROUTINE PLUME
	ICFD = 1 two-dimensional plume
	ICFD = 2 axi-symmetric plume
IDR	flag for the door routines
	IDR = 1 leads to FUNCTION DRO
	IDR = 2 leads to FUNCTION DRS
CT1, CT2	time constants used in FUNCTION DRO and FUNCTION DRS
IMAX1, IMAX2	number of openings to outdoors from rooms 1 and 2
ZU, ZL, ZB	heights to soffit and sill and widths of openings to outdoors.
	Two-dimensional array variable. First index runs from

	1 to IMAX1 (or IMAX2) and second index is 1 for room 1 and 2 for room 2
TMAX	maximum time for integration
NPRT	flag for printing. Computed results are printed at every NPRT time-step.
FLPRT	flag for printing mass fluxes through openings FLPRT = 0.0 not printed FLPRT = 1.0 printed
FPLOT	flag for plotting FPLOT = 0.0 SUBROUTINE GRAPH is not called FPLOT = 1.0 SUBROUTINE GRAPH is called
FPLOT 1	flag for plotting FPLOT 1 = 0.0 plot for room 1 only FPLOT 1 = 1.0 plot for room 1 and 2
BMF	fuel mass flow coefficient
EPSP, ITMAXP	convergence limit and maximum number of iterations in SUBROUTINE PRESS

If the values of variables are not specified through the namelist NAM1 input, the following values are assumed in the program:

YU = 0.813	YL = 0.0	BO = 0.375
H2B = 1.0	S2B = 1.0	
QREF = 0.01	C5 = -1.0	
CFLS1 = 0.0	CFLS2 = 0.0	
CMP = 0.1865	COC = 0.6	COH = 0.6
ICFD = 2	CH = 0.0	CL = 0.0
IDR = 1	CT1 = -1.0	CT2 = 0.0
IMAX1 = 0	IMAX2 = 1	
ZU(1,2) = 0.813	ZL(1,2) = 0.0	ZB(1,2) = 0.375

TMAX = 100	EPSP = 10^{-5}	ITMAXP = 5.0	
NPRT = 4	FLPRT = 0.0	FPLOT = 0.0	FPLOT1 = 0.0

This case corresponds to one interconnecting door of constant area between rooms 1 and 2, no other opening in room 1, one door to outdoors from room 2, axi-symmetric fire of constant strength on the floor, mass flows not printed, no plotting.

SUBROUTINE MODDEQ, which is called from MAIN PROGRAM, in turn calls SUBROUTINE DERIV to evaluate the derivatives used in the integration routines. This part of the code is unique to the CIT Computing Center, and needs to be changed when the code is transferred to other computing centers.

SUBROUTINE PRESS is the program for numerical solution of nonlinear algebraic equations for pressures by the Newton's method. The partial derivatives needed for the method are approximated by finite-difference quotients. This subroutine calls SUBROUTINE F78, which in turn calls SUBROUTINE FLOW1 and SUBROUTINE FLOW2. In order to prevent the loss of significant figures in the finite-difference quotient computation, these four subprograms use double-precision variables.

SUBROUTINE F78 computes the values of two algebraic expressions for given ceiling-layer heights, densities and pressures. Vanishing of those two values within the specified limit EPSP determines two room pressures.

Heat loss to the walls from hot regions are taken into account in the subroutine F78. Heat input to ceiling layer in room 1 due to the fire is reduced by an arbitrary amount. The dimensionless heat input from the fire is QB, the net amount which reaches the ceiling layer is (1-CFLS1) x QB. Thus the walls receive CFLS1 x QB. In the second room a similar procedure is followed except that the total enthalpy flux of hot gas flowing from room 1 to room 2 is used as the base instead of QB. The numbers CFLS1 and CFLS2 are chosen arbitrarily before the calculation.

SUBROUTINE FLOW1 computes mass flows through an opening from a room to outdoors for given ceiling-layer heights, density and pressure. In the present code the outdoor pressure is the same for all openings.

SUBROUTINE FLOW 2 computes mass flows through an opening between two rooms. At present, no provision is made for the case in which the ceiling-layer height in the room 1 (fire room) is lower than the ceiling-layer height in the next room; in this case, the results returned by this subprogram are incorrect.

SUBROUTINE GRAPH is called when FPLOT = 1.0, and plots the ceiling-layer height and density in the room 1 or in both rooms. This routine calls CIT library routines for plotting and is not transferable to other computing facilities.

FUNCTION FIRE computes the fire heat input rate as a function of time. The code is programed to give a linear increase from a small value (QREF x 10^{-5}) at zero time to QREF at a time specified by C5. For times greater than C5, the heat input rate is QREF. Hence, when a negative value is assigned to C5, the heat input rate is a constant QREF for all times. QREF is the variable name for the parameter Q*{H} defined below in the discussion of FUNCTION PLUME.

FUNCTION PLUME computes the mass flow from the fire plume into the ceiling layer. The notation is illustrated in Figure 6. The symbol C_h is the height of the fire above the floor, y_1 is the height of the ceiling layer, and the difference $(y_1 - C_h)$ is the plume height y_p which corresponds to Z in the description of the plumes given earlier in the discussion of entrainment in Section B- I. Axisymmetric and line plumes are included in the plume subprogram. In terms of the parameters defined above, equation for the axisymmetric case can be rewritten as:

$$\dot{m}_E = \rho_\infty \sqrt{gH}\, H^2 \, (Q^* \{H\})^{1/3} \, (\pi C_v \, C_\ell^{\,2}) \, (y_p/H)^{5/3}$$

or in terms of the normalized variables:

$$\bar{\dot{m}}_E = \frac{\dot{m}_E}{\rho_\infty \sqrt{gH}\, H^2} \quad (Q^* \{H\})^{1/3} \, (C_{mp}) \, (Y_p)^{5/3} \qquad (19)$$

Here

$$C_{mp} = \pi C_v \, C_\ell^{\,2}$$

$$Y_p = y_p/H \quad .$$

Equation (19) corresponds to Fortran statement 009 in FUNCTION PLUME.

A similar development can be carried out for the line fire example and the normalized entrainment rate for this case is

$$\bar{\dot{m}}_E = (\sqrt{\pi}\, C_{\ell 2} C_{v2}) \, (Q_2^* \{H\})^{1/3} \, (Y_p) \, (CL)^{2/3}$$

Here the plume length $\mathcal{L}$ is given by

$$\mathcal{L} = (CL)H$$

and q_2^*, $C_{\ell 2}$, C_{v2} are defined earlier in Section I. The value of the constant term was taken to be $(\pi \, C_{v2} \, C_{\ell 2}) = 2.75 \, (C_{mp})$. The Fortran equation is given in FUNCTION PLUME as statement 007.

FUNCTION DRO allows the area of an opening to be changed with time. The area is zero for time less than C_{t1}, grows linearly with time to C_{t2} and is constant for longer times. A similar subroutine, DRS, allows the opening to be closed.

A complete FORTRAN listing and a test case is given in Section C.

B. NOMENCLATURE AND DIMENSIONLESS PARAMETERS USED IN PROGRAM

The geometric parameters are described in Figure 6 and in Table V for the two-room example. Index j (= 1,2) refers to room number 1 or 2; index i refers to the i-th opening between a room and the outside space; and subscripts ℓ and u refer to the lower and upper edges of an opening. For example $y_u(2,1)$ is the distance from the floor to the upper edge of the second opening to the outdoors from room 1.

The parameters and variables are made dimensionless by dividing:

lengths	by h_1
floor areas	by S_1
pressure differences	by $\rho_\infty g h_1$
densities	by ρ_∞
temperatures	by T_∞
heat fluxes	by $\rho_\infty c_p T_\infty h_1^2 \sqrt{gh_1}$
mass flows	by $h_1^2 \sqrt{gh_1}$

where

ρ_∞, T_∞	=	density and temperature of ambient air
c_p	=	specific heat at constant pressure of air
g	=	gravitational acceleration
h_1	=	floor-to-ceiling distance in room 1
S_1	=	floor area of room 1

A partial list of variables and parameters appearing in the analysis and the corresponding FORTRAN variable names is given in Table 1. Another useful lists of definitions appears in the List of Symbols which starts on page (i), and in Figure 6 on page 20.

TABLE V

FORTRAN	dimensionless variables	definition	
YU	$\bar{y}_{iu} = y_{iu}/h_1$	floor-to-soffit height	opening between two rooms
YL	$\bar{y}_{i\ell} = y_i\ /h_1$	floor-to-sill height	
BO	$\bar{b}_i = b_i/h_i$	width	
H2B	$\bar{h}_2 = h_2/h_1$	floor-to-ceiling height	room 2
S2B	$\bar{S}_2 = S_2/S_1$	floor area	
QREF	$Q_r^* = Q_r/(\rho_\infty c_p T_\infty h_1^2 \sqrt{gh_1})$	reference heat input from fire	
C5		time constant in FUNCTION FIRE	
CFLS1	Q_{w1}/Q	ratio of heat transfer to the room-1 ceiling to the fire heat input	
CFLS2	$Q_{w2}/\left[\dot{m}_{h1}\ c_p\ (T_{h1}-T_\infty)\right]$	ratio of heat transfer to the room-2 ceiling to the enthalpy flux into room-2	
CMP	C_{mp}	coefficient of plume mass flux	
COC	C_{oc}	orifice coefficient for cold flow	
COH	C_{oh}	orifice coefficient for hot flow	
ICFD		flag for fire geometry ICFD = 1, line fire; ICFD=2, round fire	
CH	C_h/h_1	distance from floor to fire	
CL	$\mathcal{L}/h_1$	line-fire length	
BMF	$\dot{m}_f/Q$	mass flow rate of fuel	
IDR		flag for door-width variation IDR=1, door opening; IDR=2, door closing	

TABLE V (continued)

FORTRAN	dimensionless variables	definition
CT1	$(h_1\sqrt{gh_1}/S_1)\ t_1$	time constant for door variation
CT2	$(h_1\sqrt{gh_1}/S_1)\ t_2$	time constant for door variation
IMAX1		number of openings from room 1 to outdoors
IMAX2		number of openings from room 2 to outdoors
ZU(I,J)	$\bar{y}_u(i,j) = y_u(i,j)/h_1$	floor-to-soffit height
ZL(I,J)	$\bar{y}_\ell(i,j) = y_\ell(i,j)/h_1$	floor-to-sill height
ZB(I,J)	$b(i,j) = b(i,j)/h_1$	width
TMAX	$(h_1\sqrt{gh_1}/S_1)\ t_{max}$	maximum time for integration
EPSP		(see the program description in Chapter 3.)
ITMAXP		(see the program description in Chapter 3.)
NPRT		(see the program description in Chapter 3.)
FLPRT		(see the program description in Chapter 3.)
FPLOT		(see the program description in Chapter 3.)
FPLOT1		(see the program description in Chapter 3.)
Y(1)	$\bar{y}_1 = y_1/h_1$	height from floor to ceiling layer, room 1
Y(2)	$\bar{y}_2 = y_2/h_2$	height from floor to ceiling layer, room 2
Y(3)	$\rho_1^* = (\rho_{h1}-\rho_\infty)/\rho_\infty$	density in ceiling layer, room 1

TABLE V (continued)

FORTRAN	Dimensionless variables	definition
Y(4)	$\rho_2^* = (\rho_{h2} - \rho_\infty)/\rho_\infty$	density in ceiling layer, room 2
YDOT(1)	$d\bar{y}_1/d\bar{t}$	derivatives of Y(i)
YDOT(2)	$d\bar{y}_2/d\bar{t}$	
YDOT(3)	$d\rho_1^*/d\bar{t}$	
YDOT(4)	$d\rho_2^*/d\bar{t}$	
T	$\bar{t} = (h_1\sqrt{gh_1}/S_1)\ t$	time
TSTAR	$t^* = \bar{t} \cdot Q_R^{*\,1/3}$	scaled time
BME	$\bar{m}_E = \dot{m}_E/(\rho_\infty h_1{}^2\sqrt{gh_1})$	plume mass flow rate
BMJ	$\bar{m}_j = \dot{m}_j/(\rho_\infty h_1{}^2\sqrt{gh_1})$	mass flow entrained by door jet
BM1, BM2	$\bar{m}(i,j) = \dot{m}(i,j)/(\rho_\infty h_1{}^2\sqrt{gh_1})$	dimensionless mass flow into j-th room through i-th opening from outdoors
BMH1, BMH2	$\bar{m}_h(i,j) = \bar{m}_h(i,j)/(\rho_\infty h_1{}^2\sqrt{gh_1})$	dimensionless mass flow from j-th room ceiling layer to outdoors through i-th opening
SUMM1	$\sum_i \bar{m}(i,1)$	
SUMMH1	$\sum_i \bar{m}_h(i,1)$	
SUMM2	$\sum_i \bar{m}(i,2)$	
SUMMH2	$\sum_i m_h(i,2)$	

TABLE V (continued)

FORTRAN	dimensionless variables	definition
BM12	$\bar{m}_{12} = \dot{m}_{12}/(\rho_\infty h_1{}^2\sqrt{gh_1})$	cold air flow rate from room 2 to room 1
BMHij	$\bar{m}_{hij} = \dot{m}_{hij}/(\rho_\infty h_1{}^2\sqrt{gh_1})$	hot gas flow rate from room i to room j
BMT1	$\bar{m}_1 = \bar{m}_{12} + \sum_i m(i,1)$	total cold air flow into room 1
BMT2	$\bar{m}_2 = -\bar{m}_{12} + \sum_i \bar{m}(i,2)$	total cold air flow into room 2
TH1	T_{h1}/T_∞	temperature in ceiling layer, room 1
TH2	T_{h2}/T_∞	temperature in ceiling layer, room 2
QHT1	$\bar{q}_1 = q_1/(\rho_\infty c_p T_\infty h_1^2\sqrt{gh_1})$	total enthalpy flux from ceiling layer, room 1
QHT2	$\bar{q}_2 = q_2/(\rho_\infty c_p T_\infty h_1^2\sqrt{gh_1})$	total enthalpy flux from ceiling layer, room 2
QW1B	$Q_{w1}/(\rho_\infty c_p T_\infty h_1{}^2\sqrt{gh_1})$	heat transfer from ceiling layer to wall, room 1
QW2B	$Q_{w2}/(\rho_\infty c_p T_\infty h_1{}^2\sqrt{gh_1})$	heat transfer from ceiling layer to wall, room 2
MJET, MENT		as on page 82
M12, MH12,...		see BM12, BMH12 and etc. above

C. LISTING OF COMPUTER CODE (June 1978)

```
         C      THIS IS THE MAIN PROGRAM
         C
01              REAL*8 P10,P20,P1,P2,
               *               BMT1,BMT2,BMHT1,BMHT2,QHT1,QHT2,BM12,BMH12,BMH21,
               *               SUMM1,SUMMH1,SUMM2,SUMMH2
02              DIMENSION Y(4),YDOT(4),ZU(5,2),ZL(5,2),ZB(5,2)
03              DIMENSION X(903),Y1(903),Y2(903),Y3(903),Y4(903),Y5(903),Y6(903)
04              DIMENSION TITLE(10),IMAX(2)
05              EXTERNAL DERIV
06              COMMON/CCCCC/C13,C23,C53,RT2,C1,C2,DUMMY
07              COMMON/FIR/C5,C6,IFIRE
08              COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
               ,QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2
09              COMMON/INPUT1/TITLE,TMAX, FLPRT,FPLOT,FPLOT1,NPRT,LAST,
               *               TI,Y1I,Y2I,ROH1I,ROH2I,P1I,P2I,TM1,TM2,DT1,DT2,DT3
10              COMMON/INPUT2/QSCALE
11              COMMON/INPUT3/EPSP,ITMAXP,NEWT
12              COMMON/OPEN/IMAX1,IMAX2,ZU,ZL,ZB
13              COMMON/P10P20/P10,P20
14              COMMON/MASS/BMT1,BMT2,BMHT1,BMHT2,QHT1,QHT2,BM12,BMH12,BMH21,
               *               SUMM1,SUMMH1,SUMM2,SUMMH2
15              COMMON/FLOMAS/FLOMAS(903,9),IT
16              COMMON/OUT/XMA,YMA,X,Y1,Y2,Y3,Y4,Y5,Y6,RHOMAX
17              COMMON/DOOR/BI
         C
18              DATA EPS,EPSN /1.0E-4,1.0E-5/
         C         CONSTANTS FOR LATER COMPUTATIONS
19              C13=1.0/3.0
20              C23=2.0/3.0
21              C53=5.0/3.0
22              RT2=SQRT(2.0)
         C      INPUT
         C         DEFAULT VALUES FOR INPUT PARAMETERS
         C         GEOMETRICAL PARAMETERS
         C         OPENING BETWEEN TWO ROOMS
         C            YU   FLOOR TO SOFFIT HEIGHT
         C            YL   FLOOR TO SILL HEIGHT
         C            BO   FULL WIDTH
         C            BI   INITIAL WIDTH
23              YU = 0.813
24              YL = 0.
25              BO = 0.375
26              BI = 0.0
         C            IDR  FLAG FOR DOOR OPEN/CLOSE ROUTINE
         C              IDR=1  DOOR OPENING
         C              IDR=2  DOOR CLOSING
         C            CT1,CT2  TIME CONSTANTS FOR DOOR OPEN/CLOSE
27              IDR = 1
28              CT1 = -1.
29              CT2 = 0.
         C            H2B  FLOOR TO CEILING HEIGHT IN SECOND ROOM
         C            S2B  FLOOR AREA IN SECOND ROOM
30              H2B = 1.
31              S2B = 1.
         C         OPENINGS FROM ROOM 1 TO OUTDOORS
         C            IMAX1   NOMBER OF OPENINGS
```

```
C           IF IMAX1 IS NOT EQUAL TO ZERO, DIMENSIONS MUST BE GIVEN
C             ZU(I,1)  FLOOR-TO-SOFFIT HEIGHT
C             ZL(I,1)  FLOOR-TO-SILL HEIGHT
C             ZB(I,1)  WIDTH
          IMAX1 = 0
C           OPENINGS FROM ROOM 2 TO OUTDOORS
C           IMAX2, ZU(I,2), ZL(I,2), ZB(I,2)  TOTAL NUMBER AND DIMENSIONS
          IMAX2 = 1
          ZU(1,2) = 0.813
          ZL(1,2) = 0.
          ZB(1,2) = 0.375
C           PARAMETERS FOR FIRE STRENGTH
C             QREF  DIMENSIONLESS REFERENCE HEAT INPUT
C             BMF   FUEL MASS FLOW COEFFICIENT DEFINED BY
C               BMF = (FUEL MASS FLOW)/(FIRE HEAT INPUT)
C           C5  TIME CONSTANT FOR FIRE STRENGHT VARIATION
C           C6  TIME CONSTANT FOR EXPONENTIAL FIRE
C           IFIRE = 1  LINEAR RAMP FIRE
C           IFIRE = 2  EXPONENTIAL FIRE
          QREF = 0.01
          BMF=0.0
          C5 = -1.0
          C6 = 0.
          IFIRE = 1
C           CONSTANTS FOR HEAT LOSS TO WALLS
          CFLS1 = 0.0
          CFLS2 = 0.0
C           FIRE PLUME PARAMETERS
C             CMP   COEF. FOR TOTAL MASS ENTRAINED
C             ICFD  FLAG FOR FIRE GEOMETRY
C               ICFD = 1  LINE FIRE
C               ICFD = 2 POINT-SOURCE FIRE
C               ICFD = 3 FINITE DIAMETER FIRE
C             CL    LINE-FIRE LENGTH
C             CH    FLOOR-TO-FIRE HEIGHT
C             DIAMTR  FIRE DIAMETER
          CMP = 0.1865
          ICFD = 2
          CH = 0.
          CL = 0.
C           FLOW COEFFICIENTS FOR DOOR/WINDOW
          COC = 0.6
          CCH = 0.6
C           CONSTANT FOR DOOR JET
          CJ=1.0
C           MAXIMUM TIME FOR INTEGRATION
          TMAX = 100.
C           MAXIMUM INTEGRATION TIME STEPS
C           DT1  FOR TI<T<TM1
C           DT2  FOR TM1<T<TM2
C           DT3  FOR TM2<T
          TM1 = 10.
          TM2 = 50.
          DT1 = 0.025
          DT2 = 0.25
          DT3 = 2.0
```

```
C          PARAMETERS FOR PRESS SUBROUTINE
      EPSP = 1.E-5
      ITMAXP = 25
C          FLAGS FOR PRINTING AND PLOTTING
C          NPRT      RESULTS PRINTED AT EVERY NPRT STEPS
C          FLPRT=1.0  MASS FLOWS ARE PRINTED
C          FLPRT<1.0 MASS FLOWS ARE NOT PRINTED
C          FPLOT=1.0  Y1,RHO-H1 ARE PLOTTED
C          FPLOT1=1.0 Y2,RHO-H2 ALSO ARE PLOTTED
      NPRT = 4
      FLPRT = 0.
      FPLOT = 0.
      FPLOT1 = 0.
C          LAST = 0  PLOTTING TO BE CONTINUED ON ONE SHEET
C          LAST = 1  LAST CASE TO BE PLOTTED ON ONE SHEET
      LAST = 1
C          RATIO OF SPECIFIC HEATS
      GAM=1.4
C
C          INITIAL CONDITION
      TI = 0.
      Y1I = 1.
      Y2I = H2B
      ROH1I = 0.
      ROH2I = 0.
      P1I = 0.
      P2I = 0.
C          WHEN P1I=0. AND P2I=0. ARE SPECIFIED, INITIAL ESTIMATES FOR
C          PRESSURES ARE MADE LATER IN THE PROGRAM.
C
  100 CONTINUE
      CALL DATAIN
      IMAX(1) = IMAX1
      IMAX(2) = IMAX2
C
C          PRINT INPUT PARAMETERS
      WRITE(6,2000) TITLE,TMAX
 2000 FORMAT(1H1///9X,10A4,40X,'TMAX=',F6.0//9X,'INPUT PARAMETERS'/)
      WRITE(6,2010)YU,YL,BO,H2B,S2B,QREF,C5,CFLS1,CFLS2,CMP,COC,COH,
     1 ICFD,CH,CL,IDR,CT1,CT2
 2010 FORMAT(9X,'YU   =',F7.4,7X,'YL   =',F7.4,7X,'BO    =',F7.4/
     1 9X,'H2B  =',F7.4,7X,'S2B  =',F7.3//
     2 9X,'QREF =',F8.5,6X,'C5    =',F7.4,
     2 7X,'CFLS1=',F7.4,7X,'CFLS2=',F7.4/
     3 9X,'CMP  =',F7.4,7X,'COC  =',F7.4,7X,'COH  =',F7.4//
     4 9X,'ICFD =',I2,12X,'CH    =',F7.4,7X,'CL    =',F7.4/
     5 9X,'IDR  =',I2,12X,'CT1   =',F7.2,7X,'CT2  =',F7.2)
      DO 3 J=1,2
      IMA = IMAX(J)
      IF(IMA .LE. 0) GO TO 3
      WRITE(6,2020) J
 2020 FORMAT(/9X,'ADDITIONAL OPENINGS IN ROOM',I2/
     1 22X,'ZU',18X,'ZL',18X,'ZB')
      WRITE(6,2030) (I,ZU(I,J),ZL(I,J),ZB(I,J),I=1,IMA)
 2030 FORMAT(16X,I2,F9.4,2F20.4)
    3 CONTINUE
```

```
C          CONSTANTS USED IN FLOW SUBROUTINES
        C1 = RT2*COC
        C2 = RT2*COH*C23
C          QSTAR SCALING PARAMETER
        QSCALE = 1./QREF**C13
C          INTEGRATION TIME STEPS
        IF(TMAX .GT. TM1) GO TO 200
        ITMAX = (TMAX-TI)/DT1 + 1.01
        GO TO 220
  200 ITM1 = (TM1-TI)/DT1 + 1.01
        IF(TMAX .GT. TM2) GO TO 210
        ITMAX = (TMAX-TM1)/DT2 + ITM1 + 0.01
        GO TO 220
  210 ITM2 = (TM2-TM1)/DT2 + ITM1 + 0.01
        ITMAX = (TMAX-TM2)/DT3 + ITM2 + 0.01
  220 IF(TMAX .LT. 903) GO TO 230
        WRITE(6,2035) ITMAX
 2035 FORMAT('  ITMAX=',I5,' > 903 *** EXCEED OUTPUT STORAGE ALLOCATION'
     *   /'  REDUCE TMAX, OR CHANGE TM1,TM2,DT1,DT2, OR DT3')
        GO TO 100
  230 CONTINUE
        DT=DT1
C
C *** INITIAL VALUES FOR DEQ ***
        T=TI
C          ROOM-1 CEILING LAYER HEIGHT
        Y(1)=Y1I
C          ROOM-2 CEILING LAYER HEIGHT
        Y(2)=Y2I
C          (CEILING LAYER DEPTH)*(RHOSTAR) FOR ROOM-1 AND -2
        Y(3)=ROH1I*(1.-Y1I)
        Y(4)=ROH2I*(H2B-Y2I)
        IF((P1I.EQ.0.) .AND. (P2I.EQ.0.)) GO TO 7
        P10 = DBLE(P1I)
        P20 = DBLE(P2I)
        GO TO 8
C
C          ESTIMATE FOR INITIAL PRESSURES ARE MADE
      7 CONTINUE
        QB = FIRE(T,QREF)
        BME = PLUME(Y(1))
        IF(IOR .EQ. 2) GO TO 4
        BB = DRO(T)
        GO TO 5
      4 BB = DRS(T)
      5 CONTINUE
        SS = YO*BB
        DO 6 J=1,IMAX1
      6 SS = SS + (ZU(J,1)-ZL(J,1))*ZB(J,1)
        SS = SS*COC
C          INITIAL GUESS FOR ROOM PRESSURES
        P10 = DBLE(((1.+BMF-QW1)*QB/SS)**2)
        P20 = P10/2.
C
      8 CONTINUE
        RHOMAX = 0.
```

```
      IT=0
      NEWT = 0
C        HEADINGS FOR OUTPUT PRINTING
      WRITE(6,2040)
 2040 FORMAT(//3X,'IT',6X,'TSTR',7X,'Y1',9X,'RHOSTR1',9X,'PSTR1',
     *  10X,'Y2',9X,'RHOSTR2',9X,'PSTR2',11X,'QB'/)
      KOUNT = 100
      INCRMT = 1
      K=1
   10 CALL MODDEQ(DERIV,K,4,T,Y,YDOT,DT,EPS)
      IF(K .LT. 0) GO TO 400
      IF(NEWT .GT. 5) GO TO 100
      KOUNT = KOUNT + INCRMT
      IF (KOUNT .EQ.0) GO TO 10
      IT=IT+1
      DENOM = 1.-Y(1)
      IF(DENOM .GT. 0.) GO TO 20
      ROUH1=BME/(BME+QB)-1.0
      GO TO 30
   20 ROUH1=Y(3)/DENOM
   30 ROUH2 = 0.0
      DENOM=H2B-Y(2)
      IF(DENOM .NE. 0.0)ROUH2=Y(4)/DENOM
C        COMPUTE ROOM PRESSURES
      CALL PRESS(P10,P20,Y(1),Y(2),ROUH1,ROUH2,P1,P2,T)
      IF(ROUH1 .GE. -1.E-50) ROUH1 = 0.0
      IF(ROUH2 .GE. -1.E-50) ROUH2 = 0.0
C        SAVE OUTPUT FOR PLOTTING
      X(IT)=T
      Y1(IT)=Y(1)
      Y2(IT)=Y(2)
      Y3(IT)=ROUH1
      Y4(IT)=ROUH2
      S1 = SNGL(P1)
      S2 = SNGL(P2)
      Y5(IT) = S1
      Y6(IT) = S2
C        SAVE MASS FLOW RATES FOR LATER PRINTING
      BME = PLUME(Y(1))
      BMJ = RJET(Y(1),Y(2))*SNGL(BMH12)
      FLOMAS(IT,1)= SNGL(SUMM1)
      FLOMAS(IT,2)= SNGL(SUMMH1)
      FLOMAS(IT,3)= SNGL(SUMM2)
      FLOMAS(IT,4)= SNGL(SUMMH2)
      FLOMAS(IT,5)= SNGL(BM12)
      FLOMAS(IT,6)= SNGL(BMH12)
      FLOMAS(IT,7)= SNGL(BMH21)
      FLOMAS(IT,8)= BMJ
      FLOMAS(IT,9)= BME
C        ASSIGN CURRENT PRESSURES TO THE ESTIMATES FOR THE NEXT STEP
      P10=P1
      P20=P2
      IF(ROUH1 .LT. RHOMAX) RHOMAX = ROUH1
C        KOUNT = STEP COUNT FROM THE LAST PRINTED STEP
C        IF KOUNT IS LESS THAN NPRT, PRINTING IS SKIPPED
      IF(KOUNT .LT. NPRT) GO TO 35
```

```
      WRITE(6,2100) IT,T,Y(1),ROUH1,S1,Y(2),ROUH2,S2,QB
 2100 FORMAT(I5,F10.2,7E14.6)
      KCUNT = 0
   35 CONTINUE
      IF(IT .EQ. ITMAX) GO TO 90
      IF(IT .EQ. ITM1) GO TO 110
      IF(IT .EQ. ITM2) GO TO 120
      GO TO 10
C         RE-INITIALIZE MODDEQ FOR INCREASED TIME STEP
  110 K=1
      DT=DT2
      KOUNT = -1
      GO TO 10
C         RE-INITIALIZE MODDEQ FOR INCREASED TIME STEP
  120 K=1
      DT=DT3
      KOUNT = -NPRT
      INCRMT = NPRT
      GO TO 10
   90 CONTINUE
      WRITE(6,2110) RHOMAX
 2110 FORMAT(/16X,'RHOSTAR-MAX =',E14.6)
C         IF FLPRT IS LESS THAN 1.0, MASS-FLW RATES PRINTING IS SKIPPED
      IF( FLPRT .LE. 0.1) GO TO 102
      WRITE(6,2200)
 2200 FORMAT(1H1,' IT',4X,' SUM1', 9X,'SUMH1', 9X,' SUM2', 9X,'SUMH2',
     , 9X,' M12 ', 9X,' MH12',11X,'MH21',11X,'MJET',11X,'MENT'/)
      WRITE(6,2300)  (J, (FLOMAS(J,I),I=1,9),J=1,IT,NPRT)
 2300 FORMAT(1X,I3,9E14.5)
  102 CONTINUE
C         IF FPLOT IS LESS THAN 0.1, PLOTTING IS SKIPPED
      IF (FPLOT .LE. 0.1) GO TO 100
      MAX=X(IT)+1
      XMA = MAX
      YMA=1.0
      CALL GRAPH(FPLOT1,TITLE,IT,LAST)
      GO TO 100
C         IF ERROR RETURN FROM DEQ, PRINT MASS FLOWS AND GO TO NEXT CASE
  400 CONTINUE
      WRITE(6,2200)
      WRITE(6,2300)  (J, (FLOMAS(J,I),I=1,9),J=1,IT,NPRT)
      GO TO 100
  500 STOP
      END
```

```
      SUBROUTINE DATAIN
      DIMENSION ZU(5,2),ZL(5,2),ZB(5,2),IMAX(2)
      DIMENSION TITLE(10)
      COMMON/CCCCC/C13,C23,C53,RT2,C1,C2,DUMMY
      COMMON/FIR/C5,C6,IFIRE
      COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     ,QREF,CL,CH,ICFD,IDR,CT1,CT2,B0,CFLS1,CFLS2
      COMMON/INPUT1/TITLE,IMAX, FLPRT,FPLOT,FPLOT1,NPRT,LAST,
     *              TI,Y1I,Y2I,ROH1I,ROH2I,P1I,P2I,TM1,TM2,DT1,DT2,DT3
      COMMON/INPUT3/EPSP,ITMAXP
      COMMON/OPEN/IMAX1,IMAX2,ZU,ZL,ZB
      COMMON/PLUM/DIAMTR
      COMMON/DOOR/BI
      NAMELIST/NAM1/YU,YL,B0,H2B,S2B,QREF,C5,CFLS1,CFLS2,CMP,COC,COH,
     *  ICFD,CH,CL,IDR,CT1,CT2, IMAX1,IMAX2,ZU,ZL,ZB,TMAX,NPRT,FLPRT,
     *  FPLOT,FPLOT1,BMF,EPSP,ITMAXP,DIAMTR,BI,C6,CJ,LAST,IFIRE,
     *  TI,Y1I,Y2I,ROH1I,ROH2I,P1I,P2I,TM1,TM2,DT1,DT2,DT3
      READ(5,1000,END=500) TITLE
      READ(5,NAM1)
      RETURN
  500 STOP
 1000 FORMAT(10A4)
      END
```

```
      SUBROUTINE DERIV(N,T,Y,YDOT)
C        THIS PROGRAM EVALUATES THE DERIVATIVES AND RETURNS THE RESULTS
C        TO THE "MODDEQ".
      REAL*8 P10,P20,P1,P2,
     *           BMT1,BMT2,BMHT1,BMHT2,QHT1,QHT2,BM12,BMH12,BMH21,
     *           SUMM1,SUMMH1,SUMM2,SUMMH2
      DIMENSION Y(4),YDOT(4)
      COMMON/CCCCC/C13,C23,C53,RT2,C1,C2,C5
      COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     ,QREF,CL,CF,ICFD,IDR,CT1,CT2,B0,CFLS1,CFLS2
      COMMON/INPUT2/QSCALE
      COMMON/MASS/BMT1,BMT2,BMHT1,BMHT2,QHT1,QHT2,BM12,BMH12,BMH21,
     *           SUMM1,SUMMH1,SUMM2,SUMMH2
      COMMON/P10P20/P10,P20
C
C        COMPUTE CURRENT FIRE STRENGTH
      QB=FIRE(T,QREF)
C        COMPUTE INTERCONNECTING DOOR WIDTH
      GO TO (1,2),IDR
    1 BB=DRC(T)
      GO TO 3
    2 BB=DRS(T)
    3 CONTINUE
C        COMPUTE MASS FLOW ENTRAINED BY THE FIRE PLUME
      BME=PLUME(Y(1))
C        COMPUTE CEILING LAYER DENSITIES
      IF(T .NE. 0.0) GO TO 10
      BMJ=0.0
      ROUH1=BME/(BME+QB)-1.0
      GO TO 11
   10 ROUH1=Y(3)/(1.0-Y(1))
   11 ROUH2 = 0.0
      DENOM=H2B-Y(2)
      IF(DENOM .NE. 0.0)ROUH2=Y(4)/DENOM
C        COMPUTE ROOM PRESSURES AND MASS FLOWS AT DOORS AND WINDOWS
      CALL PRESS(P10,P20,Y(1),Y(2),ROUH1,ROUH2,P1,P2,T)
C        COMPUTE MASS FLOW ENTRAINED BY THE DOOR JET
      BMJ = RJET(Y(1),Y(2))*SNGL(BMH12)
C        COMPUTE DERIVATIVES
      YDOT(1) = (SNGL(BMT1) - BME)*QSCALE
      YDOT(2) = (SNGL(QHT2) + QW2B -BMJ)/S2B*QSCALE
      YDOT(3) = (SNGL(BMT1 - BMHT1) + BMF*QB)*QSCALE
      YDOT(4) = (SNGL(QHT2 - BMHT2) + QW2B)/S2B*QSCALE
      RETURN
      END
```

```
      SUBROUTINE PRESS(P10,P20,Y1,Y2,RO1,RO2,P1,P2,T)
C        THIS PROGRAM COMPUTES ROOM PRESSURES FROM TWO NONLINEAR
C        EQUATIONS BY NEWTONS METHOD.  PARTIAL DERIVATIVES ARE APPROXI-
C        MATED BY FINITE-DIFFERENCE QUOTIENTS.  TO AVOID LOSS OF SIGNIFI-
C        CANT FIGURES DOUBLE-PRECISION VARIABLES ARE USED.
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*4 Y1,Y2,RO1,RO2,T,FLOMAS,QSCALE,EPS,
     *         H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     *QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2
      COMMON/FLOMAS/FLOMAS(903,9),NT
      COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     ,QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2
      COMMON/INPUT2/QSCALE
      COMMON/INPUT3/EPS,ITMAX,NEWT
      COMMON/MASS/BMT1,BMT2,BMHT1,BMHT2,QHT1,QHT2,BM12,BMH12,BMH21,
     *         SUMM1,SUMMH1,SUMM2,SUMMH2
      DATA DP/1.E-3/
C
      ABS(Z) = DABS(Z)
C
      D1=DP/QSCALE**2
      D2=D1
      ALPHA = 0.5
      DELS1 = 100.
      DELS2 = 100.
      DELS3 = 100.
C
   10 CONTINUE
      DO 50 IT=1,ITMAX
C        WHEN MAGNITUDES OF PRESSURES BECOME VERY SMALL, SET THEM EQUAL
C        TO 0., TO AVOID UNDERFLOW CONDITION.
      IF(DABS(P10) .LE. 1.D-50) P10=0.0
      IF(DABS(P20) .LE. 1.D-50) P20=0.0
      CALL F78(Y1,Y2,P10,P20,RO1,RO2,F70,F80)
C        SOLUTION COVERGED?
      DQB = DBLE(QB)
      EPS7 = EPS*DMAX1(ABS(BMT1),ABS(QHT1),DQB)
      IF(ABS(F70) .GT. EPS7) GO TO 15
      IF(ABS(F80) .GT. EPS7) GO TO 15
      GO TO 100
   15 CONTINUE
C        COMPUTE FINITE-DIFFERENCE QUOTINTS
C        DETERMINE DELTA-P'S FOR FINITE-DIFFERENCE QUOTIENTS
      IF(P10 .NE. 0.0)D1=1.0E-4*P10
      IF(P20 .NE. 0.0)D2=1.0E-4*P20
      DDP = P10 - P20
      IF(DABS(DDP) .GE. DABS(P10)) GO TO 5
      D1 = DDP*1.0E-04
      SP1 = P10*1.0E-10
      IF(ABS(D1) .LT. ABS(SP1)) D1=SP1
      IF(DABS(DDP) .GE. DABS(P20)) GO TO 5
      D2 = DDP*1.0E-04
      SP2 = P20*1.0E-10
      IF(ABS(D2) .LT. ABS(SP2)) D2=SP2
    5 CONTINUE
      CALL F78(Y1,Y2,P10+D1,P20,RO1,RO2,F71,F81)
```

```
      DF7DP1=(F71-F70)/D1
      DF8DP1=(F81-F80)/D1
C
   20 CALL F78(Y1,Y2,P10,P20+D2,RO1,RO2,F72,F82)
      DF7DP2=(F72-F70)/D2
      DF8DP2=(F82-F80)/D2
C
C         COMPUTE PRESSURE CORRECTIONS
   30 DENOM=DF7DP1*DF8DP2-DF7DP2*DF8DP1
      IF(DENOM .NE. 0.0) GO TO 31
      WRITE(6,560) T
  560 FORMAT('  DENOM = 0 IN NEWTONS METHOD AT T=',E13.6)
      GO TO 710
   31 CONTINUE
      DELP1=(F80*DF7DP2-F70*DF8DP2)/DENOM
      DELP2=(F70*DF8DP1-F80*DF7DP1)/DENOM
      ALFA=1.0
      ALFB=1.0
C         IF CONSECUTIVE CORRECTIONS CHANGE SIGN, HALF THE CORRECTION
C         TO AVOID HUNTING
      IF(DELS1 .EQ. 0.) GO TO 32
      IF(DELP1/DELS1 .LT. -0.34) ALFA=ALPHA
   32 IF(DELS2 .EQ.0.) GO TO 34
      IF(DELP2/DELS2 .LT. -0.34) ALFB=ALPHA
   34 IF(DELS3 .EQ. 0.) GO TO 40
      DELP = DELP1 - DELP2
      IF((DELP/DELS3) .GE. -0.34) GO TO 40
      ALFA = ALPHA
      ALFB = ALFA
   40 CONTINUE
      DELS1 = DELP1*ALFA
      DELS2 = DELP2*ALFB
      DELS3 = DELS1 - DELS2
      P10=P10+DELS1
      P20=P20+DELS2
   50 CONTINUE
      NEWT = NEWT + 1
      P10 = P10 - DELS1/2.0
      P20 = P20 - DELS2/2.0
C
      WRITE(6,570) T
  570 FORMAT(/'  NEWTONS METHOD DID NOT CONVERGE AT T=',E13.6/)
      WRITE(6,2100) IT,T,Y1,RO1,P10,Y2,RO2,P20,QB
 2100 FORMAT(/'  N',I2,F10.4,2E14.6,D14.6,2E14.6,D14.6,E14.6)
      GO TO 100
  710 CONTINUE
      WRITE(6,17)
   17 FORMAT(1H1,' IT',4X,' SUM1', 9X,'SUMH1', 9X,' SUM2', 9X,'SUMH2',
     , 9X,' M12 ', 9X,' MH12',11X,'MJET',11X,'MENT',11X,'Q'/)
      WRITE(6,16)(J, (FLUMAS(J,I),I=1,9),J=1,NT)
   16 FORMAT(1X,I3,9E14.5)
      STOP
  100 P1=P10
      P2=P20
      RETURN
      END
```

```
      SUBROUTINE F78(Y1,Y2,P1,P2,RO1,RO2,F7,F8)
C        THIS PROGRAM EVALUATES TWO NONLINEAR ALGEBRAIC EXPRESSIONS
C        WHICH DETERMINE ROOM PRESSURES.
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*4 Y1,Y2,RO1,RO2,ZU(5,2),ZL(5,2),ZB(5,2),
     *              H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     *QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2,
     *              C13,C23,C53,RT2,C1,C2,C5
      COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     ,QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2
      COMMON/CCCCC/C13,C23,C53,RT2,C1,C2,C5
      COMMON/OPEN/IMAX1,IMAX2,ZU,ZL,ZB
      COMMON/MASS/BMT1,BMT2,BMHT1,BMHT2,QHT1,QHT2,BM12,BMH12,BMH21,
     *              SUMM1,SUMMH1,SUMM2,SUMMH2
C
C        COMPUTE FLOW BETWEEN ROOM 1 AND 2
      CALL FLOW2(Y1,Y2,P1,P2,RO1,RO2,BM12,BMH12,BMH21)
C        COMPUTE FLOW BETWEEN ROOM 1 AND OUTDOORS
      SUMM1=0.0
      SUMMH1=0.0
      IF(IMAX1 .EQ. 0) GO TO 10
      DO 5 I=1,IMAX1
      CALL FLOW1(P1,Y1,RO1,ZU(I,1),ZL(I,1),BM1,BMH1)
      SUMM1=SUMM1+BM1*ZB(I,1)
    5 SUMMH1=SUMMH1+BMH1*ZB(I,1)
C        COMPUTE FLOW BETWEEN ROOM 2 AND OUTDOORS
   10 SUMM2=0.0
      SUMMH2=0.0
      IF(IMAX2 .EQ. 0) GO TO 20
      DO 15 I=1,IMAX2
      CALL FLOW1(P2,Y2,RO2,ZU(I,2),ZL(I,2),BM2,BMH2)
      SUMM2=SUMM2+BM2*ZB(I,2)
   15 SUMMH2=SUMMH2+BMH2*ZB(I,2)
   20 CONTINUE
C        COMPUTE F7 AND F8
      TH1=1.0/(1.0+RO1)
      TH2=1.0/(1.0+RO2)
      BMT1=BM12+SUMM1
      BMT2=-BM12+SUMM2
      BMHT1=BMH12+SUMMH1-BMH21
      BMHT2=-BMH12+SUMMH2+BMH21
      QHT1=(BMH12+SUMMH1)*TH1-BMH21*TH2
      QHT2=(BMH21+SUMMH2)*TH2-BMH12*TH1
      QW1B=CFLS1*QB
      QW2B = CFLS2*BMH12*(TH1-1.)
      F7=BMT1-QHT1+(1.0+BMF)*QB-QW1B
      F8=BMT2-QHT2-QW2B
      RETURN
      END
```

```
      SUBROUTINE FLOW1(PS,ZC,ROUHS,ZU,ZL,BM,BMH)
C        THIS PROGRAM COMPUTES FLOW BETWEEN ROOM 1 (OR ROOM 2)
C        AND OUTDOORS
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*4 ZC,ROUHS,ZU,ZL,C13,C23,C53,RT2,C1,C2,C5
      COMMON/CCCCC/C13,C23,C53,RT2,C1,C2,C5
C
      SQRT(Z) = DSQRT(Z)
C
      IF(ROUHS .GT. -1.E-50) ROUHS=-1.E-50
      ZO=ZC+PS/ROUHS
      IF(PS .LT. 0.0) GO TO 2
C PS .GT. 0
      RTPS=SQRT(PS)
      RT1R=SQRT(1.0+ROUHS)
      IF(ZU .LE. ZC) GO TO 12
      A=    (PS-ROUHS*(ZU-ZC))
      IF(A .GT. 0)A=SQRT(A)
      IF(A .LT. 0.0)A=0
      IF(ZL .GE. ZC) GO TO 112
C ZL .LT. ZC
      BM=-C1*RTPS*(ZC-ZL)
      BMH=C2*RT1R*(ZU-ZC)*(PS/(RTPS+A)+A)
      RETURN
C ZL .GE. ZC
  112 B=PS-ROUHS*(ZL-ZC)
      BM=0.0
      BMH=C2*RT1R*(ZU-ZL)*(B/(SQRT(B)+A)+A)
      RETURN
C ZU .LE. ZC
   12 BM=-C1*RTPS*(ZU-ZL)
      BMH=0.0
      RETURN
C PS .LT. 0
    2 RTPS=SQRT(-PS)
      IF(ZU .LE. ZO) GO TO 22
C ZU .GT. ZO
      IF(ZL .GE. ZC) GO TO 212
C ZL .LT. ZC
      BM=C1*RTPS*(ZC-ZL+C23*(ZO-ZC))
      BMH=C2*SQRT(-ROUHS)   *RT1R*     (ZU-ZO)**1.5
      RETURN
C ZL .GE. ZC
  212 IF(ZL .GE. ZO) GO TO 213
C ZL .LT. ZO
      BM=C1*SQRT(-ROUHS)   *C23*(ZO-ZL)**1.5
      BMH=C2*SQRT(-ROUHS)   *RT1R*     (ZU-ZO)**1.5
      RETURN
C ZL .GE. ZO
  213 BM=0.0
      BMH=C2*SQRT(-ROUHS)   *RT1R*     ((ZU-ZO)**1.5-(ZL-ZO)**1.5)
      RETURN
C ZU .LE. ZO
   22 IF(ZU .LE. ZC) GO TO 23
C ZU .GT. ZC
      A=SQRT(ROUHS*(ZU-ZC)-PS)
```

```
      IF(ZL .GE. ZC) GO TO 222
C ZL .LT. ZC
      BM=C1*((ZC-ZL)*RTPS+C23*(ZU-ZC)*(A-PS/(A+RTPS)))
      BMH=0.0
      RETURN
C ZL .GE. ZC
  222 B=ROUHS*(ZL-ZC)-PS
      BM=C23*C1*(ZU-ZL)*(B/(SQRT(B)+A)+A)
      BMH=0.0
      RETURN
C ZU .LE. ZC
   23 BM=C1*(ZU-ZL)*RTPS
      BMH=0.0
      RETURN
      END
```

```
      SUBROUTINE FLOW2(Y1,Y2,P1,P2,ROH1,ROH2,M12,MH12,MH21)
C        THIS PROGRAM COMPUTES FLOW BETWEEN ROOMS 1 AND 2
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 M12,MH12,MH21
      REAL*4 Y1,Y2,ROH1,ROH2,SAVEY,SAVER,YT,YB,
     *            H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     *            QREF,CL,CH,CT1,CT2,BO,CFLS1,CFLS2,
     *            C13,C1,C53,C2,CONST1,CONST2,C55
      COMMON/INPUT/H2B,S2B,YT,YB,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     ,QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2
      COMMON/CCCCC/C13,C1,C53,C2,CONST1,CONST2,C55
C
C
      YU = YT
      YL = YB
      MH12 = 0.
      MH21 = 0.
      M12 = 0.
        COCB=COC*BB
        COHB=COH*BB
C
C        WHEN Y2 IS LESS THAN Y1, WE SWITCH Y,P AND ROH BETWEEN ROOMS
C        1 AND 2, COMPUTE MASS FLOWS, AND SWITCH BACK TO THE ORIGINAL
C        BEFORE RETURNING TO THE CALLING PROGRAM.  THIS IS DONE TO
C        AVOID DUPLICATION OF PROGRAM STEPS.
C
      ISWICH = 1
      IF(Y1 .LE. Y2) GO TO 400
      SAVEY = Y1
      Y1 = Y2
      Y2 = SAVEY
      SAVEP = P1
      P1 = P2
      P2 = SAVEP
      SAVER = ROH1
      ROH1 = ROH2
      ROH2 = SAVER
      ISWICH = -1
  400 CONTINUE
C
      IF(ROH1 .GT. -1.E-50) ROH1=-1.E-50
      IF(ROH2 .GT. -1.E-50) ROH2=-1.E-50
        BRHO1 = DBLE(ABS(1.+ROH1))
        C3 =DSQRT(BRHO1)
        AROH1 = DBLE(ABS(ROH1))
        C4 =DSQRT(AROH1)
        BRHO2 = DBLE(ABS(1.+ROH2))
        C5 =DSQRT(BRHO2)
        DP = P1 - P2
      IF(DP .GE. 0.0) GO TO 2
C        P1 < P2
    1   DP2= DP - ROH1*(Y2-Y1)
C        YO   NEUTRAL-PRESSURE POINT
        YO = Y1 + DP/ROH1
      IF(ROH1 .LE. ROH2) GO TO 11
      DROH = ROH1 - ROH2
```

```
      Y02 = Y2 + DP2/DROH
      IF(YU .LE. Y02) GO TO 11
        IF(YL .LT. Y02) GO TO 1101
 1105   A=DSQRT((YL-Y02)*DROH-DP2)
        B=(YL-Y02)*DROH-DP2
        MH21=C1*C2*C5*COHB*(YU-YL)*(A+B/(A+DSQRT(B)))
      GO TO 500
 1101 DY = YU - Y02
      MH21 =  C1*C2*C5*COHB*DY*DSQRT(DY*DROH)
        YU=Y02
      GO TO 111
C
   11   IF(YO.GT.Y2) GO TO 12
  111   IF (YU.LE.Y2) GO TO 112
        B=DSQRT(DP2)
        A=DSQRT(DP2+(ROH2-ROH1)*(YU-Y2))
        F2=(YU-Y2)*(A+B-(A*B)/(A+B))
 1111   MH12=C1*COHB*C3*C2*((Y2-YO)*DSQRT(DP2)+F2)
        IF (YL.GE.Y1) GO TO 1112
11211   M12=C2*COCB*(Y1-YL+C1*(YO-Y1))*DSQRT(-DP)
      GO TO 500
 1112   IF (YL.GE.YO) GO TO 1113
11221   M12=C1*C2*COCB*(YO-YL)*DSQRT(-DP - ROH1*(Y1-YL))
      GO TO 500
 1113   IF (YL.GE.Y2) GO TO 1114
        MH12=C1*COHB*C3*C2*((Y2-YO)*DSQRT(DP2)-(YL-YO)*
     *DSQRT(DP2+ROH1*(Y2-YL))+F2)
      GO TO 500
 1114   B=DSQRT(DP2+(ROH2-ROH1)*(YL-Y2))
        MH12=C1*COHB*C3*C2*(YU-YL)*(A+B-A*B/(A+B))
      GO TO 500
  112   IF (YU.LE.YO) GO TO 113
 1121   MH12=C1*COHB*C3*C2*(YU-YO)*DSQRT( DP - ROH1*(YU-Y1))
        IF (YL.GE.Y1) GO TO 1122
        GO TO 11211
 1122   IF (YL.GE.YO) GO TO 1123
        GO TO 11221
 1123   IF (YL.GE.Y2) GO TO 9999
        MH12=C1*COHB*C3*C2*((YU-YO)*DSQRT(DP - ROH1*
     *(YU-Y1))-(YL-YO)*DSQRT(DP - ROH1*(YL-Y1)))
      GO TO 500
  113   IF(YU.LE.Y1) GO TO 114
 1131   IF (YL.GE.Y1) GO TO 1132
        M12=COCB*C2*C3*(((Y1-YL)+C1*(YO-Y1))*DSQRT(YO-Y1)-
     *C1*(YO-YU)**1.5)
      GO TO 500
 1132   M12=C1*COCB*C2*C3*((YO-YL)**(1.5)-(YO-YU)**(1.5))
      GO TO 500
  114   IF (YU.LT.YL) GO TO 9999
        M12=C2*COCB*(YU-YL)*DSQRT(-DP)
      GO TO 500
C
   12   DP= -DP
        DP2=-DP2
        IF (ROH1.GE.ROH2) GO TO 13
        DROH=ROH2-ROH1
```

```
            YO=Y2+DP2/DROH
      121   IF(YU .LT. YO) GO TO 122
            IF(YL .GE. YO) GO TO 1214
            A=YU-YO
            MH12=C1*C2*C3*COHB*A*DSQRT(A*DROH)
            IF(YL .GE. Y2) GO TO 1213
            A=YO-Y2
            MH21=C1*C2*C5*CCHB*A*DSQRT(A*DROH)
            IF(YL .GE. Y1) GO TO 1212
     1211   A=DSQRT(DP)
            B=DSQRT(DP2)
            M12=C2*CCCB*(C1*(Y2-Y1)*(A+DP2/(A+B))+A*(Y1-YL))
          GO TO 500
     1212   A=DSQRT(DP+ROH1*(YL-Y1))
            B=DSQRT(DP2)
            M12=C1*C2*CCCB*(Y2-YL)*(A+DP2/(A+B))
          GO TO 500
     1213   A=YO-YL
            MH21=C1*C2*C5*COHB*A*DSQRT(A*DROH)
          GO TO 500
     1214   A=DSQRT(DROH*(YU-Y2)-DP2)
            C=DROH*(YL-Y2)-DP2
            B=DSQRT(C)
            MH12=C1*C2*C3*COHB*(YU-YL)*(A+C/(A+B))
          GO TO 500
     122    IF (YU.LT.Y2) GO TO 123
            C=DP2-(ROH2-ROH1)*(YU-Y2)
     1221   IF (YL.GT.Y1) GO TO 1222
            A=DSQRT(DP)
            M12=C2*CCCB*((Y1-YL)*A+C1*(Y2-Y1)*(DP/(A+B)+B))
            MH21= C1*C2*COHB*C5*(YU-Y2)*(B+C/(B+DSQRT(C)))
          GO TO 500
     1222   IF (YL.GT.Y2) GO TO 1223
            A=DSQRT(DP+ROH1*(YL-Y1))
            M12=C1*C2*CCCB*(Y2-YL)*(A+DP2/(A+DSQRT(DP2)))
            MH21= C1*C2*COHB*C5*(YU-Y2)*(B+C/(B+DSQRT(C)))
          GO TO 500
     1223   IF (YL.GT.YU) GO TO 9999
            B=DSQRT(DP2-(ROH2-ROH1)*(YL-Y2))
            MH21= C1*C2*COHB*C5*(YU-YL)*(B+C/(B+DSQRT(C)))
          GO TO 500
     123    IF(YU.LT.Y1) GO TO 124
     1231   B=DSQRT(DP+ROH1*(YU-Y1))
            IF (YL.GT.Y1) GO TO 1232
            M12=C2*CCCB*((Y1-YL)*DSQRT(DP)+C1*(YU-Y1)*(B+DP/(B+DSQRT(DP))))
          GO TO 500
     1232   M12=C1*C2*CCCB*(YU-YL)*(B+A/(B+DSQRT(A)))
          GO TO 500
     124    M12=C2*CCCB*(YU-YL)*DSQRT(DP)
          GO TO 500
C
     13     CONTINUE
     131    IF(YU.LE.Y2) GO TO 132
     1311   B=DSQRT(DP2)
            MH21= C2*CCHB*C5*(YU-Y2)*B
            IF (YL.GE.Y1) GO TO 1312
```

```
          A=DSQRT(DP)
          M12=C2*COCB*((Y1-YL)*A+C1*(Y2-Y1)*(B+DP/(A+B)))
        GO TO 500
 1312     IF (YL.GE.Y2) GO TO 1313
          A=DSQRT(DP+ROH1*(YL-Y1))
          M12=C1*C2*COCB*(Y2-YL)*(B+A/(B+DSQRT(A)))
        GO TO 500
 1313     MH21= C2*COHB*(YU-YL)*DSQRT(DP2)*C5
        GO TO 500
 132      IF (YU.LT.Y1) GO TO 133
 1321     B=DSQRT(DP+ROH1*(YU-Y1))
          IF (YL.GE.Y1) GO TO 1322
          A=DSQRT(DP)
          M12=C2*COCB*(A*(Y1-YL)+C1*(YU-YL)*(B+DP/(A+B)))
        GO TO 500
 1322     A=DP+ROH1*(YL-Y1)
          M12=C1*C2*COCB*(YU-YL)*(B+A/(B+DSQRT(A)))
        GO TO 500
 133      M12=C2*COCB*(YU-YL)*DSQRT(DP)
        GO TO 500
C
C          P1 > P2
C
  2     CONTINUE
          DP2=DP-ROH1*(Y2-Y1)
        IF(ROH1 .LE. ROH2) GO TO 21
        DROH = ROH1 - ROH2
        YO = Y2 + DP2/DROH
        IF(YU .LE. YO) GO TO 21
          IF(YL .LT. YO) GO TO 201
 204      A=DSQRT((YL-Y2)*DROH-DP2)
          B=(YL-Y2)*DROH-DP2
          MH21=C1*C2*C5*COHB*(YU-YL)*(A+B/(A+DSQRT(B)))
        GO TO 500
  201 DY = YU - YO
      MH21 =  C1*C2*C5*COHB*DY*DSQRT(DY*DROH)
          YU=YO
          GO TO 211
C
 21       IF (YU.LE.Y2) GO TO 22
 211      A=DP2+(ROH2-ROH1)*(YU-Y2)
          B=DSQRT(DP2)
          IF (YL.GE.Y1) GO TO 212
          C=DSQRT(DP)
          M12=-C2*COCB*(Y1-YL)*C
          MH12=C1*C2*COHB*C3*((YU-Y2)*(B+A/(B+DSQRT(A)))+(Y2-Y1)
     **(B+DP/(B+C)))
        GO TO 500
 212      IF (YL.GE.Y2) GO TO 213
          C=DP-ROH1*(YL-Y1)
          MH12=C1*COHB*C3*((YU-Y2)*(B+A/(B+DSQRT(A)))+(Y2-YL)
     **(B+C/(B+DSQRT(C))))
        GO TO 500
 213      B=DSQRT(DP2+(ROH2-ROH1)*(YL-Y2))
          MH12=C1*C2*COHB*C3*(YU-YL)*(B+A/(B+DSQRT(A)))
        GO TO 500
```

```
      22    IF (YU.LE.Y1) GO TO 23
      221   A=DP-ROH1*(YU-Y1)
            IF (YL.GE.Y1) GO TO 222
            C=DSQRT(DP)
            M12=-C2*COCB*(Y1-YL)*C
            MH12=C1*C2*COHB*C3*(YU-Y1)*(C+A/(C+DSQRT(A)))
          GO TO 500
      222   C=DSQRT(DP-ROH1*(YL-Y1))
            MH12=C1*C2*COHB*C3*(YU-YL)*(C+A/(C+DSQRT(A)))
          GO TO 500
      23    M12=-C2*COCB*(YU-YL)*DSQRT(DP)
C
      500 IF(ISWICH .GT. 0) RETURN
          Y2 = Y1
          Y1 = SAVEY
          ROH2 = ROH1
          ROH1 = SAVER
          P2 = P1
          P1 = SAVEP
          M12 = -M12
          SAVEP=MH12
          MH12 = MH21
          MH21 = SAVEP
          RETURN
C
      9999  WRITE(6,600)
      600   FORMAT(1H 'ERROR IN SUBROUTINE FLOW2')
          STOP
            END
```

```
          FUNCTION FIRE(T,QR)
          COMMON/FIR/C5,C6,IFIRE
          IF(T .GT. C5) GO TO 5
          IF(IFIRE .GT. 1) GO TO 1
          FIRE=QR*(T/C5+1.0E-5)
          RETURN
        1 FIRE = QR*EXP(C6*(T-C5))
          RETURN
        5 FIRE=QR
          RETURN
          END
```

```
      FUNCTION RJET(Y1,Y2)
      COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     ,QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2
      YJ=Y2-0.5*(YU+Y1)
      IF(YJ .GT. 0.0) GO TO 10
      RJET=0.0
      RETURN
   10 RJET=CJ*(Y2-Y1)/(YU-Y1)*(YJ/(H2B-YU))**2
      RETURN
      END
```

```
      FUNCTION DRO(T)
      COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     ,QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2
      COMMON/DOOR/BI
      IF(T .LE. CT1) GO TO 10
      IF(T .GE. CT2) GO TO 5
      DRO = (BO-BI)*(T-CT1)/(CT2-CT1)+BI
      RETURN
    5 DRO=BO
      RETURN
   10 DRO=BI
      RETURN
      END
```

```
      FUNCTION PLUME(Y1)
C        THIS PROGRAM COMPUTES MASS FLOW ENTRAINED BY FIRE PLUME
C          ICFD = 1  LINE FIRE
C          ICFD = 2 AXISYMMETRIC PLUME FROM POINT FIRE
C          ICFD = 3 AXISYMMETRIC PLUME FROM FINITE DIAMETER FIRE
      COMMON/CCCCC/C13,C23,C53,RT2,C1,C2,C5
      COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
     ,QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2
      COMMON/PLUM/DIAMTR
C
      YP=Y1-CH
      IF(YP .LE. 0.0) GO TO 10
      GO TO (1,2,3),ICFD
    1 PLUME=2.75*CMP*QB**C13*CL**C23*YP
      RETURN
    2 PLUME=CMP*QB**C13*YP**C53
      RETURN
    3 YO = DIAMTR*3.91
      PLUME = CMP*QB**C13*((YP+YO)**C53 - YO**C53)
      RETURN
   10 PLUME=0
      RETURN
      END
```

```
      SUBROUTINE GRAPH(FPLOT1,TITLE,IT,LAST)
      DIMENSION X(903),Y1(903),Y2(903),Y3(903),Y4(903),Y5(903),Y6(903)
      DIMENSION TITLE(10),DD(3)
      COMMON/OUT/XMA,YMA,X,Y1,Y2,Y3,Y4,Y5,Y6,RHOMAX
      DATA DD/3*0.0/
C
      DO 130 J=1,IT
      Y3(J) = Y3(J) + 1.
  130 Y4(J) = Y4(J) + 1.
C
      XO = 1.0
      YO = 1.0
      XMN = 0.
      YMN = 0.
      SIZEX = 8.
      SIZEY = 5.
      NDX = 8
      NDY = 5
      IF(LAST .LE. 0) GO TO 10
      CALL VLABEL(XO,YO,XMN,XMA,SIZEX,NDX,'T*  DIMENSIONLESS TIME',
     1              22,0,'(F5.0)',4)
      CALL VLABEL(XO,YO,YMN,YMA,SIZEY,NDY,'Y, RHO',0,1,'(F4.1)',4)
      TL = XO+1.
      TH = YO+SIZEY+3.
      CALL SYSSYM(TL,TH,0.20,TITLE,40,0.0)
   10 CONTINUE
      SLOPE = (XMA-XMN)/SIZEX
      XMN = XMN - SLOPE*XO
      XMA = XMN + SLOPE*15.
      SLOPE = (YMA-YMN)/SIZEY
      YMN = YMN - SLOPE*YO
      YMA = YMN + SLOPE*10.
      IF(FPLOT1 .LE. 0.1) GO TO 95
      CALL XYPLOT(IT,X,Y2,XMN,XMA,YMN,YMA,DD,0)
      CALL XYPLOT(IT,X,Y4,XMN,XMA,YMN,YMA,DD,0)
   95 CONTINUE
      CALL XYPLOT(IT,X,Y1,XMN,XMA,YMN,YMA,DD,0)
      CALL XYPLOT(IT,X,Y3,XMN,XMA,YMN,YMA,DD,LAST)
      RETURN
      END
```

```
      FUNCTION DRS(T)
      COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,CUC,COH,CJ,CMP,
     ,QREF,CL,CH,ICFD,IDR,CT1,CT2,BO,CFLS1,CFLS2
      IF(T .LE. CT1) GO TO 10
      IF(T .GE. CT2) GO TO 5
      DRS=BO*(1.0-(T-CT1)/(CT2-CT1))
      RETURN
    5 DRS=0.
      RETURN
   10 DRS=BO
      RETURN
      END
```

D. SAMPLE COMPUTATION

A sample computation was carried out for a two-room combination with the following input parameters:

a) Room 1: one closed window to outdoors. The leak through the window is simulated by having a very narrow opening specified by:

ZU(1, 1) = 0.8, ZL(1, 1) = 0.4, ZB(1, 1) = 0.0025

b) Room 2: Same height and area as 1. H2B = 1.0, S2B = 1.0; one door to outdoors, fully open:

ZU(1,2) = 0.813, ZL(1,2) = 0.0, ZB(1,2) = 0.375

c) Between two rooms: One door, closed (with leak) at the beginning, starts to open at t* = 10, fully open at t* = 11.5 and thereafter,

YU = 0.813, YL = 0.0, B0 = 0.375, BI = 0.002

where BI is width of the door leak

IDR = 1, CT1 = 10.0, CT2 = 11.5

d) Fire: starts from a small value, builds up to full strength by t* = 8.0, and remains constant thereafter.

QREF = 0.01, C5 = 8.0

e) Heat loss to the walls: Arbitrarily chosen to be

CFLS1 = 0.25, CFLS2 = 0.20

f) Other parameters are as specified in the main program listed in Section D of the Appendix.

The printed output for this case is given in Section E following the program listing. The first table, after the input parameters, gives $Y1 \equiv y_1/h_1$, $RHOSTR1 \equiv (\rho_{h1} - \rho_\infty)/\rho_\infty$, $PSTR1 \equiv (p_1 - p_\infty)/\rho_\infty g h_1$, $Y2 \equiv y_2/h_1$, $RHOSTR2 \equiv (\rho_{h2} - \rho_\infty)/\rho_\infty$, $PSTR2 \equiv (p_2 - p_\infty)/\rho_\infty g h_1$ as a function of $TSTR \equiv Q_r^{*1/3} t \sqrt{gh_1}\ h_1/S_1 \equiv t^*$. The second table lists the mass fluxes and fire strength at the corresponding time steps. In this table, the following dimensionless variables are given:

SUM1, SUM2 = algebraic sum of cold air flow between outdoors and room 1 or 2. Positive for inflow.

SUMH1, SUMH2 = sum of hot gas flow to outdoors from room 1 or 2. Positive for outflow.

M12, MH12, MH21 = cold and hot gas flow between room 1 and 2. If M12>0 the flow is from room 2 to room 1; MHij >0, from room i to room j.

MJET = cold air flow entrained by the door jet in room 2.

MENT = cold air flow entrained by the fire plume in room 1.

Q = Heat input rate normalized by $\rho_\infty C_p T_\infty h_1^2 \sqrt{gh_1}$

Also Y1, Y2, ρ_{h1}/ρ_∞, and ρ_{h2}/ρ_∞ are plotted against t^* in Figure 7. We see that Y2 = 1 and RHOSTR2 = 0 for $0 \le TSTR \leq 2.2$, since during this period Y1 > YU = 0.813 and hence, the hot gas from room 1 cannot flow into room 2. As soon as Y1 < YU in room 1, Y2 and RHOSTR2 start to change but only slowly because the width of opening is very small. Also, note that PSTR is positive in both rooms; namely, the room pressure is higher than the outdoor pressure. The cold air in room 1 is rapidly entrained by the fire plume, heated and convected into the ceiling layer, and the resulting volume expansion is forcing the air out of room 1 through small gaps in the window and the door until the door is opened. Shortly after $t^* = 2.4$ (IT = 97), the ceiling layer reaches the window soffit level, and the hot gas in addition to the cold air starts leaking out of room 1 through the window to the outdoors. (SUMH1 > 0). Around $t^* = 7.8$ (IT = 313) the ceiling layer completely covers the window and the cold air leak through the window is cut off (SUM1 = 0). In room 2, during this period, the ceiling layer is above the soffit of the door leading to the outdoors, and the growth of ceiling layer thickness and the cold air pushed into room 2 from room 1 are forcing the cold air out through the door.

As soon as the door between rooms 1 and 2 is opened (from $t^* = 10$ to 11.5), the hot gas gushes into room 2 (MH12 increases almost ten folds at $t^* = 12$, IT = 409), the ceiling layer thickness in room 1 quickly decreases, the ceiling layer in room 2 rapidly thickens, and hot gas starts flowing out of room 2 through the door to the outdoors (SUMH2>0). After these rapid changes, the flow field gradually approaches the equilibrium condition. Note also that, after the inner door is opened, the room pressures become negative (lower then the outdoor pressure) in order to bring fresh air into the rooms to balance the increased hot gas outflow.

The computation was carried out in dimensionless variables. If we take $h_1 = h_2 = 2.5$ m, $S_1 = S_2 = 20\ m^2$, $T_\infty = 20^\circ C$, then

$$Q^* = Q/(1.11 \times 10^4 \text{ kw}),\quad p^* = (p-p_\infty)/(2.94 \times 10^{-4} \text{ atm})$$
$$t^* = t/(1.62 Q^{*-1/3} \text{ sec.})$$

Thus $Q^* = 0.01$ corresponds to a five strength of 111 kw (106 Btu/sec); $p^* = 1$, to $p-p_\infty = 2.94 \times 10^{-4}$ atm ($0.62\ lb/ft^2$); and $t^* = 1$, to $t = 7.52$ sec.

E. PARAMETER VALUES FOR SAMPLE CALCULATIONS

Values of various parameters calculated as a function of time for the example shown in Figure 7 and discussed in Appendix, Section D. (Note the definitions of the parameters listed here are given in detail in Section D.)

DOOR OPENING BETWEEN ROOMS 12/16/77 IMAX= 40.

INPUT PARAMETERS

```
YU   = 0.8130      YL   = 0.0       B0    = 0.3750
H2B  = 1.0000      S2B  =  1.000

CREF = 0.01000     C5   = 8.0000    CFLS1= 0.2500     CFLS2= 0.2000
CMP  = 0.1665      COC  = 0.6000    COH   = 0.6000

ICFD = 2           CH   = 0.0       CL    = 0.0
IDR  = 1           CT1  =  10.00    CT2   =  11.50
```

ADDITIONAL OPENINGS IN ROOM 1

	ZU	ZL	ZB
1	0.8000	0.4000	0.0025

ADDITIONAL OPENINGS IN ROOM 2

	ZU	ZL	ZB
1	0.8130	0.0	0.3750

IT	TSTR	Y1	RHOSTR1	PSTR1	Y2	RHOSTR2	PSTR2
1	0.0	0.100000E 01	-0.115395E-03	0.113294E-08	0.100000E 01	0.0	0.322250E-13
9	0.20	0.991787E 00	-0.106054E-01	0.708659E-02	0.100000E 01	0.0	0.201568E-06
17	0.40	0.979390E 00	-0.168977E-01	0.283351E-01	0.100000E 01	0.0	0.805952E-06
25	0.60	0.964855E 00	-0.222924E-01	0.637451E-01	0.100000E 01	0.0	0.181314E-05
33	0.80	0.948871E 00	-0.272399E-01	0.113317E 00	0.100000E 01	0.0	0.322315E-05
41	1.00	0.931843E 00	-0.319276E-01	0.177051E 00	0.100000E 01	0.0	0.503596E-05
49	1.20	0.914047E 00	-0.364560E-01	0.254946E 00	0.100000E 01	0.0	0.725160E-05
57	1.40	0.895690E 00	-0.408870E-01	0.347003E 00	0.100000E 01	0.0	0.987004E-05
65	1.60	0.876929E 00	-0.452621E-01	0.453223E 00	0.100000E 01	0.0	0.128913E-04
73	1.80	0.857892E 00	-0.496103E-01	0.573603E 00	0.100000E 01	0.0	0.163154E-04
81	2.00	0.838682E 00	-0.539535E-01	0.708146E 00	0.100000E 01	0.0	0.201422E-04
89	2.20	0.819384E 00	-0.583078E-01	0.856851E 00	0.100000E 01	0.0	0.243719E-04
97	2.40	0.800074E 00	-0.626664E-01	0.101905E 01	0.999787E 00	-0.162346E-02	0.290041E-04
105	2.60	0.780854E 00	-0.670996E-01	0.119310E 01	0.999373E 00	-0.378470E-02	0.339949E-04
113	2.80	0.761803E 00	-0.715562E-01	0.137993E 01	0.998815E 00	-0.563700E-02	0.393672E-04
121	3.00	0.742968E 00	-0.760632E-01	0.157923E 01	0.998091E 00	-0.724670E-02	0.451156E-04
129	3.20	0.724389E 00	-0.806261E-01	0.179077E 01	0.997177E 00	-0.866527E-02	0.512376E-04
137	3.40	0.706099E 00	-0.852457E-01	0.201420E 01	0.996052E 00	-0.993374E-02	0.577274E-04
145	3.60	0.688125E 00	-0.899379E-01	0.224918E 01	0.994692E 00	-0.110840E-01	0.645791E-04
153	3.80	0.670491E 00	-0.946937E-01	0.249535E 01	0.993078E 00	-0.121418E-01	0.717874E-04
161	4.00	0.653214E 00	-0.995195E-01	0.275234E 01	0.991190E 00	-0.131281E-01	0.793464E-04
169	4.20	0.636308E 00	-0.104417E 00	0.301977E 01	0.989011E 00	-0.140601E-01	0.872500E-04
177	4.40	0.619786E 00	-0.109389E 00	0.329724E 01	0.986526E 00	-0.149525E-01	0.954919E-04
185	4.60	0.603655E 00	-0.114435E 00	0.358433E 01	0.983721E 00	-0.158173E-01	0.104065E-03
193	4.80	0.587921E 00	-0.119556E 00	0.388062E 01	0.980589E 00	-0.166654E-01	0.112964E-03
201	5.00	0.572588E 00	-0.124754E 00	0.418568E 01	0.977123E 00	-0.175055E-01	0.122181E-03
209	5.20	0.557657E 00	-0.130028E 00	0.449907E 01	0.973321E 00	-0.183458E-01	0.131708E-03
217	5.40	0.543128E 00	-0.135378E 00	0.482034E 01	0.969182E 00	-0.191930E-01	0.141540E-03
225	5.60	0.529001E 00	-0.140805E 00	0.514903E 01	0.964711E 00	-0.200535E-01	0.151668E-03
233	5.80	0.515273E 00	-0.146308E 00	0.548466E 01	0.959915E 00	-0.209328E-01	0.162085E-03
241	6.00	0.501940E 00	-0.151886E 00	0.582679E 01	0.954803E 00	-0.218356E-01	0.172784E-03
249	6.20	0.488997E 00	-0.157539E 00	0.617493E 01	0.949388E 00	-0.227665E-01	0.183757E-03
257	6.40	0.476441E 00	-0.163266E 00	0.652862E 01	0.943685E 00	-0.237296E-01	0.194996E-03
265	6.60	0.464263E 00	-0.169066E 00	0.688738E 01	0.937709E 00	-0.247286E-01	0.206494E-03
273	6.80	0.452459E 00	-0.174938E 00	0.725074E 01	0.931480E 00	-0.257667E-01	0.218244E-03
281	7.00	0.441022E 00	-0.180880E 00	0.761822E 01	0.925017E 00	-0.268472E-01	0.230237E-03

289	7.20	0.429943E 00	-0.186892E 00	0.798934E 01	0.918339E 00	-0.279728E-01	0.242465E-03
297	7.40	0.419217E 00	-0.192972E 00	0.836366E 01	0.911467E 00	-0.291464E-01	0.254922E-03
305	7.60	0.408834E 00	-0.199118E 00	0.874068E 01	0.904422E 00	-0.303703E-01	0.267599E-03
313	7.80	0.398787E 00	-0.205330E 00	0.912233E 01	0.897224E 00	-0.316468E-01	0.280563E-03
321	8.00	0.389031E 00	-0.211605E 00	0.952396E 01	0.889888E 00	-0.329790E-01	0.294295E-03
329	8.20	0.379589E 00	-0.217843E 00	0.944977E 01	0.882520E 00	-0.343519E-01	0.293441E-03
337	8.40	0.370502E 00	-0.223951E 00	0.937665E 01	0.875221E 00	-0.357482E-01	0.292614E-03
345	8.60	0.361751E 00	-0.229940E 00	0.930428E 01	0.867997E 00	-0.371672E-01	0.291803E-03
353	8.80	0.353319E 00	-0.235819E 00	0.923266E 01	0.860853E 00	-0.386083E-01	0.291009E-03
361	9.00	0.345190E 00	-0.241594E 00	0.916177E 01	0.853793E 00	-0.400710E-01	0.290230E-03
369	9.20	0.337350E 00	-0.247273E 00	0.909158E 01	0.846820E 00	-0.415550E-01	0.289466E-03
377	9.40	0.329785E 00	-0.252863E 00	0.902205E 01	0.839937E 00	-0.430597E-01	0.288714E-03
385	9.60	0.322482E 00	-0.258367E 00	0.895319E 01	0.833145E 00	-0.445849E-01	0.287975E-03
393	9.80	0.315428E 00	-0.263793E 00	0.888498E 01	0.826446E 00	-0.461301E-01	0.287248E-03
401	10.00	0.308612E 00	-0.269142E 00	0.881740E 01	0.819840E 00	-0.476950E-01	0.286533E-03
409	12.00	0.375538E 00	-0.316838E 00	-0.254075E-01	0.602249E 00	-0.129898E 00	-0.167842E-03
417	14.00	0.453057E 00	-0.345760E 00	-0.135990E-01	0.504091E 00	-0.189166E 00	-0.417909E-02
425	16.00	0.469699E 00	-0.361139E 00	-0.124798E-01	0.496021E 00	-0.223178E 00	-0.626466E-02
433	18.00	0.474192E 00	-0.370640E 00	-0.126132E-01	0.508858E 00	-0.249591E 00	-0.658810E-02
441	20.00	0.478127E 00	-0.376568E 00	-0.124741E-01	0.523824E 00	-0.271102E 00	-0.637353E-02
449	22.00	0.481979E 00	-0.379895E 00	-0.121266E-01	0.537167E 00	-0.288081E 00	-0.599881E-02
457	24.00	0.485299E 00	-0.381408E 00	-0.117253E-01	0.547993E 00	-0.300925E 00	-0.561450E-02
465	26.00	0.487885E 00	-0.381773E 00	-0.113576E-01	0.556271E 00	-0.310235E 00	-0.528266E-02
473	28.00	0.489757E 00	-0.381498E 00	-0.110584E-01	0.562322E 00	-0.316707E 00	-0.502098E-02
481	30.00	0.491036E 00	-0.380930E 00	-0.108304E-01	0.566584E 00	-0.321025E 00	-0.482555E-02
489	32.00	0.491866E 00	-0.380282E 00	-0.106651E-01	0.569485E 00	-0.323785E 00	-0.468544E-02
497	34.00	0.492379E 00	-0.379672E 00	-0.105495E-01	0.571397E 00	-0.325467E 00	-0.458808E-02
505	36.00	0.492679E 00	-0.379151E 00	-0.104712E-01	0.572615E 00	-0.326432E 00	-0.452234E-02
513	38.00	0.492842E 00	-0.378735E 00	-0.104198E-01	0.573360E 00	-0.326942E 00	-0.447919E-02
521	40.00	0.492921E 00	-0.378417E 00	-0.103872E-01	0.573795E 00	-0.327175E 00	-0.445174E-02

RFCSTAR-MAX = -0.381773E 00

IT	SUM1	SUMH1	SUM2	SUMH2	M12	MH12	MJET	MENT	Q
1	-0.28561E-07	0.0	-0.46439E-07	0.0	-0.46439E-07	0.0	0.0	0.86566E-03	0.10000E-06
9	-0.71431E-04	0.0	-0.11614E-03	0.0	-0.11614E-03	0.0	0.0	0.11590E-01	0.25010E-03
17	-0.14283E-03	0.0	-0.23224E-03	0.0	-0.23224E-03	0.0	0.0	0.14298E-01	0.50010E-03
25	-0.21423E-03	0.0	-0.34834E-03	0.0	-0.34834E-03	0.0	0.0	0.15964E-01	0.75010E-03
33	-0.28564E-03	0.0	-0.46444E-03	0.0	-0.46444E-03	0.0	0.0	0.17089E-01	0.10001E-02
41	-0.35704E-03	0.0	-0.58054E-03	0.0	-0.58054E-03	0.0	0.0	0.17861E-01	0.12501E-02
49	-0.42844E-03	0.0	-0.69663E-03	0.0	-0.69663E-03	0.0	0.0	0.18379E-01	0.15001E-02
57	-0.49984E-03	0.0	-0.81273E-03	0.0	-0.81273E-03	0.0	0.0	0.18705E-01	0.17501E-02
65	-0.57124E-03	0.0	-0.92883E-03	0.0	-0.92883E-03	0.0	0.0	0.18879E-01	0.20001E-02
73	-0.64265E-03	0.0	-0.10449E-02	0.0	-0.10449E-02	0.0	0.0	0.18929E-01	0.22501E-02
81	-0.71405E-03	0.0	-0.11610E-02	0.0	-0.11610E-02	0.0	0.0	0.18880E-01	0.25001E-02
89	-0.78545E-03	0.0	-0.12771E-02	0.0	-0.12771E-02	0.0	0.0	0.18747E-01	0.27501E-02
97	-0.85657E-03	0.0	-0.13932E-02	0.0	-0.13706E-02	0.21444E-04	0.35382E-03	0.18547E-01	0.30001E-02
105	-0.88248E-03	0.42860E-04	-0.15083E-02	0.0	-0.14474E-02	0.57579E-04	0.45874E-03	0.18292E-01	0.32501E-02
113	-0.90159E-03	0.91760E-04	-0.16231E-02	0.0	-0.15187E-02	0.98407E-04	0.58229E-03	0.17993E-01	0.35001E-02
121	-0.91429E-03	0.14624E-03	-0.17376E-02	0.0	-0.15845E-02	0.14368E-03	0.72515E-03	0.17659E-01	0.37501E-02
129	-0.92086E-03	0.20598E-03	-0.18518E-02	0.0	-0.16451E-02	0.19314E-03	0.88764E-03	0.17298E-01	0.40001E-02
137	-0.92155E-03	0.27065E-03	-0.19655E-02	0.0	-0.17006E-02	0.24653E-03	0.10695E-02	0.16914E-01	0.42501E-02
145	-0.91664E-03	0.33992E-03	-0.20789E-02	0.0	-0.17513E-02	0.30357E-03	0.12702E-02	0.16515E-01	0.45001E-02
153	-0.90641E-03	0.41343E-03	-0.21919E-02	0.0	-0.17974E-02	0.36398E-03	0.14883E-02	0.16103E-01	0.47501E-02
161	-0.89114E-03	0.49086E-03	-0.23044E-02	0.0	-0.18391E-02	0.42751E-03	0.17224E-02	0.15683E-01	0.50001E-02
169	-0.87111E-03	0.57185E-03	-0.24164E-02	0.0	-0.18765E-02	0.49386E-03	0.19701E-02	0.15259E-01	0.52501E-02
177	-0.84661E-03	0.65609E-03	-0.25280E-02	0.0	-0.19099E-02	0.56278E-03	0.22291E-02	0.14832E-01	0.55001E-02
185	-0.81791E-03	0.74322E-03	-0.26390E-02	0.0	-0.19395E-02	0.63400E-03	0.24964E-02	0.14406E-01	0.57501E-02
193	-0.78529E-03	0.83294E-03	-0.27495E-02	0.0	-0.19654E-02	0.70726E-03	0.27689E-02	0.13983E-01	0.60001E-02
201	-0.74903E-03	0.92492E-03	-0.28595E-02	0.0	-0.19880E-02	0.78230E-03	0.30432E-02	0.13564E-01	0.62501E-02
209	-0.70938E-03	0.10188E-02	-0.29689E-02	0.0	-0.20073E-02	0.85887E-03	0.33161E-02	0.13150E-01	0.65001E-02
217	-0.66661E-03	0.11144E-02	-0.30777E-02	0.0	-0.20236E-02	0.93674E-03	0.35841E-02	0.12743E-01	0.67501E-02
225	-0.62096E-03	0.12114E-02	-0.31859E-02	0.0	-0.20371E-02	0.10157E-02	0.38441E-02	0.12345E-01	0.70001E-02
233	-0.57268E-03	0.13094E-02	-0.32935E-02	0.0	-0.20479E-02	0.10955E-02	0.40929E-02	0.11954E-01	0.72501E-02
241	-0.52199E-03	0.14083E-02	-0.34005E-02	0.0	-0.20562E-02	0.11759E-02	0.43279E-02	0.11573E-01	0.75001E-02
249	-0.46914E-03	0.15077E-02	-0.35068E-02	0.0	-0.20621E-02	0.12567E-02	0.45466E-02	0.11202E-01	0.77501E-02
257	-0.41432E-03	0.16075E-02	-0.36124E-02	0.0	-0.20659E-02	0.13377E-02	0.47468E-02	0.10841E-01	0.80001E-02
265	-0.35776E-03	0.17073E-02	-0.37174E-02	0.0	-0.20677E-02	0.14188E-02	0.49270E-02	0.10490E-01	0.82501E-02
273	-0.29965E-03	0.18070E-02	-0.38217E-02	0.0	-0.20676E-02	0.14998E-02	0.50857E-02	0.10150E-01	0.85001E-02
281	-0.24019E-03	0.19063E-02	-0.39253E-02	0.0	-0.20657E-02	0.15804E-02	0.52222E-02	0.98201E-02	0.87501E-02
289	-0.17954E-03	0.20051E-02	-0.40282E-02	0.0	-0.20623E-02	0.16606E-02	0.53358E-02	0.95012E-02	0.90001E-02
297	-0.11789E-03	0.21032E-02	-0.41304E-02	0.0	-0.20574E-02	0.17401E-02	0.54265E-02	0.91930E-02	0.92501E-02
305	-0.55403E-04	0.22003E-02	-0.42319E-02	0.0	-0.20512E-02	0.18189E-02	0.54943E-02	0.88954E-02	0.95001E-02
313	0.0	0.22898E-02	-0.43331E-02	0.0	-0.20440E-02	0.18970E-02	0.55404E-02	0.86083E-02	0.97501E-02
321	0.0	0.23306E-02	-0.44379E-02	0.0	-0.20374E-02	0.19762E-02	0.55710E-02	0.83302E-02	0.10000E-01
329	0.0	0.23127E-02	-0.44315E-02	0.0	-0.19802E-02	0.20046E-02	0.54497E-02	0.79959E-02	0.10000E-01
337	0.0	0.22952E-02	-0.44252E-02	0.0	-0.19253E-02	0.20310E-02	0.53233E-02	0.76795E-02	0.10000E-01
345	0.0	0.22779E-02	-0.44191E-02	0.0	-0.18726E-02	0.20555E-02	0.51930E-02	0.73796E-02	0.10000E-01
353	0.0	0.22610E-02	-0.44131E-02	0.0	-0.18219E-02	0.20782E-02	0.50598E-02	0.70951E-02	0.10000E-01
361	0.0	0.22442E-02	-0.44072E-02	0.0	-0.17731E-02	0.20991E-02	0.49246E-02	0.68251E-02	0.10000E-01
369	0.0	0.22277E-02	-0.44014E-02	0.0	-0.17262E-02	0.21184E-02	0.47881E-02	0.65687E-02	0.10000E-01
377	0.0	0.22113E-02	-0.43956E-02	0.0	-0.16810E-02	0.21362E-02	0.46511E-02	0.63251E-02	0.10000E-01
385	0.0	0.21952E-02	-0.43900E-02	0.0	-0.16375E-02	0.21526E-02	0.45141E-02	0.60933E-02	0.10000E-01
393	0.0	0.21793E-02	-0.43845E-02	0.0	-0.15956E-02	0.21676E-02	0.43776E-02	0.58728E-02	0.10000E-01
401	0.0	0.21636E-02	-0.43790E-02	0.0	-0.15551E-02	0.21812E-02	0.42421E-02	0.56628E-02	0.10000E-01
409	0.10473E-04	0.15157E-03	0.24863E-02	0.69085E-02	0.21669E-01	0.19783E-01	0.18673E-04	0.78542E-02	0.10000E-01
417	0.19611E-04	0.13373E-03	0.10672E-01	0.13359E-01	0.14553E-01	0.14307E-01	0.0	0.10738E-01	0.10000E-01
425	0.21977E-04	0.12884E-03	0.12964E-01	0.14669E-01	0.12070E-01	0.12388E-01	0.0	0.11404E-01	0.10000E-01
433	0.23081E-04	0.12791E-03	0.13597E-01	0.14623E-01	0.11980E-01	0.12146E-01	0.0	0.11586E-01	0.10000E-01
441	0.23742E-04	0.12692E-03	0.13705E-01	0.14256E-01	0.12151E-01	0.12139E-01	0.0	0.11747E-01	0.10000E-01
449	0.24122E-04	0.12573E-03	0.13581E-01	0.13821E-01	0.12273E-01	0.12151E-01	0.0	0.11905E-01	0.10000E-01
457	0.24301E-04	0.12457E-03	0.13362E-01	0.13412E-01	0.12337E-01	0.12161E-01	0.0	0.12042E-01	0.10000E-01
465	0.24352E-04	0.12358E-03	0.13128E-01	0.13070E-01	0.12363E-01	0.12172E-01	0.0	0.12149E-01	0.10000E-01
473	0.24333E-04	0.12281E-03	0.12917E-01	0.12805E-01	0.12370E-01	0.12182E-01	0.0	0.12227E-01	0.10000E-01
481	0.24282E-04	0.12225E-03	0.12745E-01	0.12610E-01	0.12367E-01	0.12192E-01	0.0	0.12280E-01	0.10000E-01

489	0.24221E-04	0.12185E-03	0.12614E-01	0.12472E-01	0.12361E-01	0.12201E-01	0.0	0.12315E-01	0.10000E-01
497	0.24164E-04	0.12159E-03	0.12518E-01	0.12379E-01	0.12354E-01	0.12210E-01	0.0	0.12336E-01	0.10000E-01
505	0.24115E-04	0.12142E-03	0.12451E-01	0.12318E-01	0.12348E-01	0.12216E-01	0.0	0.12349E-01	0.10000E-01
513	0.24075E-04	0.12132E-03	0.12405E-01	0.12279E-01	0.12344E-01	0.12222E-01	0.0	0.12355E-01	0.10000E-01
521	0.24046E-04	0.12126E-03	0.12375E-01	0.12255E-01	0.12340E-01	0.12226E-01	0.0	0.12359E-01	0.10000E-01