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Technical Reference Guide for FAST Version 18

Walter W. Jones and Richard D. Peacock

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FAST (fire and smoke transport) is a zone model capable of predicting the environment in a multi-compartment structure subjected to a fire. This reference guide provides a detailed description of the source terms used in the model, data input requirements, and the output produced by version 18 of the model.

Key words: compartment fires; fire growth; mathematical models; numerical models; room fires; smoke; toxicity

1. INTRODUCTION

Considerable research has been done regarding the spread of fire and smoke from a room of fire origin to connected compartments. The work is motivated by a need to understand and predict the environmental conditions which occur as a fire develops and spreads. Much of the attention has focused on the development of numerical models which are able to make a reasonably accurate assessment of the environment resulting from a specified fire. We have built such a model, FAST [1][1].

FAST is a model to describe fire growth and smoke transport in multi-compartment structures. The implementation consists of a set of programs to describe the structure to be modeled, run the model and produce usable output. This reference guide describes the equations which constitute the model, data which are used by the model and explains how to operate the model. The physical basis of zone models, their limitations, and development of the predictive equations are described elsewhere [1] and are only summarized here. The intent of this paper is to provide a complete description of the way the model is structured. In

[1] Numbers in brackets refer to literature references listed in section 9 at the end of this report.

particular the relationship between the equations and the numerical implementation of the equations is laid out. It is intended as a complete description of the parameters and key words available to control various aspects of a simulation. It is hoped that there is sufficient information provided that one could adapt the model for specialized applications.

Functionality is provided by the following programs:

FAST	the model itself
FAST_in	interactive input
FASTplot	interactive output to display data produced by the model
BUILD	generate descriptor files for graphics output

FAST, FASTplot, and BUILD work on a wide variety of hardware, from supercomputers through microcomputers. FAST_in is specific to MS DOS based microcomputers, although it does generate an ASCII data file which can be used to run FAST on other computers.

Section 2 describes the structure of the model. Section 3 deals with the mathematical basis of the model. Section 4 is a discussion of source terms which appear in section 3, and the titles of the subsections reference the modules within the program which actually performs the respective calculations. Section 5 documents the relevant source code modules described in section 4. Section 6 describes the files used by the model. Every attempt has been made to maintain a correspondence between the terms in the mathematical formulae and those used in the computer programs. There are differences, but the correspondence should be clear. The final sections describe the interactive programs which help put the input and output data into usable forms. In the appendices, examples of input data files and corresponding output are given.

The utility BUILD is not described in this paper. It is documented in reference [2], including the file structure of the picture descriptor files, the mathematical basis and the command structure. The salient difference between the PC version and that on a mainframe is that in the former case the interaction as well as the display are on the same screen. Otherwise, they are identical.

There are several calculations presented to illustrate particular points. The calculations refer to the sample #5 data file. These examples are data that can not be obtained from other models, and so show some of the unique features of FAST. A more complete description of the model can be found in the paper by Jones [3] and the experimental work in Peacock et. al. [4].

2. STRUCTURE OF THE MODEL

The primary element of the model is a compartment. The interest in these predictive schemes lies in the environment within the compartments, so the model is structured around variables such as temperature, pressure, etc., in the compartment. Predictive equations for the gas layers in each compartment are derived from conservation of mass, momentum and energy, an equation of state, and the boundary conditions to which each compartment is subject. The term "boundary condition" refers to the transfer points at the boundaries of the compartments; examples are vents, air conditioning ducts, etc. The actual physical phenomena which drive the transport are then couched as source terms. Such a formulation allows the greatest flexibility in adding, modifying, or deleting terms which are appropriate to the problem at hand.

The conservation equations used are for mass, momentum and energy. These equations are fundamental to predictive models, and must hold in all cases. These conservation equations are rearranged to form a set of predictive equations for the sensible variables in each compartment. An important concession which is made for computational speed is that the fluid momentum between the compartments is calculated, but not within a compartment. The work term (volumetric expansion and contraction) is included in the energy equation, however. The result is that we can not follow acoustic waves anywhere, or gravitational waves within a compartment. The concomitant improvement is that we are not limited by the Courant time step condition for wave motion within a compartment.

Each compartment is subdivided into a few "control volumes," which we call zones. The premise is that the details which occur within such volumes do not concern us (at present), but their interaction does. We base this simplification on the observation that when a fire grows and spreads, the gases in a compartment stratify into distinct zones. In the present calculation we use only two zones per compartment. There is reasonably good agreement between theory and experiment for this choice, and there are other phenomena which put a more severe constraint on the validity of the model. An example of a compartment which might reasonably contain more than two zones would be a long corridor whose aspect ratio (length to width or height) is greater than 10 [17]. The general layout of the zones and the form of the conservation equations is discussed elsewhere [1] and will not be repeated here.

FAST is formulated as a set of ordinary differential equations. It was the first model of fire growth and smoke spread to cast the entire model in this form and was done because of the efficiency of solving the conservation equations this way. In addition, as discussed in the section on the form of the equations, the entire model is implemented in single precision arithmetic. It is the only fire growth and smoke transport model done this way. Single

precision arithmetic is faster and more compact than the equivalent code in double precision, and often the algorithms for calculation are better[2].

It is important to keep in mind that this model is based on a control volume concept. To that end, one gives up knowledge of some of the details of the internal structure of the problem being modeled, such as temperature variation within a zone. The model must be used cautiously for situations where these approximations may not be valid, such as the initial filling of a tall shaft, or a very long corridor.

[2] Implementation of Algorithms by W. Kahan - notes for a lecture given at the University of California at Berkeley, 1971 and 1972.

3. THE PREDICTIVE EQUATIONS USED BY THE MODEL

The space with which we are concerned usually consists of several compartments with a hot upper zone and a relatively cool lower zone for each compartment, and objects such as chairs, plumes and fires. Interactions occur at the boundary of these zones. Examples of possible interactions are the flow through vents connecting compartments, the radiation from one compartment through a vent to another compartment and a plume which connects the upper zone and the lower zone of a compartment.

Using the nomenclature in section 10, the predictive equations can be written [1]:

$$\frac{dP}{dt} = \frac{\dot{s}}{(\beta - 1)\, V} \tag{1}$$

$$\frac{dT_u}{dt} = \frac{1}{\beta}\left(\frac{T_u}{PV_u}\right)\left(\dot{E}_u + \frac{V_u}{(\beta - 1)V}\,\dot{s}\right) \tag{2}$$

$$\frac{dT_\ell}{dt} = \frac{1}{\beta}\left(\frac{T_\ell}{PV_\ell}\right)\left(\dot{E}_\ell + \frac{V_\ell}{(\beta - 1)V}\,\dot{s}\right) \tag{3}$$

$$\frac{dV_u}{dt} = \frac{1}{P\beta}\left(c_p \dot{m}_u T_u + \dot{E}_u - \frac{V_u}{V}\,\dot{s}\right) \tag{4}$$

where $\dot{s} = c_p \dot{m}_u T_u + c_p \dot{m}_\ell T_\ell + \dot{E}_u + \dot{E}_\ell$ and $\beta = c_p / R = \gamma/(\gamma-1)$ with the assumption for the pressure $P_R = P_u = P_\ell = \rho_u R\, T_u = \rho_\ell R\, T_\ell$ and the constraint that the total volume of a compartment is fixed $V = V_u + V_\ell$. There is a set of these equations for each compartment.

The form of the energy terms ($\dot{E}_u$, $\dot{E}_\ell$) is important. With the choice that the reference temperature is the ambient, we obtain

$$\dot{E}_j = \dot{Q}_f(j) + \dot{Q}_r(j) + \dot{Q}_c(j)$$

$$+ \sum_i c_p \dot{m}^{in}_{i,j} (T_i - T_u) + R(T_a - T_u)\dot{m}_{i,j} \qquad (5)$$

$$+ \sum_i c_p \dot{m}_{i,j} (T_j - T_k)$$

and the source term "s" becomes

$$\dot{s} = \sum_j \dot{Q}_f(j) + \dot{Q}_r(j) + \dot{Q}_c(j) \qquad (6)$$

$$+ \sum_j \sum_i c_p \dot{m}^{in}_{i,j} (T_i - T_j) + c_p \dot{m}_j (T_j - T_a) + c_v \dot{m}_j T_j$$

The index "j" is for the layers "u" and "ℓ" and "i" is for the compartments which have connections to the compartment under consideration. If there is more than one connection between the compartments, then this latter summation is multi-valued. The mass flow terms are written as

$$\dot{m}_{i,j} = \dot{m}^{in}_{i,j} - \dot{m}^{out}_{i,j}$$

$$\dot{m}_j = \sum_i \dot{m}^{in}_{i,j} - \dot{m}^{out}_{i,j}$$

and $$T_k = \begin{cases} T_u & \text{if } j = \text{"}\ell\text{"} \\ T_\ell & \text{if } j = \text{"u"} \end{cases}$$

In addition, for each compartment in which a plume is present there is a term for the reduction in the energy release for bringing the fuel and entrained air from its initial temperature to that of the upper layer.

This form is important, especially for eq (6), as it is the means by which the numerical implementation is done in single precision. The equations are now in a form that allows us to consider all physical phenomena as source terms in the conservation equations.

4. SOURCE TERMS

The conserved quantities in each compartment are described by the set of predictive equations shown above. The form of the equations is such that the physical phenomena are source terms on the right-hand-side of these equations. Such a formulation makes the addition (and deletion) of physical phenomena and changing the form of algorithms a relatively simple matter.

4.1 Source Terms: Radiation (Implemented in FIRRAD)

Objects such as walls, gases and fires radiate as well as absorb radiation. Each object has its own properties, such as temperature, emissivity, etc. As we are solving the energy equation for the gas temperature, the primary focus is in finding out how much energy is gained or lost by the gas layers due to radiation. In order to calculate the net radiation absorbed in a zone, a heat balance must be done which includes all surfaces which radiate to and absorb radiation from a zone. The form of the terms which contribute heat to an absorbing layer are the same for all layers. We assume that all zones in these models are similar so we can discuss them in terms of a general layer contribution. In order for this calculation to be done in a time commensurate with the other sources, some approximations are necessary.

Radiation can leave a layer by going to another layer, by going to the walls, by exiting through a vent, by heating an object, or by changing the pyrolysis rate of the fuel source. Similarly, a layer can be heated by absorption of radiation from these surfaces and objects as well as from the fire itself. The formalism which we employ for the geometry and view factor calculation is that of Siegel and Howell [5]. Although the radiation could be done with a great deal of generality, we assume that the zones and surfaces radiate and absorb like grey bodies.

The fire is assumed to be a point source and the view factor into the upper and lower layers is calculated as a tetrahedron from the fire base to the zone interface. A plume is assumed not to radiate, and at present we do not have defined objects other than the fire. We use a simplified geometrical equivalent of the compartment in order to calculate the radiative transfer between the ceiling, floor and layer(s). We assume that the upper wall and ceiling, and the lower wall and floor are equivalent to two flat plates with the gas layers in between. See figure 5.1. Thus, this is a two wall radiation model. A difficulty arises in arriving at consistent boundary conditions commissural with the four wall convective heat transfer model. The extended ceiling (ceiling plus upper wall) has two temperatures associated with it, and similarly for the extended floor (floor plus lower wall). The ambiguity of chosing the temperature to use for the radiative transfer calculation can cause the upper and lower wall temperatures to be reversed in some cases. This most commonly occurs for highly conductive

floor material and well insulated walls. Energy is conserved, but the radiative flux boundary condition for the upper and lower walls is partitioned incorrectly. For the remaining discussion we use the following notation

F_{jk} = Geometrical view factor of surface j by surface k
σ = Stefan-Boltzmann constant = 5.67×10^{-8} W/m^{2}K^4
α = Absorption coefficient of the upper gas layer, m^{-1}
$\epsilon_{u/\ell}$ = Emissivity of the upper/lower walls
ϵ_g = Emissivity of the upper gas layer

Using the formalism of Siegal and Howell [5] we have

$$D = [1 - (1-\epsilon_u)(1-\epsilon_g) F_{uu}][1 - (1-\epsilon_\ell) F_{\ell\ell}] - [(1-\epsilon_u)(1-\epsilon_\ell)(1-\epsilon_g)^2 F_{u\ell}F_{\ell u}] \quad (7)$$

$$\Pi_u = \{[(1 - (1-\epsilon_g) F_{uu}][1 - (1-\epsilon_\ell) F_{\ell\ell}] - [(1-\epsilon_\ell)(1-\epsilon_g)^2 F_{u\ell}F_{\ell u}]\}\sigma T_{uw} - (1-\epsilon_g) F_{u\ell}\epsilon_\ell\sigma T_{\ell w}^4 - \{1 + (1-\epsilon_\ell)[(1-\epsilon_g) F_{u\ell}F_{\ell u} - F_{\ell\ell}]\}\epsilon_g\sigma T_g^4 \quad (8)$$

$$\Pi_\ell = \{[1 - (1-\epsilon_u)(1-\epsilon_g) F_{uu}](1-F_{\ell\ell}) - (1-\epsilon_u)(1-\epsilon_g)^2 F_{u\ell}F_{\ell u}\}\sigma T_{\ell w}^4 - (1-\epsilon_g) F_{\ell u}\epsilon_u\sigma T_{uw}^4 - \{[1 - (1-\epsilon_u)(1-\epsilon_g) F_{uu}] F_{\ell u} + (1-\epsilon_u)(1-\epsilon_g) F_{\ell u}\} \epsilon_g\sigma T_g^4 \quad (9)$$

As formulated in Siegal and Howell, the equations for radiative transfer are written in terms of transmissivity. We use the "equivalent" sphere analogy to relate this to an emissivity for the gas layer. If we assume that the gas layer is equivalent to a gaseous sphere of equivalent volume, then we can calculate an effective radius from R=4V/A, where V is the volume, and A the area of the ceiling plus upper wall. The transmission factor is approximately exp(-αR). The absorptivity is then 1-exp(-αR) and becomes the emissivity of an equivalent grey body which radiates as σT^4.

With these definitions we can calculate the energy radiated from the upper gas layer to the upper and lower walls respectively as

$$\dot{Q}(\text{upper}) = A_u \epsilon_u \Pi_u / D \quad (10)$$

$$\dot{Q}(\text{lower}) = A_\ell \, \epsilon_\ell \, \Pi_\ell \, / \, D$$

By summing these two terms together with the energy radiated by the fire, we obtain the negative of the heat flux absorbed by the upper layer. A heat balance with the fire is not done simply because the amount of heat radiated by the fire is usually much greater than that absorbed by the fire (from external sources). In other words, the radiation balance in the compartments does not affect the temperature of the flames.

For the case when $\epsilon_u = \epsilon_\ell = 1$ we have a simple expression for the energy absorbed by the gas layer, namely

$$\dot{Q}_g = -\sigma \left[\epsilon_g T_u^4 A + (1-\epsilon_g) T_{uw}^4 (A_u + A_{uv}) - T_{uw}^4 A_u - \epsilon_g T_u^4 A_d - T_\ell^4 A_{uv} \right] + F_f Q_f \qquad (11)$$

where

A_{uv} = Area of the vents which the gas layer "sees"

F_f = fraction of the released heat which radiates times its view factor for the gas layer

$A = A_u + A_d$.

A schematic of this is shown in section 5.1

Note that although radiation can exit a vent, we do not do specific heating of a wall or object in an adjacent compartment. Further, there is no attempt to acccount for radiation blockage by objects or flames. The algorithm is appropriate for a compartment where the joints are concave, so that no surface is hidden from any other surface. For "L" shaped compartments, our view factor calculation would not be appropriate, and would overestimate the amount of radiative transfer. All of these phenomena require a much more extensive model which includes a ray tracing algorithm.

4.2 Source Terms: Convective Heating (Implemented in CONVEC)

Convection is one of the mechanisms by which the gas layers lose (or gain) energy to walls, objects or through openings. Conduction is a process which is intimately associated with convection, but as it does not show up directly as a term for heat gain or loss, it will be discussed separately. Convective heating describes the energy transfer between solids and gases. The enthalpy transfer associated with flow through openings will be discussed in the section on flow through vents.

Convective heat flow is energy transfer across a thin boundary layer. The thickness of this layer is determined by the temperature difference between the gas zone and the wall or object being heated [6]. We can write the heat flux term as

$$\dot{Q}_c = h_c(T_g - T_w)A_w \tag{12}$$

where the transfer coefficient can be written as

$$h_c = \frac{\kappa}{\ell} C_o(Gr\ Pr)^{1/3} \tag{13}$$

The terms are

A_w = area of surfaces in contact with the zone

Gr = Grashof number = $g\ell^3|T_g - T_w|/\nu^2 T_g$,

Pr = Prandtl number = 0.72,

κ = thermal conductivity of the gas = $2.72\times10^{-4}\left(\frac{T_g + T_w}{2}\right)^{4/5}$,

ℓ = length scale $\approx \sqrt{A_w}$,

C_o = coefficient which depends on orientation [6],

ν = $7.18\times10^{-10}\left(\frac{T_g + T_w}{2}\right)^{7/4}$.

For the cases of interest we use the coefficients shown below. The coefficients for horizontal surfaces apply to a slab over a zone (such as ceiling surfaces). For a floor, the conditions (T_g and T_w) are reversed. For the outside boundary condiction, the condition is reversed, at least for the ceiling and floor. Physically, outside a compartment, the ceiling of a compartment will behave as if it were the floor of a compartment over it, and similarly for the floor of a compartment. Thus, we use the floor boundary coefficient for the outside boundary of the ceiling and the ceiling coefficient for the outside boundary of a compartment floor. For vertical boundaries, the coefficient remains the same on the interior and exterior.

Orientation	Coefficient[C_0]	Condition
Vertical	0.130	all
Horizontal	0.210	$T_g > T_w$
Horizontal	0.012	$T_g < T_w$

These coefficients are for turbulent boundary layer flow. Thus they overestimate the heat transfer which can occur in a quiescent compartment.

The boundary condition which connects the interior of the wall to the zone is fairly straightforward. This convective heating generates a flux from the gas layer which becomes a derivative boundary condition for the conduction algorithm. A similar boundary condition must be applied on the exterior of the walls. The assumption made is that the exterior portion of a wall is truly facing the ambient. This precludes a fire in one compartment heating a connected compartment through conduction. The omission is due to the difficulty of specifying how compartment walls are connected and not to the difficulty of specifying the boundary conditions or solving the equations. So the boundary condition for the exterior of a wall is similar to the interior, except that the exterior surface is assumed to be convecting and radiating to the ambient. With this caveat in mind, we can use the convection routine to calculate the boundary condition for the exterior wall also.

The current model allows for a ceiling, floor and two walls. Actually the two walls are the same material, but a separate temperature profile is maintained for the wall in contact with the upper and lower zones respectively. Therefore we have four components for convective heat transfer. See section 5.2 for a schematic of this division and a discussion of how it is implemented.

4.3 Source Terms: Plumes (Implemented in FIRPLM)

Buoyancy generated by the combustion processes in a fire causes the formation of a plume. Such a plume can transport mass and energy from the fire into the lower or upper layer of a compartment. In the present implementation, we assume that both mass and energy from the fire are deposited only into the upper layer. In addition the plume entrains mass from the lower layer and transports it into the upper layer. This yields a next enthalpy flux between the two layers. Actually, the flame and plume will generally radiate somewhat into the lower layer, at least if it is not diathermous. So our approximation causes the upper layer to be somewhat hotter, and the lower layer somewhat cooler than is the case, at least in a well developed fire.

A fire generates energy at a rate $\dot{Q}$. Some fraction, χ_R, will exit the fire as radiation, some into heating additional fuel for burning, χ_c, and the remainder will be available to drive the plume. This quantity is $(1-\chi_R)\dot{Q}$. Defining this quantity to be the convective heat release rate, we can use the work of McCaffrey [7] to estimate the mass flux from the fire into the upper layer.

This correlation divides the flame/plume into three regions as shown below. This prescription agrees with the work of Cetegen et al. [8] in the intermittent regions but yields

greater entrainment in the other two regions. This difference is particularly important for the initial fire since the upper layer is far removed from the fire.

$$\begin{array}{lll} \text{flaming:} & \dot{m}_e/\dot{Q} = 0.011\ (Z/\dot{Q}^{2/5})^{0.566} & 0.00 \le Z/\dot{Q}^{2/5} < 0.08 \\ \text{intermittent:} & \dot{m}_e/\dot{Q} = 0.026\ (Z/\dot{Q}^{2/5})^{1.85} & 0.08 \le Z/\dot{Q}^{2/5} \le 0.20 \\ \text{plume:} & \dot{m}_e/\dot{Q} = 0.124\ (Z/\dot{Q}^{2/5})^{1.895} & 0.20 \le Z/\dot{Q}^{2/5} \end{array} \qquad (14)$$

McCaffrey's correlation is in general valid for all fires, everywhere. It is an extension of the common point source plume model, with a different set of coefficients for each region. These coefficients are experimental correlations, and are not based on theory. The theory appears only in the form of the fitted function. The binding to the point source plume model is for the value for Z where the mode changes, namely from flaming to intermittent to plume.

4.4 Source Terms: Vent Flow (Implemented in FLOW, FRFLOW, and ENTRFL)

Mass flow (in the remainder of this section, the term "flow" will be used to mean mass flow) is the dominant source term for the predictive equations because it fluctuates most rapidly and transfers the greatest amount of enthalpy on an instantaneous basis of all the source terms. Also, it is most sensitive to changes in the environment. One of the improvements which we have incorporated into the model is a means of calculating these flow fields with the correct number of neutral planes. In these situations, it is possible to have up to three neutral planes [10].

Flow at vents is governed by the pressure difference across a vent. In the control volume approximation, it is not calculated by solving the momentum equation directly. Rather, momentum transfer at the zone boundaries is included by using Bernoulli's solution for the velocity equation. This solution is augmented for restricted openings by using flow coefficients [9]. The flow coefficients allow for an effective constriction of fluid flow which occurs for vents with sharp edges, that is for openings for which the size of the orifice changes abruptly, such as a window in a room. The coefficients embodied in FAST are for rectangular openings in walls of compartments whose surface area is much larger than the opening.

There are two situations which give rise to flow through vents. The first, and most usually thought of in fire problems, is that of air or smoke which is driven from a compartment by buoyancy. The second type of flow is due to a piston effect which is particularly important when conditions in the fire environment are changing rapidly. Rather than depending on density differences between the two gases, the flow is forced by volumetric expansion, mostly caused by changes in gas density or pressure. Atmospheric pressure is about 100 000 Pa, fires produce pressure changes from 1 to 1 000 Pa, and mechanical ventilation systems typically involve pressure changes about 1 to 100 Pa. In order to solve these interactions correctly, we must be able to follow pressure differences of about 0.1 Pa out of 10^5.

The general form for the velocity field is given by

$$V = C\ S\ (2\rho|P_i - P_o|)^{\frac{1}{2}} \tag{15}$$

where C is an orifice coefficient (≈0.65 to 0.75), S is the opening area, ρ is the gas density on the source side and P is the pressure on the source(i) and destination(o) sides, respectively.

We apply the above equation to rectangular openings which allows us to remove the width from the mass flux integral. That is

$$\text{flow} = \int_{\text{width}} \int_{\text{height}} \rho V\ dz db \rightarrow \text{width} \int_{z_1}^{z_2} \rho V\ dz \tag{16}$$

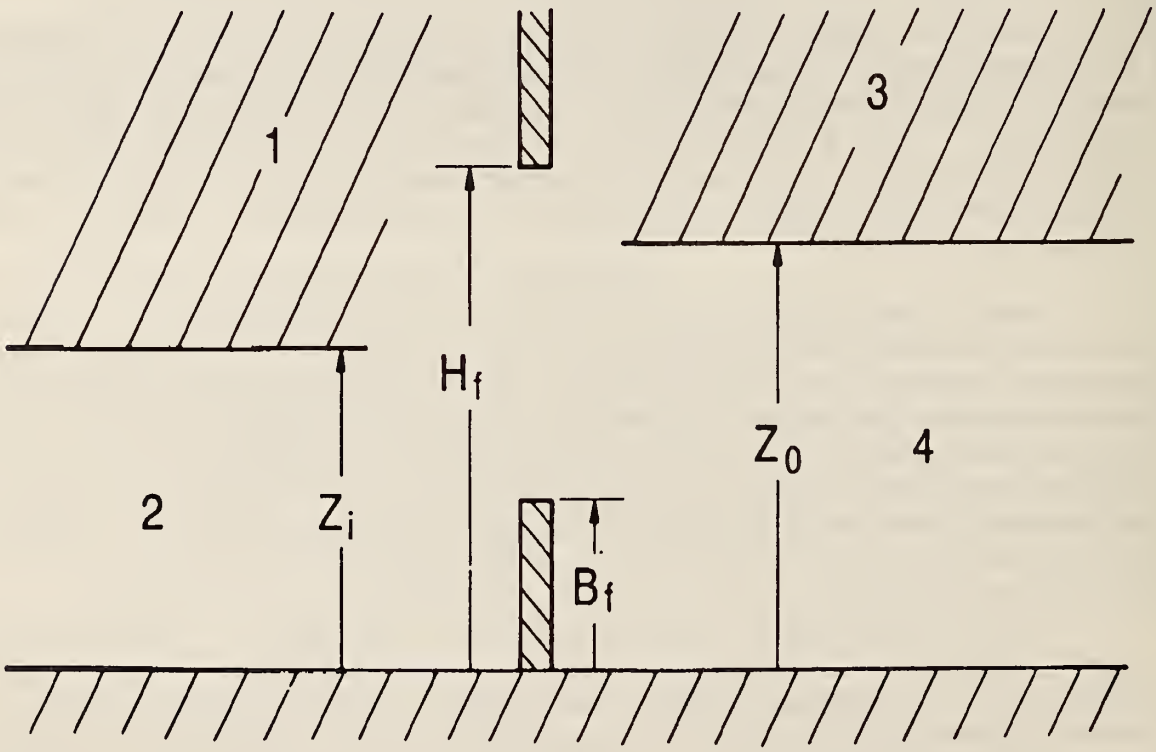


Figure 1. Notation convention for interface, sill, and soffit.

The simplest means to define the limits of integration is with neutral planes, that is the height at which flow reversal occurs, or physical boundaries such as a sill or soffit. By breaking the

integral into intervals defined by flow reversal, a soffit, a sill, or a zone interface, the integral itself can be done analytically. We have for the internal pressure on each side of the opening as shown in figures 1 and 2:

$$P_i(z) = P_i(0) - \min(z,Z_i)\ \rho_2 g - \max(z-Z_i,0)\ \rho_1 g \tag{17}$$

$$P_o(z) = P_o(0) - \min(z,Z_o)\ \rho_4 g - \max(z-Z_o,0)\ \rho_3 g \tag{18}$$

where P(0) represents the base (reference) pressure at the floor. The pressure then appears only as a difference of these two terms, namely $F(z) = P_i(z) - P_o(z)$. These equations form an inordinately large family of curves as a function of the parameters ρ and Z. However, if the restrictions found in fire scenarios are imposed then we end up with only a five possibilities as shown below.

Restrictions		Maximum number of neutral planes
$\rho_2 \le \rho_4$,	$Z_i \le Z_o$	1
$\rho_2 > \rho_4$,	$Z_i \le Z_o$	2
$\rho_3 \le \rho_2 \le \rho_4$,	$Z_i > Z_o$	3
$\rho_2 > \rho_4$,	$Z_i > Z_o$	2
$\rho_2 < \rho_3$,	$Z_i > Z_o$	1

If there were no soffits or sills to consider, then the calculation would be fairly straightforward. However, the possibility of soffit/sill combinations requires many numerical tests in the calculation. The first condition allows 44 different flow combinations, depending on the relative position of H_f, B_f, Z_i and Z_o. It contains at most a single neutral plane. Twenty-four of these combinations are without a neutral plane and 20 with a neutral plane. For the other cases, the interval $[B_f,H_f]$ can be partitioned into intervals which contain at most a single neutral plane. An important caveat is to be sure that the inequalities as shown above are treated consistently.

The approach we have used to calculated the flow field is of some interest because of the way it is implemented numerically. The general flow equation is

$$\dot{m}_{i\to o} = \frac{2}{3} C S (2\rho)^{1/2} (z_2-z_1) \frac{1}{(P_2-P_1)} (P_2^{3/2} - P_1^{3/2}) \tag{19}$$

For the situation when one of the endpoints (z_1, or z_2) defines a neutral plane, then this expression simplifies. As a specific example, let $P_1 \to 0$, whence the expression becomes

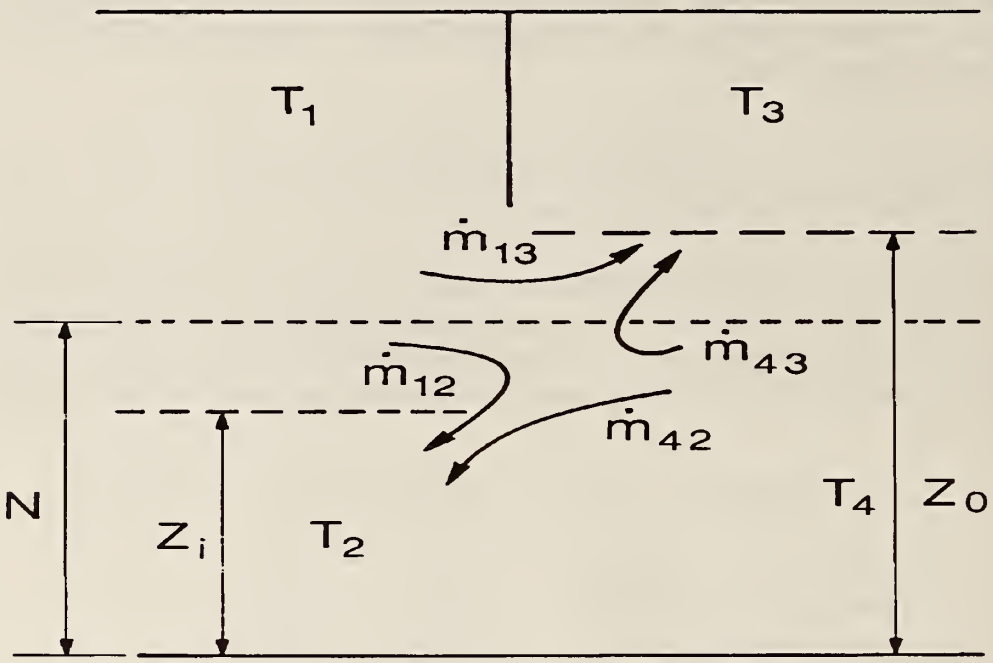


Figure 2. Example of a possible flow pattern and layer numbering convention.

$$\dot{m}_{i\to o} = \frac{2}{3} C S (z_2 - z_1) (2\rho P_2)^{\frac{1}{2}} \tag{20}$$

The latter expression is much faster to evaluate than the former. We can partially ameliorate the difference in computation speed by rewriting eq (19) in a better form, using a continued fraction, as

$$x \equiv \text{minimum} \left(P_2^{\frac{1}{2}}, P_1^{\frac{1}{2}} \right)$$

$$y \equiv \text{maximum} \left(P_2^{\frac{1}{2}}, P_1^{\frac{1}{2}} \right)$$

$$\dot{m}_{i\to o} = \frac{2}{3} C S (2\rho)^{\frac{1}{2}} (z_2 - z_1) \left[x + \frac{y}{1 + x/y} \right]. \tag{21}$$

This form is considerably faster to evaluate, approaching the time required to evaluate eq (20).

The integration is started at the lowest point at which flow can occur, the sill or floor. Then the next change point is found. It is either a soffit or a change in the relative gas density. Within this interval there is either a neutral plane or not. The appropriate form, eq (20) or (21) is used. Then a check is then made to see if there is more opening through which flow can occur. If so, then the integration process starts from the last endpoint (z_2) and continues until the soffit is reached.

A mixing phenomenon occurs at vents which is similar to entrainment in plumes. As hot gases from one compartment leave that compartment and flow into an adjacent compartment a door jet can exist which is analogous to a normal plume. Mixing of this type occurs for $\dot{m}_{13} > 0$ as shown in figure 2. To calculate the entrainment ($\dot{m}_{43}$ in this example), once again we use a plume description, but with an extended source point. The estimate for the point source extension is given by Cetegen et al. [8]. This virtual point source is chosen so that the flow at the door opening would correspond to a plume with the heating (with respect to the lower layer) given by

$$\dot{Q}_o = c_p(T_1 - T_4)\dot{m}_{13}$$

The concept of the virtual source is that the enthalpy flux from the virtual point source should equal the actual enthalpy flux in the door jet at the point of exit from the vent using the same prescription. Thus the entrainment is calculated the same way as was done for a normal plume. The height of the plume is

$$z_p = z_3/eq^{2/5} + v_p,$$

where v_p, the virtual source point, is defined by inverting the entrainment process to yield

$$xq = eq / \dot{m}$$

$$v_p = (90.9/xq)^{1.76} \qquad \text{if} \quad 0.00 < v_p <= 0.08$$

$$v_p = (38.5/xq)^{1.1001} \qquad \text{if} \quad 0.08 < v_p <= 0.20$$

$$v_p = (8.10/xq)^{0.528} \qquad \text{if} \quad 0.20 < v_p.$$

The units of this height, z_p and v_p, are not length, but rather in the reduced notation of McCaffrey [7]. That is, the z_p defined here is the term $z/\dot{Q}^{2/5}$ used earlier. The agreement between experiment and theory is quite good even though we are outside of the normal range

of validity of a plume model. In particular, a door jet forms a flat plume whereas a normal fire plume will be approximately circular.

The other type of mixing is much like an inverse plume and causes contamination of the lower layer. It occurs when there is flow of the type $\dot{m}_{12} > 0$. The shear flow causes vortex shedding into the lower layer and thus some of the particulates end up in the lower layer. The actual amount of mass or energy transferred is usually not large, but its effect can be large. For example, even minute amounts of carbon can change the radiative properties of the gas layer, from negligible to something finite. It changes the rate of radiation absorption by orders of magnitude which invalidates the notion of a diathermous lower layer. This term is predicated on the Kelvin-Helmholz flow instability and requires shear flow between two separate fluids. The mixing is enhanced for greater density differences between the two layers. However, the amount of mixing has never been well characterized. Quintiere et al. [11] discuss this phenomena for the case of crib fires in a single room, but their correlation does not yield good agreement with experimental data in the general case. So we have assumed that the incoming cold plume behaves like the inverse of the usual door jet between adjacent hot layers; thus we have a descending plume. It is possible that the entrainment is overestimated in this case, since buoyancy, which is the driving force, is not nearly as strong as for the usually upright plume.

4.5 Source Terms: Fire (Implemented in PYROLS and CHEMIE)

At present, the model has only a specified fire implemented. A specified fire is one for which the time dependent characteristics are specified as a function of time. Under development are pool fire and burning furniture algorithms. The specified fire can be unconstrained or constrained. These fires are later referred to as type 1 and type 2, respectively. The meaning of this assignment will become clearer in the discussion of the algorithm itself (sec. 5.5) and the data file structure (sec. 6.7). For the constrained fire, the constraint is based on the minimum of the fuel and oxygen available for combustion. For either, the pyrolysis rate is specified as $\dot{m}_f$, the burning rate as $\dot{m}_b$ and the heat of combustion as h_c so that the nominal heat release rate is

$$\dot{Q}_f = h_c \dot{m}_b - c_p(T_u - T_v) \dot{m}_b . \qquad (22)$$

For the unconstrained fire, $\dot{m}_b = \dot{m}_f$, whereas for the constrained fire, the burning rate will be less than the pyrolysis rate. Models of specified fires generally use a heat of combustion which is obtained from an experimental apparatus such as the Cone Calorimeter [12]. The shortcoming of this approach is that the pyrolysis rate is not connected to radiative feedback

from the flame or compartment. In an actual fire, this is an important consideration, and the specification used should match the experimental conditions as closely as possible.

The energy which is released goes into radiation and enthalpy flux

$$\dot{Q}_r(\text{fire}) = \chi_R \dot{Q}_f$$

$$\dot{Q}_c(\text{fire}) = (1-\chi_R)\dot{Q}_f.$$

The term $\dot{Q}_c$(fire) then becomes the driving term in the plume flow. In the actual implementation these formulas are modified somewhat. For a specified fire there is radiation to both the upper and lower layers, whereas the convective part contributes only to the upper layer. For the radiative portion a view factor must be calculated. Currently we do this on the basis of the view factor for the interface as seen from the fire source. The view factor is calculated on the basis of a tetrahedron formed by the point source fire, and the interface rectangle.

If the fire is constrained by the amount of available oxygen, then we can calculate a species balance. The scheme is applied in three places. The first is burning in the portion of the plume which is in the lower layer of the room of fire origin (region #1). The second is the portion in the upper layer, also in the room of origin (region #2). The third is in the vent flow which entrains air from a lower layer into an upper layer in an adjacent compartment (region #3). Figure 3 is a schematic of the concept of division of burning regions.

The species which are affected by this scheme are O_2, CO_2, CO, H_2O, unburned hydrocarbons (TUHC), and soot (OD). In a chemical equation, the individual atoms on the left and right hand sides must balance. This is true regardless of whether the reaction is considered to be stoichiometric. We apply this idea to the combination of fuel and oxygen to yield a balance of number density (#/volume) as follows:

$$(C_{N_C} H_{N_H} O_{N_O}) + N_{O_2} \rightarrow N_{CO_2} + N_{H_2O} + N_{CO} + N_S^3. \qquad (23)$$

Equating like species (take the separate components of the orthonormal set representing the constituent atoms),

[3] In the present context soot consists only of carbon. Also we do not maintain a separate variable for the number density of soot as opposed to the mass density, so N_S is actually the production rate of carbon atoms. Thus, $m_S = 12\ N_S$.

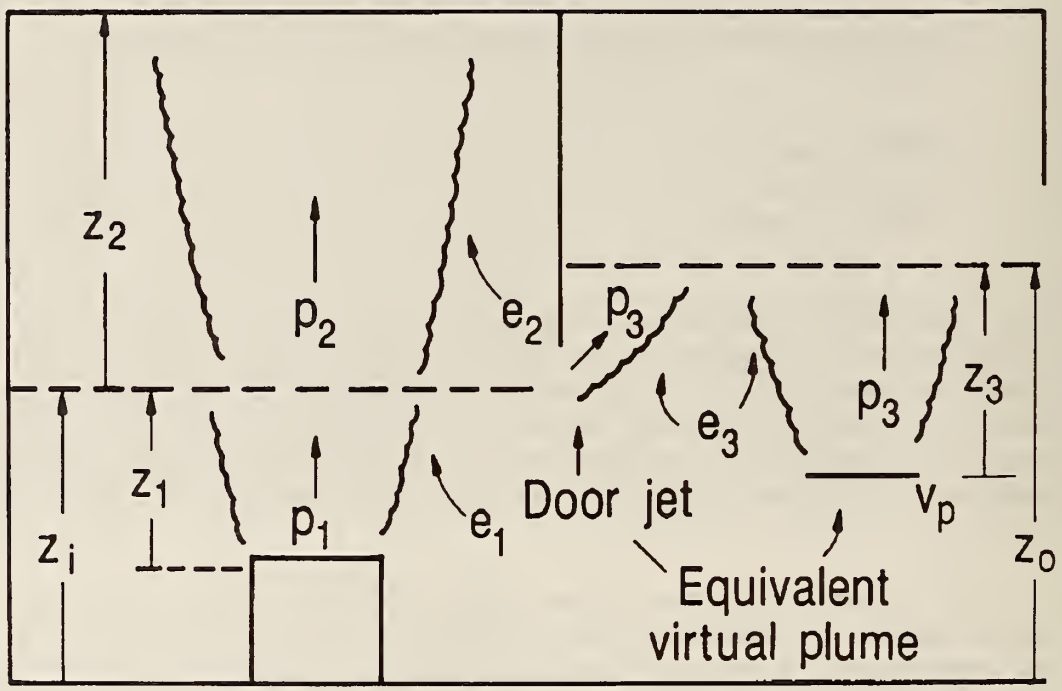


Figure 3. Schematic of entrainment and burning regions.

$$N_H = 2\ N_{H_2O} \tag{24}$$

$$N_C = N_{CO_2} + N_{CO} + N_S \tag{25}$$

$$N_O = 2\ N_{CO_2} + N_{H_2O} + N_{CO} - 2\ N_{O_2}. \tag{26}$$

This is the most general scheme which will be considered at present. The third equation (for O_2 balance) is not actually used in the following discussion but is included for completeness. Later there is a discussion of a more general scheme and the difficulties which might be encountered. A point to note is that we assume that the oxygen content of the fuel is negligible. If oxygen is a significant component of the fuel, the mass pyrolysis rate which is used to specify the fire should be reduced by the percentage of oxygen present.

The relative amounts of carbon and carbon monoxide are then specified with respect to the amount of carbon dioxide produced as

$$\frac{N_S}{N_{CO_2}}, \quad \frac{N_{CO}}{N_{CO_2}}, \text{ with } \frac{N_H}{N_C} \text{ giving the hydrogen/carbon ratio of the fuel.}$$

These parameters are functions of time and the type of fuel. With these definitions in mind, equate like species and take first order time derivatives to obtain

$$\dot{N}_{CO_2} = \frac{\dot{N}_C}{1 + \frac{N_{CO}}{N_{CO_2}} + \frac{N_S}{N_{CO_2}}}$$

$$\dot{N}_{H_2O} = \tfrac{1}{2}\,\dot{N}_C \left(\frac{N_H}{N_C} \right). \tag{28}$$

Time derivatives of the densities rather than the actual densities themselves are used. Although the balance is done for the atoms, the primary interest is in how the number of each species is changing. Obviously, if the number density is correct for all time, then the time rate of change of this density is also always correct.

For consistency in the model, it is more convenient to express these numbers in terms of masses rather than mole or number density. After the transformation from number density to mass density we have[4]

input:

$\dot{m}$(fuel) = pyrolysis rate of the source (kg/sec) (region #1)

or

$\dot{m}$(fuel) = $\dot{m}$(tuhc) from a previous region (kg/sec) (region #2 and #3)

[4] The terms in parenthesis (burn, fuel, tuhc etc.) are equivalent to the subscripts (b, f, tuhc, etc.) but are written out in the form found in the parameterization in the FORTRAN implementation. It is hoped that this will clarify the use of these equations in the code itself.

with the constraint:

$$\dot{m}(\text{burn}) = \min\left([O_2]_{\text{entrained}} \frac{1.32\text{x}10^7}{h_c} \;,\; \dot{m}(\text{fuel})\right) \tag{29}$$

and results:

$$\dot{m}(\text{tuhc}) = \dot{m}(\text{fuel}) - \dot{m}(\text{burn}) \tag{30}$$

$$\dot{q} = \dot{m}(\text{burn}) \times h_C \tag{31}$$

$$\dot{m}(\text{oxygen}) = -\frac{\dot{q}}{1.32\text{x}10^7} \tag{32}$$

$$\dot{m}(H_2O) = 9\,\frac{\dot{m}(\text{burn})}{\left(1 + \left(\frac{m_H}{m_C}\right)\right)}\left(\frac{m_H}{m_C}\right) \tag{33}$$

$$\dot{m}(CO_2) = \frac{3.67\,\dot{m}(\text{burn})}{\left(1 + \left(\frac{m_H}{m_C}\right)\right)\left(1 + 1.57\,\frac{m_{CO}}{m_{CO_2}} + 3.67\,\frac{m_S}{m_{CO_2}}\right)} \tag{34}$$

$$\dot{m}(CO) = \dot{m}_{CO_2}\left(\frac{m_{CO}}{m_{CO_2}}\right) \tag{35}$$

$$\dot{m}(S) = \dot{m}_{CO_2}\left(\frac{m_S}{m_{CO_2}}\right) \tag{36}$$

The term $[O_2]$ is the amount of entrained oxygen multiplied by a factor to force cutoff of burning at the limiting oxygen index. The term $[O_2]$ is calculated as follows:

```
o2index = max (0.,(o2frac-limo2)*4.83)
o2mass =  o2entr * 0.995 * (1-exp(-10*o2index))
```

where 4.83 is the inverse of 20.7%. The term "fuel" implies no oxygen in the present context. If there is oxygen in the original fuel, then the net production of unburned hydrocarbons will be incorrect. If this is the case, the prescribed fuel production must be decreased by the fraction of oxygen present. The energy balance is not affected by this change.

For region #1, the source will be the fuel source itself; for regions #2 and #3, the source will be the $\dot{m}$(tuhc) flowing from the previous region. The number $1.32\text{x}10^7$ is the

heat release rate per kilogram of oxygen consumed as discussed by Huggett [13]. Thus for each region, the burning rate is the minimum of the two possible rates, the rate due to the fuel present, and the rate due to the oxygen present. Note that the production and fuel ratios are now in terms of masses. The limit on the hydrogen-carbon ratio should be zero to one third. Obviously this is not quite the correct effect for a general fuel such as a piece of furniture or a cable, but should suffice at least to get started. Given the above production rates, the carbon monoxide and soot fraction can be calculated in terms of carbon dioxide. These latter two are just the terms in the denominator of the CO_2 production rate. As pointed out earlier, an assumption has been made that soot is composed primarily of carbon. A more complete description should be undertaken, but this would complicate the above scheme considerably.

4.6 Source Terms: Conduction (Implemented in CNDUCT)

Conduction of heat through solids is not a source term in the sense discussed earlier. That is, loss or gain of energy from solids occurs by convective heating, which in turn is influenced by subsequent gain or loss through the solids. However, as much of the net heat loss from a compartment occurs through loss to the walls and heating of interior objects, the form of the heat propagation will be discussed here.

The equation which governs the heat transfer in solids is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho\, c} \nabla^2 T \qquad (37)$$

and is a linear parabolic equation. As such it must be solved by a different technique than is used for the ordinary differential equations which describe mass and enthalpy flux. The equation is linear only if the coefficients k, ρ and c are constant throughout the material. This may not be the case, especially for some materials such as gypsum for which the value of k may vary by a factor of two or more. However, to the accuracy that we know the thermal properties, it is a reasonable approximation. For a given wall we allow multiple layers (slabs) whose properties can differ. As explained in section 5.6, eq (37) is then solved for each layer as a linear system with the appropriate boundary conditions between the layers.

In order to couple these systems in a reasonable way, we appeal to the principle of time splitting. Simply stated we have two systems of equations which can be decoupled and solved independently as long as the time step used is short compared to the characteristic time scale for either set of equations. For fires of interest, wall temperatures change on the order of minutes. By using a time step of no more than 0.2 seconds, the applicability of time splitting is assured. This decoupling breaks down for very large fires (larger than 50 MW) when the radiant flux to a wall can cause its surface and subsurface temperatures to change in seconds rather than minutes. Of greater interest is the number of nodes used for the actual numerical

calculation. As discussed below, we use 48 nodes (36 in the PC version) for this calculation. This is a compromise between computer memory required and the computation time required. The method used (discussed later) is referred to as a Crank-Nicholson scheme and is absolutely stable and convergent. The only difficulty is that with only a few nodes, iteration may be required if the heat flux boundary condition is changing rapidly. With a sufficient number of nodes, a single pass through the solver is sufficient. However, this requires additional computer memory. Most of the time, a single pass is sufficient with our choice of node structure.

Heat conduction is calculated on a compartment by compartment basis, with each bounding surface specified and calculated independently. Any combination of compartments and surfaces within a compartment can be specified. For example, both the ceiling and walls might be done in the room of fire origin and only the walls in the adjacent hallway. At present conduction is one dimensional only, perpendicular to the bounding surface. It is a limitation in moving from compartments near the fire source to distant spaces. In particular, the mechanism for complete mixing is flow down the walls and the degree of mixing is affected by heat conduction parallel to the wall, especially in the direction in which the interface is moving. A corollary is that the wall in contact with the gas layer changes temperature instantaneously as the layer interface moves up and down. This inconsistency would be removed with the introduction of a two dimensional heat flow calculation. As discussed by Goldman et al. [14] the phenomena can be important, especially as the thermocline in the wall will influence the direction in which the wall boundary flow propagates.

Conduction through solids occurs in two places: the compartment walls and interior objects. The technique used is the same in both cases, although the boundary conditions on the equation may be different. Generally a slab is cut into N intermediate slices or N+1 nodes. Then the one dimensional form of the heat equation is solved for each slice. It is the choice of the maximum number of nodes that is a compromise between precision and computation time. The finite difference implementation of the equation is a time-centered, implicit scheme which is symmetric about the nodes. For interior nodes we have

$$T_i'(1+\eta) = \frac{\eta}{2}\,(T_{i+1}' + T_{i-1}') + \left(T_i + \frac{\eta}{2}\,(T_{i+1} - 2T_i + T_{i-1})\right) \qquad (38)$$

and for boundary or edge nodes we have

$$T_1'\left(1+\frac{\eta}{2}\right) = \frac{\eta}{2}\left(T_2' + \frac{\Delta x \dot{Q}_c}{k}\right) + \left(T_1 + \frac{\eta}{2}\left(T_2 - T_1 + \frac{\Delta x \dot{Q}_c}{k}\right)\right) \qquad (39a)$$

$$T_N'\left(1+\frac{\eta}{2}\right) = \frac{\eta}{2}\left(T_{N-1}' - \frac{\Delta x \dot{Q}_c}{k}\right) + \left(T_N + \frac{\eta}{2}\left(T_{N-1} - T_N - \frac{\Delta x \dot{Q}_c}{k}\right)\right) \qquad (39b)$$

where $\eta = \frac{\Delta t}{(\Delta x)^2} \frac{k}{\rho c}$.

The former is for the interior boundary and the latter for the exterior boundary (i=N). The temperature at the starting time at node "i" is T_i and at time $t+\delta t$ is $T_{i'}$.

To solve this system of equations, two boundary conditions must be specified. For this problem mixed boundary conditions are used. For the inside edge (adjacent to the gas layer) there is a heat flux which is comprised of convective and radiative components. On the outside the ambient is fixed and an outflow boundary condition is calculated based on an average convective heat flow coefficient and the temperature of the last node. Both boundary conditions are represented symbolically as $\dot{Q}_c$.

One limitation of our implementation of conduction is that it serves only as a loss term for energy. Heat lost from a compartment by conduction is assumed to be lost to the outside ambient. In reality, compartments adjacent to the room which contains the fire can be heated, possibly catastrophically, by conducted energy not accounted for in the model. Although solving the conduction equations for this situation is not difficult, the geometrical specification is. For this reason, we have chosen to assume that the outside of a boundary is always the ambient.

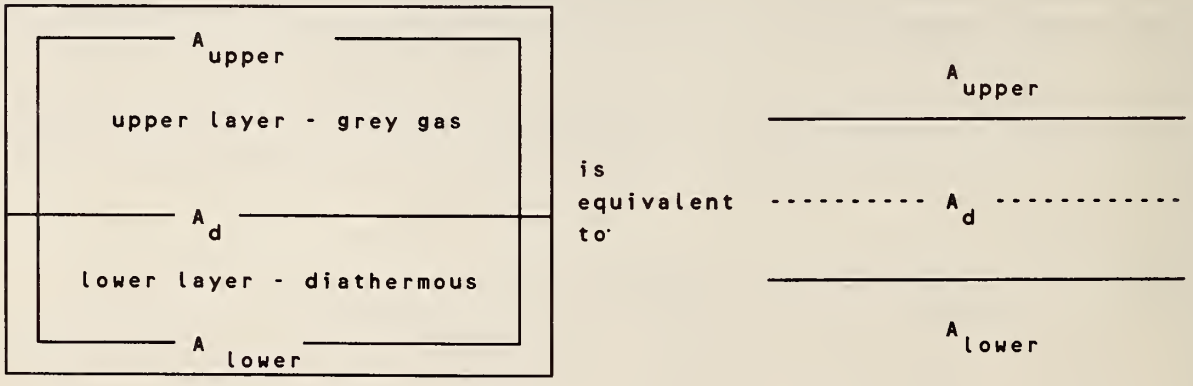
We allow for multi-layered walls, floors and ceilings. This requires additional internal boundary conditions at each material interface. Two additional nodes are necessary. These are used to force continuity of the heat flux across each interface.

5. SOURCE MODULES

The routines described below come directly from the FAST program. The modules have been annotated to make them more understandable. For example, comments within the code which are directives for changing the routines are not included. There are also comments which appear here which are not shown in the actual code. The part that is strictly in upper case is FORTRAN code, whereas text in lower or mixed case are extra comments.

5.1 FIRRAD (sec. 4.1)

This routine calculates the quasi-steady radiative flux between one gas layer and two walls. The wall surfaces are the extended floor and ceiling. That is, the extended ceiling is the sum of the areas of the ceiling and upper wall, and similarly for the extended floor. This routine is coded from the work of Siegal and Howell [5]. It assumes two flat plates facing a single grey sphere. The view factor for a hemisphere facing a flat plate can be integrated analytically. The lower layer is assumed to be diathermous, so it need not be taken into account. However, the interface between the lower wall and the atmosphere in the upper layer is the actual discontinuity area, so the view factors correspond to appropriate areas.



There are three surface areas of interest: A_{upper}, the area of the extended upper surface; A_{lower}, the area of the extended lower surface; and A_d the area of the interface, that is the separation between the upper and lower layers.

```
SUBROUTINE FIRRAD(T, TG, AW, AD, EPR, EG, QSRAD, QRADG, NC)

FAST COMMON BLOCK GOES HERE
```

```
      DIMENSION T(4),AW(2),EP(2),PI(2),QRAD(4),QSRAD(4,NC),QRADG(2,NC)
      DIMENSION TG(2),EPR(4)
```

aw(1) = A_{upper}

aw(2) = A_{lower}

ad = area of the discontinuity - generally same as floor area
t and tg are the wall and gas temperatures, respectively
epr and eg are the emissivities of the walls and gas layer, respectively
f11, f12, f21 and f22 are the view factors between the surfaces

```
      F11=1.-AD/AW(1)
      F12=AD/AW(1)
      F21=AD/AW(2)
      F22=1.-AD/AW(2)
      EP(1) = MAX(EPR(1), EPR(3))
      EP(2) = MAX(EPR(2), EPR(4))
      SO = EG * SIGM * TG(UPPER)**4
```

use of the "max" function resolves the conflict between four walls in convection and two walls in radiation

```
      S1 =      SIGM * MAX(T(1),T(3))**4
      S2 =      SIGM * MAX(T(2),T(4))**4

      D=(1.-(1.-EP(1))*(1.-EG)*F11)*(1.-(1.-EP(2))*F22)
     1  -(1.-EP(1))*(1.-EP(2))*(1.-EG)**2*F12*F21
      PI(1)=((1.-(1.-EG)*F11)*(1.-(1.-EP(2))*F22)
     1  -(1.-EP(2))*(1.-EG)**2*F12*F21)*S1
     2  -(1.-EG)*F12*EP(2)*S2
     3  -(1.+(1.-EP(2))*((1.-EG)*F12*F21-F22))*SO
      PI(2)=((1.-(1.-EP(1))*(1.-EG)*F11)*(1.-F22)
     1  -(1.-EP(1))*(1.-EG)**2*F12*F21)*S2
     2  -(1.-EG)*F21*EP(1)*S1
     3  -((1.-(1.-EP(1))*(1.-EG)*F11)*F21+(1.-EP(1))*(1.-EG)*F21)*SO

      ONED = 1. / D
      DO 10 I = UPPER, LOWER
```

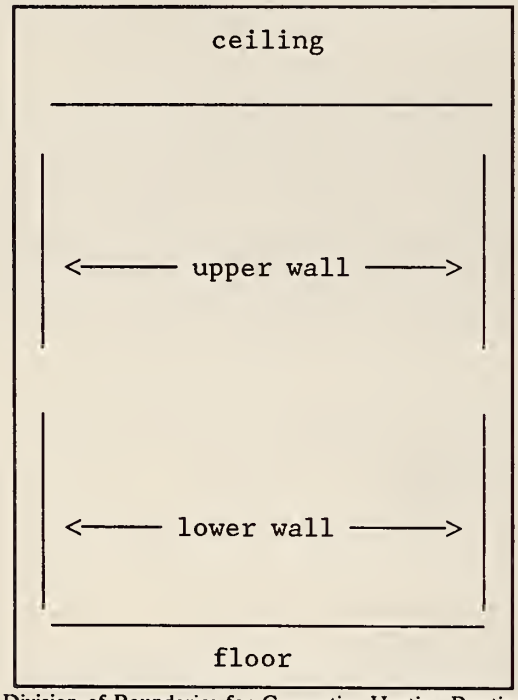
qsrad is the radiation to the surfaces, and qradg is the total radiative heat flux into the gas

```
      QSRADL       = -EP(I) * PI(I) * ONED
      QSRAD(I,NC) = QSRADL
   10 QRAD(I)      = QSRADL * AW(I)
      QRADG(UPPER,NC) = - (QRAD(UPPER) + QRAD(LOWER))
```

```
      QRADG(LOWER,NC) = 0.0
      RETURN
      END
```

5.2 CONVEC (sec. 4.2)

The model allows for a ceiling, floor and two walls. Actually the two walls are always the same material, but a separate temperature profile is maintained for the wall in contact with the upper and lower zones, respectively. Therefore we have four components for convective heat transfer.



Division of Boundaries for Convective Heating Routine

$$h = \frac{lmd}{l} \quad NU = \frac{lmd}{l} C (Gr\ Pr)^{1/3}$$

Orientation	Coefficient	Condition
walls	0.130	all
ceiling and floor	0.210	$T_g > T_w$
ceiling and floor	0.012	$T_g < T_w$

The coefficient in the above table is the "C" in the previous equation.

Reference [6] discusses this aspect.

```
      SUBROUTINE CONVEC(IW, TG, TW, AW, QDINL, QCNVGO)

C     TG = GAS LAYER TEMPERATURE
C     TW = WALL TEMPERATURE OF WALL "IW"
C     AW = AREA OF THIS WALL
C     ANET = TOTAL AREA OF WALL "IW" IN CONTACT WITH THE GAS LAYER (TG)
C     QDINL = HEAT CONVECTIVE FLUX TO THE WALL BOUNDING THIS GAS LAYER
C     QCNVGO = NET CONVECTIVE HEAT FLUX TO THE GAS LAYER
```

```
      FAST COMMON BLOCK GOES HERE
      REAL LMD,NU
```

pr = Prandtl number = 0.72 for air
nu = Nusselt number
lmd = lambda = an equivalent conductivity for air
v = viscosity of air

The power law for turbulent flow is 1/3 and for laminar flow it is 1/4. We have simplified the convection calculation by using only the turbulent flow power law. If a more general relationship is used, then the following note shows how to convert the final "q" to yield the correct relationship between the heat transfer and the heat transfer coefficient as formulated by the Nusselt number.

```
      PR=0.72
      V=7.18E-10*((TW+TG)/2.)**(7./4.)
      LMD = 2.72E-4 * ((TW+TG)*0.5)**0.8

C     NOTE: GRASHOF NUMBER HAS THE L**3 DIVIDED OUT TO
C           PREVENT DIVIDE BY ZERO ERRORS AS THE SURFACE
C           VANISHES - DEPENDS ON THE NU(1/3) POWER.
C           RESULT MUST BE MULTIPLIED BY (L**3)**(1/A)*L/(L**2) WHERE
C           A IS THE POWER IN THE NUSSELT NUMBER CALCULATION AND
C           L = SQRT(AW)

      GR=G*ABS(TG-TW)/(V**2*TG)

      GO TO (20,30,10,10),IW

C     VERTICAL WALL

   10 NU=0.13*(GR*PR)**(1./3.)
      GO TO 40

C     CEILING

   20 IF(TG.LT.TW) GO TO 21
      NU=0.21*(GR*PR)**(1./3.)
      GO TO 40
   21 NU=0.012*(GR*PR)**(1./3.)
      GO TO 40

C     FLOOR

   30 IF(TG.LT.TW) GO TO 31
      NU=0.012*(GR*PR)**(1./3.)
      GO TO 40
```

```
      31 NU=0.21*(GR*PR)**(1./3.)

      40 QDINL = LMD * NU * (TG-TW)
         QCNVG0 = QCNVG0 - QDINL * AW
         RETURN
         END
```

5.3 FIRPLM (sec. 4.3)

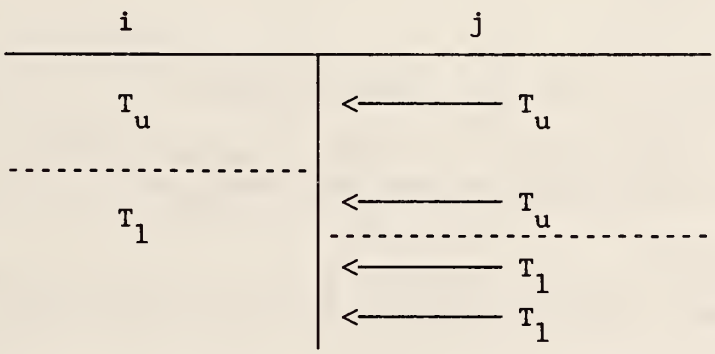
```
         SUBROUTINE FIRPLM(QJL, Z, R, FMZ, EMZ, LFBT)

   C     "Momentum Implications for Buoyant Diffusion Flames"
   C     Combustion and Flame 52,149(1983)

   C     LFBT = FIRE TYPE FOR ENTRAINMENT MODIFICATION
   C     QJ = FIRE SIZE (W)
   C     R  = MASS LOSS RATE OF THE FIRE
   C     FMZ = TOTAL MASS TRANSFER RATE AT THE TOP OF THE PLUME
   C     EMZ = NET MASS ENTRAINMENT RATE
   C     Z = PLUME HEIGHT

         DIMENSION F(4)
         DATA F/1.,2.,4.,1./

   C     NOTE UNITS CONVERSION JOULES->KILOJOULES

         QJ = 0.001 * QJL
         IF(Z.GT.0.) THEN
           IF(QJ.GT.0) THEN
             ZDQ=Z/(F(LFBT)*QJ)**0.4
             IF(ZDQ.GT.0.2) THEN
               FMZ = 0.124* ZDQ**1.895 * QJ
             ELSE IF (ZDQ.GT.0.08) THEN
               FMZ = 0.026 * ZDQ**0.909 * QJ
             ELSE
               FMZ = 0.011 * ZDQ**0.566 * QJ
             ENDIF
             FMZ = MAX (R, FMZ/F(LFBT))
             EMZ = MAX (FMZ-R, 0.0)
           ELSE
             FMZ = R
             EMZ = 0.0
           ENDIF
         ELSE
           FMZ=R
           EMZ=0.0
```

```
ENDIF
RETURN
END
```

5.4 FLOW, FRFLOW AND ENTRFL (sec. 4.4)

Fluid flow is the primary mechanism for transport of mass and enthalpy from one compartment to another. We divide flow into two classes which we refer to as horizontal and vertical flow. The terms are symbolic of the approximate direction of the flow with respect to gravity. Vertical flow is parallel to the direction of gravity and horizontal flow is perpendicular. Vents are then named by the same convection, so HVENT is the acronym for vents through which there will be horizontal flow and are referred to as "horizontal vents," and VVENT is the equivalent specification for vertical flow and "vertical vents." Unlike the plume model, there is no constraint on the amount of gas entrained, except that it must satisfy the equivalency principle discussed earlier. So it is possible for short (low soffit) vents in tall compartments to overestimate the amount of gas entrained.

The following three routines calculate fluid movement which nominally is in a horizontal direction. The following schematic illustrates the normal rule used to deposit fluid which flows from one compartment to another.



This selection rule is that the upper layer gases flow into an upper layer, and similarly for the lower layer. However, for an outside ambient that is warmer or colder than either layer, the in-flow must force air into one or the other, respectively. As an example, if we are modeling a warm building in a winter scenario, the air which infiltrates the building should go into the lower layer. The modified selection rules become

$T_\ell(j) < T_u(j) < T_\ell(i) < T_u(i)$ ——— all into lower layer

$T_\ell(j) < T_\ell(i) < T_u(j) < T_u(i)$

$T_\ell(i) < T_\ell(j) < T_u(j) < T_u(i)$ ——> usual selection rules (see above)

$T_\ell(j) < T_\ell(i) < T_u(i) < T_u(j)$

$T_\ell(j) < T_\ell(i) < T_u(i) < T_u(j)$

$T_\ell(i) < T_u(i) < T_\ell(j) < T_u(j)$ ——— all into upper layer

The first routine (FLOW) simply adjusts the boundary conditions for interior or exterior flow and does the redundancy check mentioned earlier on the symmetry aspects of the bidirectional flow.

```
      SUBROUTINE FLOW(I, J, K, TU, Z, TL)

i and j specify two compartments, and k is the vent number (1->4)
tu and tl are the upper and lower layer temperatures respectively
z is the interface height

      DIMENSION TU(N), Z(N), TL(N), R(4) , TM(4,4), ZN(6)
      RG(I) = (RAMB(I) * TAMB(I)) / (PAMB(I)+POFSET)

C     IF WE REFER TO THE OUTSIDE COMPARTMENT, THEN THE INTERFACE
C     MUST REFER TO THE EXTERNAL AMBIENT, WIND INCLUDED

      IF (I.LT.N) THEN
        R(1) = (RAMB(I)*TAMB(I))/(PAMB(I)+POFSET) * (P(I)+POFSET)/TU(I)
        R(2) = (RAMB(I)*TAMB(I))/(PAMB(I)+POFSET) * (P(I)+POFSET)/TL(I)
        PI =   P(I)
        ZAI =  HRP(I) - Z(I)
        HFI =  HFLR(I)
      ELSE
        R(1) = ERA(J)
        R(2) = ERA(J)
        PI =   EPA(J)
        ZAI =  1.E+5
        HFI =  HFLR(J)
      ENDIF
      IF (J.LT.N) THEN
        R(3) = (RAMB(J)*TAMB(J))/(PAMB(J)+POFSET) * (P(J)+POFSET)/TU(J)
        R(4) = (RAMB(J)*TAMB(J))/(PAMB(J)+POFSET) * (P(J)+POFSET)/TL(J)
```

```
          PJ =   P(J)
          ZAJ =  HRP(J) - Z(J)
          HFJ =  HFLR(J)
        ELSE
          R(3) = ERA(I)
          R(4) = ERA(I)
          PJ =   EPA(I)
          ZAJ =  1.E+5
          HFJ =  HFLR(I)
        ENDIF

C       START WITH THE ASSUMPTION THAT R(I) < R(J) - THIS REMOVES THE
C       SYMMETRY

        IF(R(1).GT.R(3)) RETURN

C       FIND THE WIDTH BY MULTIPLYING THE OPENING BY THE WIDTH FRACTION FROM
C       CVENT

        IF (ITERPT.EQ.1) THEN
           FACTOR = (QCVENT(I,J,K,ITIME1)*TIMEI1-QCVENT(I,J,K,ITIME2)*
     .              TIMEI2) * TIMEI3
        ELSE
           FACTOR = QCVENT(I,J,K,LFMAX+1)
        ENDIF

        HH0 = HHP(I,J,K)
        HL0 = HLP(I,J,K)
        BW0 = BW(I,J,K) * FACTOR
        CALL FRFLOW(PI,PJ,HFI,HFJ,ZAI,ZAJ,R,HL0,HH0,BW0,TM,IZN,ZN)

C       KEEP TRACK OF THE NUMBER OF NEUTRAL PLANES, BUT NOT THE ACTUAL
C       POSITION OF THE NEUTRAL PLANE(S)

        NEUTRAL(I,J) = IZN

        RETURN
        END
```

The routine FRFLOW does the actual integration along the vertical axis of the vent, that is from z_1 to z_2 (see eq (16)). A more detailed discussion of the algorithm is given in reference [15]. The effects of wind are included in the external pressure applied to a vent which is connected to the outside ambient. As such, it does not explicitly show up in the calculations, but is part of the term EPA above. We use the equation for pressure as a function of height as given in reference [17]. Starting with an initial temperature and pressure of T_a, P_a for the ambient at the station, we can calculate the pressure at a height H_i. The station information

is at a reference height H_r and the wind speed is V_w at a relative height H_w above the reference height H_r. The form for the pressure with the wind added is

$$P_w \rightarrow P_a \left(\frac{T_a - 0.0065\, H_i}{T_a + 0.0065\, H_r} \right)^{5.26} \left[1 + \frac{C_w * V_w}{2\, R\, (T_a - 0.0065 H_i)} \left(\frac{H_i}{H_w} \right)^{p_w} \right].$$

The power law p_w defines the lapse rate for the pressure, and the coefficient C_w is the relative effect that the wind will have on an opening. It varies from -1 to +1 and is the dot product of the wind direction vector and the vent direction.

```
      SUBROUTINE FRFLOW(PIO,PEO,HI,HE,ZI,ZE,RH,BF,HF,ALF,TM,IZN,ZN)

C     PIO = PRESSURE AT A CERTAIN REFERENCE LEVEL, SIDE I
C     PEO =  " " " " "  THE SAME   " " " " " " " , SIDE E
C     ZI = DISCONTINUITY HEIGHT, SIDE I (OVER REF. LEVEL)
C     ZE =  " " " " " " " " " " " " " E   " " " " " " "
C     RH(1)= GAS DENSITY OF THE UPPER LAYER, SIDE I
C     RH(3)=  " " " " " " " " " " " " " " " " " " " E
C     RH(2)=  " " " " " " " " " LOWER " " " " " " I
C     RH(4)=  " " " " " " " " " " " " " " " " " " E
C     BF = OPENING SILL HEIGHT (OVER REF. LEVEL)
C     HF =  " "  SOFFIT " " " " " " " " " " " " "
C     ALF = " " "  WIDTH
C     CD = CONSTRICTION COEFFICIENT

C     ZN = TABLE OF THE NEUTRAL PLANE HEIGHTS COMPUTED IN THE
C          THE OPENING: AS TWO OF THESE MAY BE EQUAL, THE DIMENSION
C          IS 6, BUT THERE ARE AT MOST THREE NEUTRAL PLANE HEIGHTS.
C          THE INITIAL VALUES ARE 100000 METERS.

C     TM = TABLE(4,4) OF THE MASS FLOW RATES THROUGH OPENING, EACH
C          ELEMENT TM(I,J) REPRESENTING THE ABSOLUTE VALUE OF THE MASS
C          FLOW RATE (IF ANY) FROM I TO J (IF NOT: TM(I,J)= 0)
C           1 IS RELATIVE TO THE UPPER GASEOUS LAYER, SIDE I
C           2  " " " " " " " " " " LOWER " " " " " " " " " "
C           3  " " " " " " " " " " UPPER " " " " " " ", SIDE E
C           4  " " " " " " " " " " LOWER " " " " " " " " " "

      DIMENSION RH(4),TM(4,4),ZN(6)
      DATA G/9.80665/ , CD/0.7/, DMP/1.0/
      DATA ZERO/0./

C     INITIALIZATION
```

```
      DO 1 K=1,4
      DO 1 L=1,4
1     TM(K,L)=0
      DO 2 K=1,6
2     ZN(K) = 100000.
      IZN = 0
      I=2
      J=4
      DPO = PIO - PEO
      DPI = G * (MIN(ZI,BF-HI)*RH(2) + MAX(ZERO,BF-ZI)*RH(1))
      DPE = G * (MIN(ZE,BF-HE)*RH(4) + MAX(ZERO,BF-ZE)*RH(3))
      DP =  DPO + DPE - DPI
      TTCA = 0.6666667 * CD * ALF

C     MAIN LOOP: INTEGRATION OVER INTERVALS [ZA,ZB] FROM BF TO HF

      ZA = BF
10    ZB = HF

C     FLOW RATE FROM OR TO ZONE 1 IF ZI <= ZA

      IF(ZI.LE.ZA)THEN
        I = 1

C     MAKE ZB=MIN(HF,ZI) IF ZA < ZI < ZB

      ELSE IF (ZI.LT.ZB)THEN
        ZB = ZI
      END IF

C     FLOW RATE TO OR FROM ZONE 3 IF ZE <= ZA

      IF(ZE.LE.ZA)THEN
        J = 3

C     MAKE ZB=MIN(HF,ZI,ZE) IF ZA < ZE < MIN(HF,ZI)

      ELSE IF (ZE.LT.ZB)THEN
        ZB = ZE
      ENDIF

C     EXPRESSION OF PRESSURE DIFFERENCES IN ZA AND ZB

      DPA = DP
      DPB = DPA+(RH(J)-RH(I))*G*(ZB-ZA)

C     NO NEUTRAL PLANE IN [ZA,ZB]
```

```
      IF (DPA*DPB.GT.ZERO)THEN

C     .....FROM I TO J

        IF (DPA.GT.ZERO)THEN
          X = SQRT(DPA)
          Y = SQRT(DPB)
          XX = MIN(X,Y)
          YY = MAX(X,Y)
          Y2 = YY * YY
          TM(I,J) = TTCA * SQRT(2.*RH(I))*(ZB-ZA)*(XX+YY/(1.+XX/YY))
     .            * TTCB(DMP,Y2) + TM(I,J)

C     .....FROM J TO I

        ELSE
          X = SQRT(-DPA)
          Y = SQRT(-DPB)
          XX = MIN(X,Y)
          YY = MAX(X,Y)
          Y2 = YY * YY
          TM(J,I) = TTCA * SQLRT(2.*RH(J))*(ZB-ZA)*(XX+YY/(1.+XX/YY))
                  * TTCB(DMP,Y2) + TM(J,I)
        ENDIF

C     NEUTRAL PLANE HEIGHT IN [ZA,ZB]

      ELSE IF (DPB.EQ.ZERO.AND.DPA.EQ.ZERO)THEN
        IZN = IZN + 1
        ZN(IZN) = (ZA+ZB)/2
      ELSE
        IZN = IZN+1
        ZN(IZN) = ZA-(DPA/(DPB-DPA))*(ZB-ZA)

C     ..BOTTOM FLOW I TO J

        IF(DPA.GT.DPB)THEN
          TM(I,J) = TTCA*(ZN(IZN)-ZA)*SQRT(2.*RH(I)*DPA)
     .            * TTCB(DMP,DPA) + TM(I,J)
          TM(J,I) = TTCA*(ZB-ZN(IZN))*SQRT(-2.*RH(J)*DPB)
     .            * TTCB(DMP,-DPB) + TM(J,I)

C     ..BOTTOM FLOW J TO I

        ELSE
          TM(J,I) = TTCA*(ZN(IZN)-ZA)*SQRT(-2.*RH(J)*DPA)
                  * TTCB(DMP,-DPA) + TM(J,I)
```

```
          TM(I,J) = TTCA*(ZB-ZN(IZN))*SQRT(2.*RH(I)*DPB)
     .              * TTCB(DMP,DPB) + TM(I,J)
        ENDIF
      ENDIF

C     REASSIGN LOWER BOUND AND LOWER BOUND PRESSURE DIFFERENCE

      IF (ZB.GE.HF) RETURN
      ZA = ZB
      DP = DPB
      GO TO 10
      END
```

We now can do the entrainment for the flow through vents.

```
      SUBROUTINE ENTRFL(TU, TL, FMD, Z, FMZ)
```

the conversion from Watts used by FAST to the units of McCaffrey [7] is the factor .001.

```
      XQJ = CP * (TU-TL) * 0.001
      QJ = XQJ * FMD
      FMDQJ = 1. / XQJ
      ZODQ = (FMDQJ/0.011)**1.767
      IF(ZODQ.LE.0.08) GO TO 10
      ZODQ = (FMDQJ/0.026)**1.1001
      IF(ZODQ.LE.0.20) GO TO 10
      ZODQ = (FMDQJ/0.124)**0.528

   10 ZDQ = Z/QJ**0.4 + ZODQ
      IF(ZDQ.GT.0.2) THEN
        FMZ = 0.124 * ZDQ**1.895 * QJ
      ELSE IF (ZDQ.GT.0.08) THEN
        FMZ = 0.026 * ZDQ**0.909 * QJ
      ELSE
        FMZ = 0.011 * ZDQ**0.566 * QJ
      ENDIF
```

the following statement insures that the entrainment is physical. We are limited by the correlation that we use of momentum driven jets are strictly functions of the heat release rate.

```
      FMZ = MAX (0.0, FMZ-FMD)
      RETURN
      END
```

5.5 PYROLS, CHEMIE (sec. 4.5)

A specified quantity is any quantity for which there is a specified time history. The specification is set of data of the quantity of interest as a function of time. To obtain values between the specified points, we use an interpolating polynomial. The routine PYROLS calculates the coefficients of the interpolating polynomial and most of the specified quantities. The values for CVENT are actually done in FLOW, but with the same interpolation coefficients. The output from PYROLS is then used by CHEMIE to calculate the burning rate. If a type 1 fire is selected (unconstrained) then the burning rate is set to the pyrolysis rate, and the heat release rate is found by multiplying the burning rate by the heat of combustion. Otherwise, the prescription discussed in section 4.5, and shown below, is used to constrain the burning rate based on both the fuel and oxygen available.

```
      SUBROUTINE PYROLS(TIME, BFIRET, AFIRET, HFIRET, QFIRET,
     . HCOMBT)

C     PYROLYSIS RATE OF THE FUEL - HCRATT IS IN COMMON SINCE IT IS USED
C     IN SEVERAL PLACES

      FAST COMMON BLOCK GOES HERE

      IF(TIME.GE.TFMAXT) GO TO 20
    1 TI0 = TFIRET
      TI = TI0 + TFIRED(IFIRED)
      I = IFIRED
      IF(TIME.LE.TI) GO TO 10
      IFIRED = IFIRED + 1
      IF(IFIRED.GT.LFMAX) GO TO 20
      TFIRET = TI
      GO TO 1

C     TYPE 1 INTERPOLATION - ITERPT = 1

these are the interpolating coefficients

   10 TI1 = TI - TIME
      TI2 = TI0 - TIME
      OVTFD = 1. / TFIRED(I)
      ITERPT = 1

this is the interpolating polynomial

      BFIRET = (TI1 * BFIRED(I) - TI2 * BFIRED(I+1)) * OVTFD
      AFIRET = (TI1 * AFIRED(I) - TI2 * AFIRED(I+1)) * OVTFD
      HFIRET = (TI1 * HFIRED(I) - TI2 * HFIRED(I+1)) * OVTFD
```

```
      QFIRET = (TI1 * QFIRED(I) - TI2 * QFIRED(I+1)) * OVTFD
      HCRATT = (TI1 * HCRATIO(I)- TI2 * HCRATIO(I+1)) * OVTFD
      CCO2T = (TI1 * CCO2(I) - TI2 * CCO2(I+1)) * OVTFD
      COCO2T = (TI1 * COCO2(I)  - TI2 * COCO2(I+1)) * OVTFD
      HCOMBT = (TI1 * HOCBMB(I) - TI2 * HOCBMB(I+1)) * OVTFD
      DO 15 J = 1, NS
      IF(.NOT.ACTIVS(J)) GO TO 15
      MFIRET(J) = (TI1*MPRODR(I,J) - TI2*MPRODR(I+1,J)) * OVTFD * BFIRET
   15 CONTINUE
      TIMEI1 = TI1
      TIMEI2 = TI2
      TIMEI3 = OVTFD
      ITIME1 = I
      ITIME2 = I+1
      RETURN

the following is done at an end point

C     TYPE 2 INTERPOLATION - ITERPT = 2 - NOW TIMEI* HAS NO MEANING

   20 ITERPT = 2
      BFIRET = BFIRED(LFMAX+1)
      AFIRET = AFIRED(LFMAX+1)
      HFIRET = HFIRED(LFMAX+1)
      QFIRET = QFIRED(LFMAX+1)
      HCRATT = HCRATIO(LFMAX+1)
      CCO2T = CCO2(LFMAX+1)
      COCO2T = COCO2(LFMAX+1)
      HCOMBT = HOCBMB(LFMAX+1)
      DO 30 J = 1, NS
      IF(.NOT.ACTIVS(J)) GO TO 30
      MFIRET(J) = BFIRET * MPRODR(LFMAX+1,J)
   30 CONTINUE
      RETURN
      END
```

CHEMIE is the routine which calculates the heat release rate and species production. The primary input is the mass pyrolysis rate, and the primary output is the heat generation rate. This routine is only used for a type 2 (constrained) fire.

```
      SUBROUTINE CHEMIE (QPYROL, PYROL, ENTRAIN, NETFUEL, TARGET, LAYER)
```

"pyrol" is the mass pyrolysis rate from the PYROL routine, and qpyrol the heat generation rate, "entrain" is the entrainment rate (we are dealing with diffusion limited combustion) and "netfuel" is the fuel actually burned as opposed to the possible "pyrol" value. "netxx" then are the species production rates, based on the formulae discussed in section 4.5

```
      FAST COMMON BLOCK GOES HERE

      REAL NETFUEL, NEWNET, NETH2O, NETCO2, NETCO, NET
      REAL TMASS, NETFUL, XMASS(NS)
      EQUIVALENCE (NETO2,XMASS(2)),(NETCO2,XMASS(3)),(NETCO,XMASS(4))
      EQUIVALENCE (NETFUL,XMASS(7)),(NETH2O,XMASS(8)),(NETC,XMASS(9))
      INTEGER SOURCE, TARGET
      DATA XMASS/NS*0.0/
```

"source" specifies the compartment of origin of the flow, and "layer" is the corresponding layer from which the fuel and oxygen originate.

```
      SOURCE = TARGET
      TMASS = 0.0
      DO 2 LSP = 1, 9
    2 TMASS = TMASS + MASS(LAYER,SOURCE,LSP)
      TMASS = MAX (TMASS, MINMAS)
      O2FRAC = MASS(LAYER,SOURCE,2) / TMASS
      O2ENTR =  ENTRAIN * O2FRAC
```

4.83 is the inverse of 20.6 %

```
      O2INDEX = MAX(0.,(O2FRAC-LIMO2)*4.83)
      O2MASS =  O2ENTR * 0.995 * (1-EXP(-10*O2INDEX))
      OOSTOK =  13200000. / HCOMBA
      QPYROL =  MAX(0.,MIN(PYROL, OOSTOK*O2MASS)) * HCOMBA
      NETFUEL = QPYROL / HCOMBA

C     THIS IS THE REAL KINETICS SCHEME AS DRIVEN BY DIFFUSION

      NETFUL = - NETFUEL      NETO2 = - QPYROL / 1.32E+7
      NETH2O = 9.0 * NETFUEL * HCRATT / (1+HCRATT)
      NETCO2 = 3.67 * NETFUEL / ((1+HCRATT)*(1.+1.57*COCO2T+3.67*CCO2T))
      NETCO = NETCO2 * COCO2T
      NETC =  NETCO2 * CCO2T

    1 NETMAS(UPPER,TARGET,I) = NETMAS(UPPER,TARGET,I) + XMASS(I)

C     NO POINT IN ENTRAINING FROM THE UPPER LAYER INTO THE UPPER LAYER

      IF (LAYER.EQ.UPPER) RETURN

C     ADD IN THE FLOW ENTRAINED BY THE PLUME

      DO 8 LSP = 1, NS
      IF (.NOT.ACTIVS(LSP)) GO TO 8

C     PLUME CONTRIBUTION FOR ALL ENTRAINED GASES
```

```
      NEWNET = ENTRAIN * MASS(LOWER,SOURCE,LSP) / OLDMAS(LOWER,SOURCE)
      NETMAS(UPPER,TARGET,LSP) = NETMAS(UPPER,TARGET,LSP) + NEWNET
      NETMAS(LOWER,TARGET,LSP) = NETMAS(LOWER,TARGET,LSP) - NEWNET
    8 CONTINUE
      RETURN
      END
```

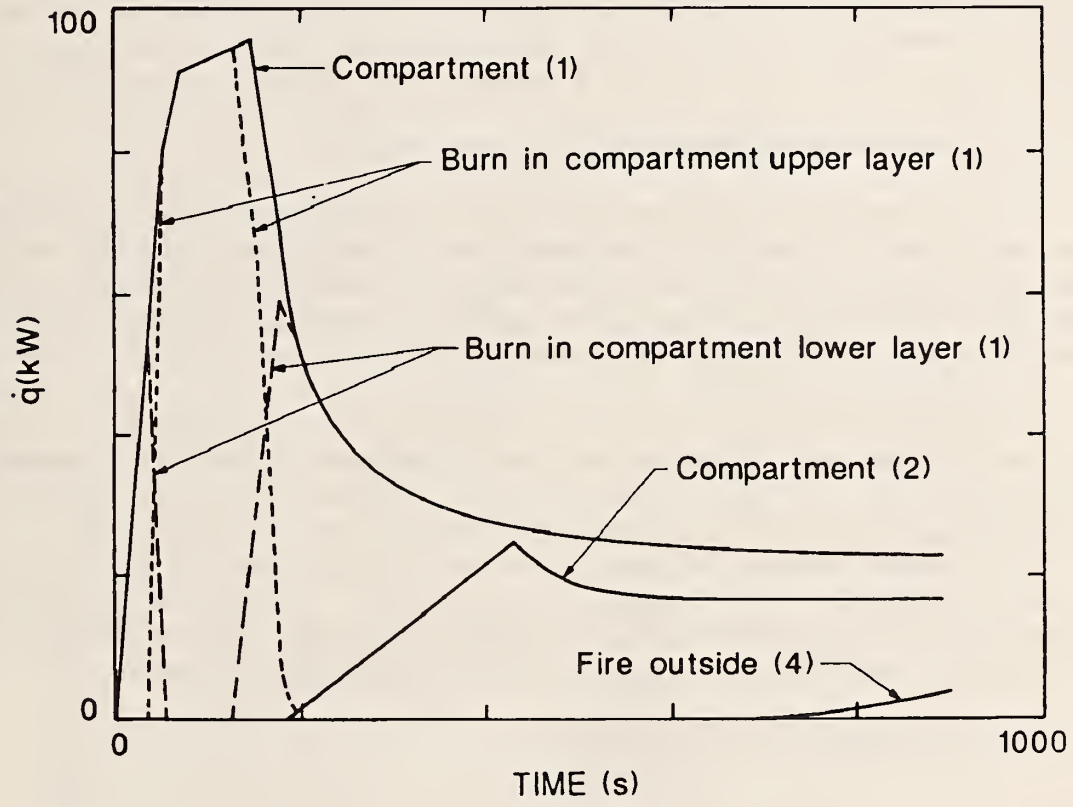


Figure 4. Heat release rate in a vitiated atmosphere.

An example of what happens in a vitiated atmosphere can be demonstrated by example. The data file used is the three compartment model shown in Appendix A with door heights modified to accentuate the effect of vitiation. The building was a nominal two compartment structure connected by a door, with another door to the outside. The door to the third compartment was shut as part of this calculation. The fire simulated a free burn going from zero to 100 kW over 30 seconds, and then remaining fixed at that level. That is, the pyrolysis rate was such that if no constraint existed, the fire would burn at the 100 kW level. The effect

of vitiation is shown in figure 4. During the process of filling, the effect of vitiation is such that the total heat release in all spaces is less than the 100 kW nominal value. Eventually there will be no accumulation of fuel, and the burning outside of the structure will make up the difference. Compartment (3) is effectively cut off.

Figure 4 shows the total heat release rate in compartment (1) together with the contribution of the release in the lower layer and the upper layer. As the interface approached the fire source, the entrainment and relative contribution from the lower layer (region #1) decreased until the fire was in the upper layer only (region #2). Subsequently, the fire burned only in the upper layer and depleted the oxygen of this layer. Since no fuel is then burned in the lower layer, all is available to burn in the upper layer. Also, since there was no plume in the lower layer to pump oxygen into the upper layer, the oxygen level decreased until the fire was extinguished in regions #1 and #2 in compartment (1).

As the burning rate was constricted in compartment (1), unburned fuel began to spill into the adjacent compartment (2) and burned in the flow from the doorway. Once again, burning took place until the layer in this compartment reached a point where there is not sufficient oxygen to support burning of all the fuel. At this point fuel began to flow to the outside and burn. This sequence of events is also illustrated in figure 4.

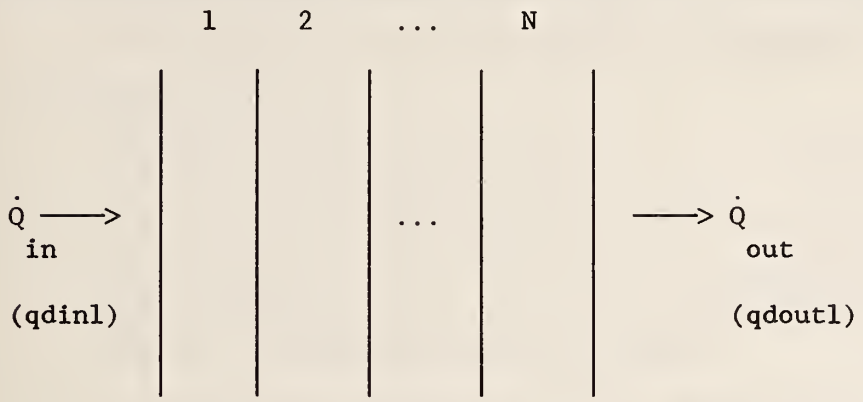
Note that the burning in the compartments was never fully extinguished. As the fire decreased in compartment 1, and fuel began to flow out, the layer moved up somewhat so that burning once again took place in the lower layer. After 400 seconds, a steady state was reached where some fuel was burned in the lower layer, and the remaining fuel is deposited in the upper layer. This then became a source of fuel to burn upon exiting to compartment (2) and subsequently to the outside, compartment (4). A steady state was reached in compartment #2 at about 600 seconds. From this time on, the vent fire to the outside grew. The calculation was terminated prior to the latter reaching a steady state.

The vent specification for this calculation is

```
HVENT   1  2   1 0.81   0.55   0.00
HVENT   2  4   1 0.79   0.75   0.00
HVENT   2  3   1 0.00   0.00   0.00
```

5.6 CNDUCT (sec. 4.6)

"CNDUCT" solves a series of linear parabolic equations which describe heat flow through a solid. Each boundary is partitioned into N+1 nodes (N slabs) and looks something like



A set of these nodes exists for each boundary. The boundary can consist of up to three materials, whose properties can differ. The solver is applied to each layer (slab) of the boundary, with appropriate boundary conditions at the real physical boundaries, and between the slabs. The solver uses a time centered, space centered (Crank-Nicholson) successive over relaxation method to solve the temperature field for given boundary conditions. The boundary conditions are the heat flux at the interior and exterior nodes. Because of the possible change in material properties, we imposed the additional constraint that both the temperature and gradient of the temperature must be continuous across the interior interfaces. We do not allow for a film resistance between the various materials. The "B" coefficients are defined in Mitchell and Griffiths [16]. The specific form is not transparent because of the time and space centering formulation of the solver.

```
      SUBROUTINE CNDUCT(QDINL,QDOUTL,DT,NC,NWW)

C     NSLB.....NUMBER OF SLABS.IN.WALL.NWW......
C     FLW......SLAB THICKNESS.....(M).....
C     CW.......SPEC HEAT.....(J/KG/K).
C     RW.......DENSITY.....(KG/M*3).
C     FKW......CONDUCTIVITY.....(J/M/S/K)
C     QDOT.....HEAT FLUX.....(J/S/M*2)
C     TWJ......TEMP PROFILE.....(K).....
C     DT.......TIME STEP.....(S).....
```

nmaxit is the maximum number of iterations allowed for the solver.

```
      PARAMETER (NMAXIT=100)

      FAST COMMON BLOCK GOES HERE

      INTEGER NODE(0:MXSLB)
      REAL XM(MXSLB),MAXDIF,B(NN),DX(MXSLB),FK(MXSLB)
      REAL EPS, NEWT(NN), OLDT(NN), R1(MXSLB), R2(MXSLB)
      DATA EPS/0.9/, MAXDIF/0.0/
```

```
C     PRECALCULATE CONSTANTS

      NTOT = 0
      NSL = NSLB(NWW,NC)
      DO 4 I = 1, NSL
    4 NTOT = NTOT + NDIV(I,NWW,NC)
      DO 1 I = 1, NTOT
      NEWT(I) = TWJ(NWW,NC,I)
    1 OLDT(I) = TWJ(NWW,NC,I)

      DO 2 I = 1, NSL
      FK(I) = 1. / FKW(I,NWW,NC)
      DX(I) = FLW(I,NWW,NC) / FLOAT(NDIV(I,NWW,NC))
      XM(I)=FKW(I,NWW,NC)*DT/(DX(I)*DX(I)*RW(I,NWW,NC)*CW(I,NWW,NC)*2.)
      R1(I) = 1. / (1.+XM(I))
      R2(I) = 1. / (1.+2.*XM(I))
      IF (XM(I).GT.(.5)) THEN
        diagnostic write
        STOP 'CNDUCT'
      ENDIF
  2   CONTINUE

C     NOTE THE CHANGE IN QDOUTL TO OBTAIN EXTERIOR CONVECTION FROM
C     THE "CONVEC" ROUTINE - ALSO THERE IS A SIGN CHANGE REQUIRED TO
C     MAINTAIN CONSISTENCY WITH IMPLEMENTATION OF THE B COEFFICIENTS

      DUMY = 0.0
      CALL CONVEC(NWW, TWE(NWW,NC), TWJ(NWW,NC,NTOT), 1.0, QDOUTL, DUMY)
      QDOUTL = -QDOUTL

      NODE(0) = 0
      DO 3 I = 1, NSL
    3 NODE(I) = NDIV(I,NWW,NC) + NODE(I-1)
      NODE(0) = 1
      NODE(NSL) = NODE(NSL) - 1

      ITER = 0

C     CALCULATE B VALUES

      B(1)=(OLDT(1)+XM(1)*(OLDT(2)-OLDT(1)+QDINL*DX(1)*FK(1)))*R1(1)
      DO 15 J = 1,NSL
      DO 15 I = NODE(J-1)+1, NODE(J)
   15 B(I)=(OLDT(I)+XM(J)*(OLDT(I-1)-2.*OLDT(I)+OLDT(I+1)))*R2(J)
      B(NTOT) =(OLDT(NTOT)-XM(NSL)*(OLDT(NTOT)-OLDT(NTOT-1)+QDOUTL
             * DX(NSL)*FK(NSL)))*R1(NSL)
```

```
C     NOW CALCULATE THE NEW TEMPERATURE FOR THE NEXT TIME STEP

 20   ITER = ITER + 1
      MAXDIF = 0.0
      IF (ITER.GT.NMAXIT) GOTO 300

C     CALCULATE THE FIRST NODE DATA

      TCHK = NEWT(1)
      NEWT(1)=(XM(1)*(NEWT(2)+DX(1)*QDINL*FK(1)))*R1(1) + B(1)
      MAXDIF = MAX(MAXDIF,ABS(NEWT(1)-TCHK))

C     CALCULATE THE INTERIOR NODE DATA

      DO 35 J = 1, NSL
      DO 30 I = NODE(J-1)+1, NODE(J)
      TCHK = NEWT(I)
      NEWT(I) =(XM(J)*(NEWT(I-1)+NEWT(I+1)))*R2(J) + B(I)
   30 MAXDIF = MAX(MAXDIF,ABS(NEWT(I)-TCHK))
   35 CONTINUE

C      CALCULATE THE LAST NODE DATA

      TCHK = NEWT(NTOT)
      NEWT(NTOT) = (-XM(NSL) * (QDOUTL*DX(NSL)*FK(NSL) - NEWT(NTOT-1)))
     .      * R1(NSL) + B(NTOT)
      MAXDIF = MAX(MAXDIF,ABS(NEWT(NTOT)-TCHK))

C     CHECK THE CONVERGENCE CRITERION

      IF (MAXDIF.GT.EPS) GOTO 20

C     CONVERGENCE ACHIEVED IF WE GET TO HERE

      DO 7 I = 1,NTOT
    7 TWJ(NWW,NC,I) = NEWT(I)
      RETURN

C     NO CONVERGENCE AFTER NMAXIT ITERATIONS

  300 diagnostic output
      STOP 'CNDUCT'
      END
```

Figure 5 shows a comparison of measured and calculated temperatures of a wall for the three compartment data file in Appendix A. The experimental data is discussed by Peacock et al. [4].

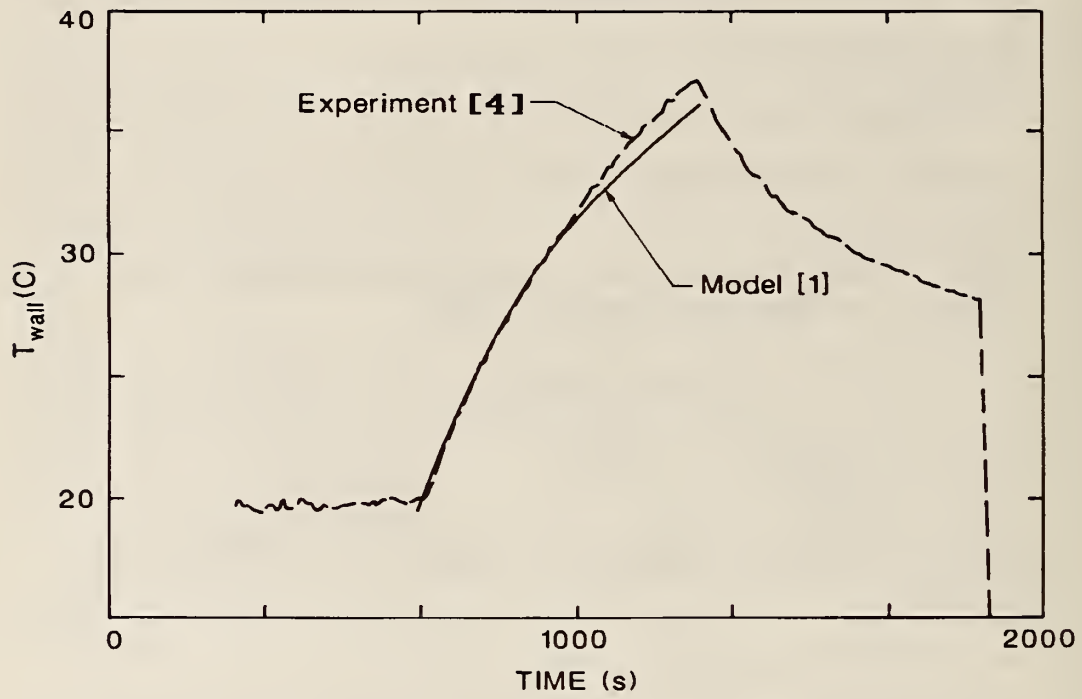


Figure 5. Comparison of measured and calculated wall temperatures.

6. DESCRIPTION OF THE DATA FILE USED BY FAST

The computer model requires a description of the problem to be solved. The following description is for the input data used by the model. In general, the order of the data is not important. The one exception to this is the first line which specifies the version number and gives the data file a title.

The data are grouped as

- Version and title (6.1)
- Time specification (6.2)
- Ambient conditions (6.3)
- Floor plan data (6.4)
- Connections (6.5)
- Thermophysical properties of the enclosing surfaces (6.6)
- Fire specifications (6.7)
- Species production (6.8)
- Files (6.9)
- Graphics specification (6.10).

The number of lines in a given data set will vary depending for example on the number of openings or the number of species tracked. A sample input data file is given in Appendix A. A number of parameters such as heat transfer and flow coefficients have been set within the program as constants. Please refer to the section on source terms to ascertain the values for these parameters.

Each line of the input data file begins with a key word which identifies the type of data on the line. The key words which are currently available are

CEILI	specify name of ceiling descriptor(s)	(N)
CHEMI	miscellaneous parameters for kinetics	(5)
CO	CO/CO_2 mass ratio	(lfmax+1)
CT	fraction of fuel which is toxic	(lfmax+1)
CVENT	opening/closing parameter	(lfmax + 4)
DEPTH	depth of compartments	(N)
DUMPR	specify a file name for saving time histories	(1)
EAMB	external ambient	(3)
FAREA	area of the base of the fire	(lfmax+1)
FHIGH	height of the base of the fire	(lfmax+1)
FLOOR	specify the name of floor property descriptor(s)	(N)
FMASS	pyrolysis rate	(lfmax+1)
FQDOT	heat release rate	(lfmax+1)

FTIME	length of time intervals	(lfmax)
HCL	hcl/pyrolysis mass ratio	(lfmax+1)
HCN	hcn/pyrolysis mass ratio	(lfmax+1)
HCR	hydrogen/carbon mass ration of the fuel	(lfmax+1)
HEIGH	interior height of a compartment	(N)
HI/F	absolute height of the floor of a compartment	(N)
HVENT	specify vent which connect compartments horizontally	(7)
INTER	initial height of the upper/lower interface	(2)
LFBO	compartment of fire origin	(1)
LFBT	type of fire	(1)
LFMAX	number of time intervals	(1)
LFPOS	position of the fire in the compartment	(1)
OD	C/CO_2 mass ratio	(lfmax+1)
RESTR	specify a restart file	(2)
TAMB	ambient inside the structure	(3)
TIMES	time step control of the output	(5)
VVENT	specify a vent which connects compartments vertically	(3)
VERSN	version number and title	(fixed format 2)
WALLS	specify the name of wall property descriptor(s)	(N)
WIDTH	width of the compartments	(N)
WIND	scaling rule for wind effects	(3)

The number in parenthesis is the maximum number of entries for that line. "N" represents the number of compartments being modeled and "lfmax" is the number of time intervals used to describe the fire, detailed below in section 6.7. The outside (ambient) is designated by one more than the number of compartments, N+1. So a three compartment model would refer to the outside as compartment four.

Each line of input consists of a label followed by one or more alphanumeric parameters associated with that input label. The label must always begin in the first space of the line and be in capital letters. Following the label, the values may start in any column and all values must be separated by either a comma or a space. Values may contain decimal points if needed or desired. They are not required. Units are standard SI units. Most parameters have default values which can be utilized by omitting the appropriate line. These will be indicated in the discussion. The maximum line length is 128 characters, so all data for each key word must fit in this number of characters. For each entry which requires more than one type of data, the first entry under the column "parameter" indicates the number of data required.

6.1 Version and Title

This line must be the first line in the file. It is the line that FAST keys on to determine whether it has a correct data file. The format is fixed, that is the data must appear in the columns specified in the text.

Label	Parameter	Comments
VERSN	(2)	The VERSN line is a required input.
	Version Number	The version number parameter specifies the version of FAST for which the input data file was prepared. Normally, this would be 18. It must be in columns 8-9.
	Title	The title is optional and may consist of letters, numbers, and/or symbols that start in column 11 and may be up to 50 characters. It permits the user to uniquely label each run.

Example:

```
VERSN   18 Simulation for Building XYZ
```

6.2 Time Specification

Label	Parameter	Comments	Units
TIMES	(5)	The TIMES line is required data.	
	Simulation Time	Simulation time is the length of time over which the simulation takes place. The maximum value for this input is 86400 seconds (1 day). The simulation time parameter is required.	s

Print Interval	The print interval is the time interval between each printing of the output values. If omitted or less than or equal to zero, no printing of the output values will occur.	s
Dump Interval	The dump interval is the time interval between each writing of the output to the dump file. The dump file stores all of the output of the model at the specified interval in a format which can be efficiently retrieved for use by other programs. Section 6.9 provides details of the dump file. A zero must be used if no dump file is to be used. There is a maximum of 50 intervals allowed. If the choice of this parameter would yield more than 50 writes, it is adjusted so that this limit is not exceeded.	s
Display Interval	The display interval is the time interval between each graphical display of the output as specified in the graphics specification, section 6.10. If omitted, no graphical display will occur. There is a limit on the display of 50 for the microcomputer versions and 100 for the mainframe versions of FAST. This parameter is not adjusted; rather graphs will be truncated to the first 50 or 100 points, respectively.	s
Copy Count	Copy count is the number of copies of each graphical display to be made on the selected hard copy device as specified in the graphics specification, section 2.9. If omitted, a value of zero (no copies) is assumed.	

Examples:

```
TIMES  360  0  0
TIMES  360 10 30
TIMES  900    30    10    10    0
```

In the first example, a simulation time of 360 seconds is specified. The output values will not be printed or stored in a dump file. No graphical display of the output will occur. In the second example, a 360 second simulation with printed output every 10 seconds and output to a dump file every 30 seconds is specified. No graphical display of the output values will be generated. In the third example, all parameters are specified. A 900 second simulation with

printed output every 30 seconds, output to a dump file every 10 seconds and a graphical display with no copies will occur every 10 seconds. Note the free field format of these parameters - multiple spaces between parameters are permitted.

6.3 Ambient Conditions

The ambient conditions section of the input data allows the user to specify the temperature and pressure and station elevation of the ambient atmosphere, as well as the absolute wind pressure to which the structure is subjected. There is an ambient for the interior and for the exterior of the building. The key word for the interior of the building is TAMB and for the exterior of the building is EAMB. The form is the same for both. The key word for the wind information is WIND. The wind modification is applied only to the vents which lead to the exterior. Pressure interior to a structure is calculated simply as a lapse rate based on the NOAA tables [17]. For the exterior, the nominal pressure is modified by

$$\delta(p) = C_w \rho V^2, \qquad \text{where} \quad V = V_w \left(\frac{H_i}{H_w}\right)^{p_w}$$

This modification is applied to the vents which lead to the exterior ambient. The pressure change calculated above is modified by the wind coefficient for each vent. This coefficient, which can vary from -1.0 to +1.0, nominally from -0.8 to +0.8, determines whether the vent is facing away from or into the wind. The pressure change is multiplied by the vent wind coefficient and added to the external ambient for each vent which is connected to the outside.

Label	Parameter	Comments	
TAMB or EAMB	(3)	These data are optional.	
	Ambient Temperature	Ambient temperature is the temperature of the ambient atmosphere. Default is 300.	K
	Ambient Pressure	The ambient pressure is the pressure of the ambient atmosphere. Default is 101300.	Pa

	Station Elevation	The station elevation is the elevation of the point at which the ambient pressure and temperature (see above) are measured. The reference point for the elevation, pressure and temperature must be consistent. This is the reference datum for calculating the density of the atmosphere as well as the temperature and pressure inside and outside of the building as a function of height. Default is 0.	m
WIND	(3)	This line is optional.	
	Wind Speed	Wind speed at the reference elevation. The default is 0.	m/s
	Reference Height	Height at which the reference wind speed is measured. The default is 10 meters.	m
	Lapse Rate Coefficient	The power law used to calculate the wind speed as a function of height. The default is 0.16.	

The choice for the station elevation, temperature and pressure must be consistent. Outside of that limitation, the choice is arbitrary. It is often convenient to choose the base of a structure to be at zero height and then reference the height of the building with respect to that height. The temperature and pressure must then be measured at that position. Another possible choice would be the pressure and temperature at sea level, with the building elevations then given with respect to mean sea level. This is also acceptable, but somewhat more tedious in specifying the construction of a building. Either of the these choices works though because consistent data for temperature and pressure are available from the Weather Service for either case.

Examples:

```
TAMB 300
TAMB 288 101000 200.
```

The first example sets the ambient temperature to 300 Kelvin, but leaves the ambient pressure at 101300 and the reference elevation at 0 meters. The second specifies a temperature of 15 degrees Celsius at 200 meters and a pressure of 101000 Pa. In both of these cases the external ambient is set to the same values. An example of different inside and outside values is a warm building in a winter setting and might be described as

```
TAMB  288 101305 0.0
EAMB  270 101315 0.0
```

6.4 Floor Plan Data

The floor plan data section allows the user to portray the geometry of the structure being modeled. The size and location of every room in the structure MUST be described. The maximum number of rooms is dependent upon the local implementation of FAST. Usually a total of 10 rooms (plus the outdoors) is available for a single simulation. For the PC versions, a maximum of six compartments (plus the outdoors) is allowed. The structure of the data is such that the compartments are described as entities, and then connected in appropriate ways. It is thus possible to have a set of rooms which can be configured in a variety of ways. In order to specify the geometry of a building, it is necessary to give its physical characteristics. Thus the lines labelled HI/F, WIDTH, DEPTH AND HEIGH are all required. Each of these lines requires "N" data entries, that is one for each compartment.

Label	Parameter	Comments	Units
HI/F	**Floor Height**	The floor height is the height of the floor of each room with respect to station elevation specified by the TAMB parameter. The reference point must be the same for all elevations in the input data. The number of values on the line must equal the number of rooms in the simulation.	m
WIDTH	**Room Width**	Room width specifies the width of the room. The number of values on the line must equal the number of rooms in the simulation.	m
DEPTH	**Room Depth**	Room depth specifies the depth of the room. The number of values on the line must equal the number of rooms in the simulation.	m
HEIGH	**Room Height**	Room Height specifies the height of the room. The number of values on the line must equal the number of rooms in the simulation.	m

Example:

```
HI/F   0.0   0.0   0.0
```

```
WIDTH  6.1   4.6   4.6
DEPTH  9.1  14.3   4.3
HEIGH  3.6   2.4   2.4
```

This floor plan data specifies the sizes for a three room simulation with rooms sizes of 6.1 x 9.1 x 3.6 m, 4.6 x 14.3 x 2.4 m, and 4.6 x 4.3 x 2.4 m, respectively. All rooms are at the same elevation at a reference height of 0.0 m.

6.5 Connections

The connections section of the input data file describes any horizontal or vertical vents between rooms in the structure. These may include doors between rooms in the structure, windows in the rooms (between rooms or to the outdoors), or vertical openings between floors of the structure. Openings to the outside are included as openings to the room with a number one greater than the number of rooms described in the floor plan data section. Doors, windows, and the like are called horizontal vents because the direction of the vent, or vent connection, is in the horizontal direction. The key word is HVENT. Horizontal vents may be opened or closed during the fire with the use of the CVENT key word. For vertical vents, such as scuddles, the key word is VVENT; at present there is not an equivalent mechanism for opening or closing the vertical vents. The form for horizontal and vertical vents is necessarily different.

Label	Parameter	Comments	Units
HVENT	(7)	Required to specify connections between compartments. No openings prevents flow. Each HVENT line in the input file describes one horizontal vent between rooms in the structure (or between a room and the outdoors). The first six entries on each line are required. There is an optional seventh parameter to specify a wind coefficient.	
	First Room	The first room is simply the first connection.	
	Second Room	The second room is the room number to which the first room is connected. The order has one significance. The height of the sill and soffit are with respect to the first compartment specified.	

	Vent Number	There can be as many as four vents between any two compartments. This number specifies which vent is being described. It can range from one to four.	
	Width	The width of the opening.	m
	Soffit	Position of the top of the opening above the floor of the room number specified as the first room.	m
	Sill	Sill height is the height of the bottom of the opening above the floor of the room number specified as the first room.	m
	Wind	The wind coefficient is the cosine of the angle between the wind vector and the vent opening. This applies only to vents which connect to the outside ambient (specified with EAMB). The range of values is -1.0 to +1.0. If omitted, the value defaults to zero.	
VVENT	(3)	Required to specify a vertical connection between compartments. Each VVENT line in the input file describes one vertical vent between rooms in the structure (or between a room and the outdoors). There are three parameters, the connected compartments, and the effective area of the vent.	
	First Room	The first room is simply the first connection.	
	Second Room	The second room is the room number to which the first room is connected. The order has one significance. The height of the sill and soffit are with respect to the first compartment specified.	
	Area	This is the effective area of the opening. For a hole, it would be the actual opening. For a diffuser, then the effective area will be somewhat less than the geometrical size of the opening.	

Examples:

```
HVENT 1  2  1 1.1  2.1  0.0
HVENT 1  3  1 1.1  2.1  0.0
HVENT 2  4  1 1.3  2.1  0.6
VVENT 1  3  3.0
```

Assuming the three room structure as described in the floor plan data section, the above examples describe two openings 1.1 x 1.5 m betweens rooms 1 and 2 and between rooms 1 and 3. An 1.3 x 2.1 m opening between room 2 and the outside (room 4 for a three room simulation) is raised 0.6 m off the floor of room 2.

```
HVENT 2  4  2 1.3  2.1  0.6 1.0
```

This specifies vent #2 between compartment (2) and the outside, with a wind coefficient of 1.0, which implies that the vent is facing directly into the wind.

CVENT is a parameter which is used to open a close vents. It multiples the width in the vent flow calculation. The default is 1.0 which is a fully open vent. A value of 0.5 would specify a vent which was halfway open.

Label	Parameter	Comments	Units
CVENT	(LFMAX+4)	Specify closing value. Each CVENT line in the input file describes one horizontal vent between rooms in the structure (or between a room and the outdoors).	
	First Room	The first compartment.	
	Second Room	The second room is the room number to which the first room is connected.	
	Vent Number	This number specifies which vent is being described. It can range from one to four. These parameters correspond to the first three parameters in HVENT.	
	Width (LFMAX+1)	Fraction that the vent is open. This applies to the width only. The sill and soffit are not changed.	%

CVENT has a form similar to HVENT but in addition contains the opening data. The additional data is in the same form as all the time dependent specifications, namely a value for each endpoint in the heat release curve. The form is

CVENT C#1 C#2 V# x x x x,...

By way of example, the default value for CVENT for the example show above with LFMAX=5 would be

```
CVENT 1 2 1 1.0 1.0 1.0 1.0 1.0 1.0
```

and would specify that the first vent between compartments (1) and (2) would be open at all times. Another example would be

```
CVENT 1 3 1 0.5 0.5 0.5 0.5 0.5 0.5
```

and would specify that the first vent between compartments (1) and (3) would be half open all of the time. These fractions refer to the width given in the HVENT specification and for the cases above would be 1.1 meters.

6.6 Thermophysical Properties of Enclosing Surfaces

The thermophysical properties of the enclosing surfaces are described by specifying the thermal conductivity, specific heat, emissivity, density, and thickness of the enclosing surfaces for each room. If the thermophysical properties of the enclosing surfaces are not included, FAST will treat them as adiabatic (no heat transfer). Since most of the heat conduction is through the ceiling and since the conduction calculation takes a significant fraction of the computation time, it is recommended that initial calculations be made using the ceiling only. Adding the walls generally has a small effect on the results and the floor contribution is usually negligible. Clearly, there are cases where the above generalization does not hold, but it may prove to be a useful screening technique. Currently, thermal properties for materials are read from a thermal database file unique to FAST. The data in the file for FAST simply gives a name (such as CONCRETE) which is a pointer to the properties in the thermal database. (For computers which do not support extensions, the ".DAT" is dropped.) For the PC version, this is an installation parameter. All of these specifications are optional. The thermal properties are assumed to be constant; that is, we do not account for the variation with temperature or water content.

The thermophysical properties are specified at <u>one</u> condition of temperature, humidity, <u>etc</u>. There can be as many as three layers per boundary, but they are specified in the thermal database itself.

Label	Parameter	Comments	Units
CEILI	(N)	The label CEILI indicates that the names of thermophysical properties on this line describe the ceiling material. If this parameter is present, there must be an entry for each compartment.	
WALLS	(N)	The label WALLS indicates that the names of thermophysical properties on this line describe the wall material. If this parameter is present, there must be an entry for each compartment.	
FLOOR	(N)	The label FLOOR indicates that the names of thermophysical properties on this line describe the floor material. If this parameter is present, there must be an entry for each compartment.	

Examples:

```
CEILI OFF         REDOAK     CONCRETE
WALLS CONCRETE    CONCRETE   CONCRETE
```

The corresponding thermal data base might appear as

```
CONCRETE    1.75  1000.   2200.   0.1500  0.94
BRICK       0.18   900.    790.   0.016   0.90
REDOAK      0.15  1300.    640.   0.025   0.99
```

The names of the materials can be **any** ASCII string up to 8 characters. So a valid name is $%#@**% although this admittedly does not convey much information. The key word "OFF" is used to tell the model not to compute the heat loss for the ceiling in compartment (1). In this case the FLOOR parameter is not present at all, so there will be no heat transfer through the floor in any room and the calculation will not be done for the ceiling in compartment (1), where the key word "off" is present. This is most useful for doing the heat transfer calculation in the burn room and adjacent rooms and then turning it off in distant compartments. See Appendix D for a complete description of the form of the thermal database.

6.7 Fire Specifications

The fire specifications allow the user to describe the fire source in the simulation. The location and position of the fire is specified along with the chemical properties of the fuel. Finally, the fire is described with a series of mass loss rate, fuel height, and fuel area inputs. All of these specifications are optional and each line requires a single number. The defaults for the fire specification is a methane burner in the center of compartment (1). The defaults shown for each key word reflect the values for methane.

Label	Parameter	Comments	Units
LFBO	**Room of Fire Origin**	Room of fire origin is the room number in which the fire originates. Default is 1.	
LFBT	**Fire Type**	This is a number indicating the type of fire. 1 Unconstrained fire 2 Constrained fire. The default is 1. See sections 4.5 and 5.5 for a discussion of the implications of this choice.	
LFPOS	**Fire Position**	The fire position is the area of the room in which the fire originates and is one of the following values: 1 Center of the room, 2 Corner of the room, or 3 Along a wall of the room, but not near a corner of the room. The fire position is used to account for the entrainment rate of the plume, which depends on the location of the fire plume within the compartment. Fire positions 2 and 3 should only be used when the fire is very close to the corner or wall respectively. The default is 1.	

CHEMI	(6)	Chemical kinetics and miscellaneous parameters.	
	Molar Weight	Molecular weight of the fuel vapor. This is the conversion factor from mass density to molecular density for "tuhc." Default is 16. It is used only for conversion to ppm, and has no effect on the model itself.	
	Relative Humidity	The initial relative humidity in the system. This is converted to kilograms of water per cubic meter from the table from "Dynamical and Physical Meteorology" by Haltiner and Martin (1957)	%
	Limiting Oxygen Index	The limit on the ratio of oxygen to other gases in the system below which a flame will not burn. This is applicable only to type (LFBT) 2 or later fires. The default is 10.	%
	Heat of Combustion	Heat of combustion of the fuel. Default is 50000000.	J/kg
	Initial Fuel Temperature	Typically, the initial fuel temperature is the same as the ambient temperature as specified in the ambient conditions section.	K
	Gaseous Ignition Temperature	Minimum temperature for ignition of the fuel as it flows from a compartment through a vent into another compartment. The default is the initial fuel temperature.	K

LFMAX	**Number of Intervals**	This is the number of time intervals for the mass loss rate, fuel height and species inputs. The mass loss rate, fuel height and species are entered as series of points with respect to time. This is referred to in this document as a specified fire. A sufficient number of intervals should be selected to provide a reasonable approximation (using straight line segments) for the input variables which specify the fire. A example of this is shown in figure 6. The mass loss rates P_1-P_7 are specified over the time intervals I_1-I_6. The number of points specified must be one greater than the number of time intervals. For example, if there are six mass loss points there should be a total of five time intervals (or one interval between every two consecutive points). The maximum number of intervals allowed in version 18 of FAST is 21.	
FTIME	**Time Interval (LFMAX)**	Time interval is the time between each point (mass loss rate, fuel height and species) specified for the fire. The total duration of the fire is the sum of the time intervals. This time is independent of the simulation time which is specified for the TIMES label. If the simulation time is longer than the total duration of the fire, the final values specified for the fire (mass loss rate, fuel height, fuel area, and species) will be continued until the end of the simulation. The number of values on the line must equal the number of time intervals specified by LFMAX, above.	s
FMASS	**Mass Loss Rate (LFMAX+1)**	The rate at which fuel is pyrolyzed at times corresponding to each point of the specified fire.	kg/s
FHIGH	**Fuel Height (LFMAX+1)**	The height of the base of the flames above the floor of the room of fire origin for each point of the specified fire.	m
FQDOT	**Heat Release Rate (LFMAX+1)**	The heat release rate of the specified fire.	W

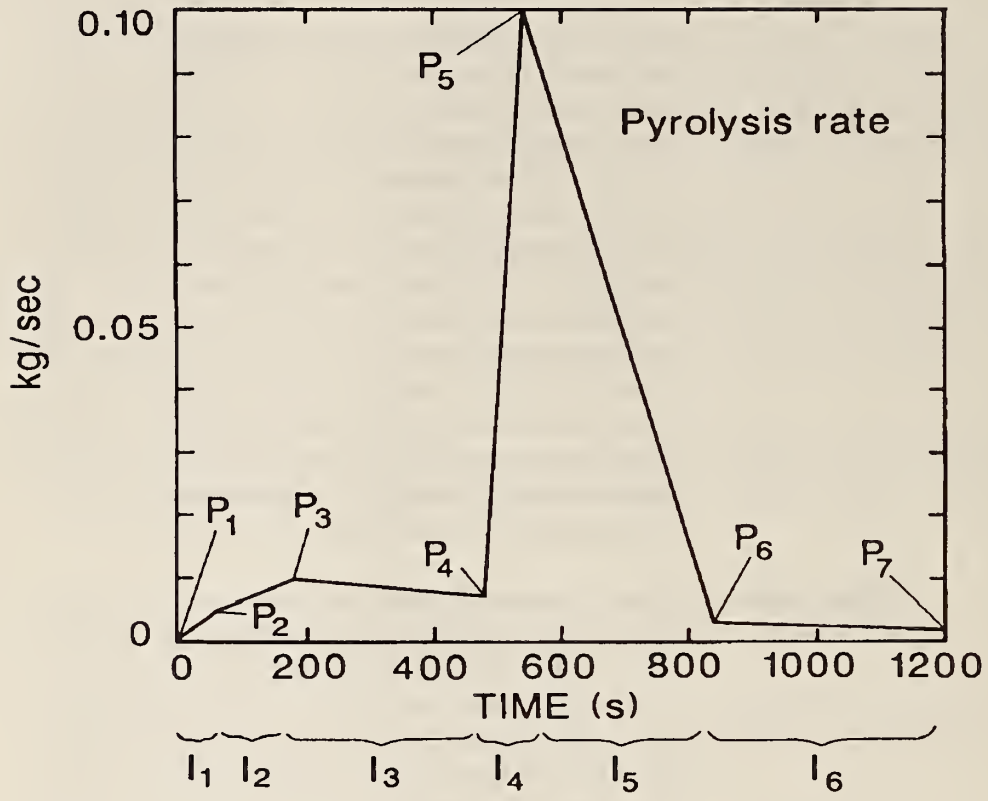


Figure 6. Pyrolysis rate for LFMAX=6.

With the three parameters, the heat of combustion (HOC) from CHEMI, FMASS and FQDOT, the pyrolysis and heat release rate are over specified. The model uses the last two of the three to obtain the third parameter. That is, if the three were specified in the order HOC, FMASS and FQDOT, then FQDOT would be divided by FMASS to obtain the HOC for each time interval. If the order were FMASS, FQDOT and HOC, then the pyrolysis rate would be determined by dividing the heat release rate by the heat of combustion. If only two of the three are given, then those two will determine the third, and finally, if none or only one of the parameters is present, the defaults shown will be used.

Example:

```
LFBO     1
LFBT     1
LFPOS    1
CHEMI    0.0  0.0 10.  18100000. 300.
LFMAX    7
FMASS  .014   .0014 .025   .045   .050   .0153 .0068 .0041
```

```
FAREA  .5    .5    .5    .5    .5    .5    .5    .5
FHIGH  .25   .25   .25   .25   .25   .25   .25   .25
FTIME      20.   20.   50.   50.  100.  100.  400.
```

In the example, a specified fire (LFBT 1) originates in room number 1 (LFBO 1) in the center of the room (LFPOS 1). A seven segment (LFMAX) fire is specified. The fuel burns with a heat of combustion of 18100000 J/kg. The initial relative humidity is 0%, the molecular weight is 16 (zero is not allowed, so the default is used) and the limiting oxygen index is 10%. Since the type of fire is 1, an unconstrained fire, this latter parameter has no meaning in this context.

```
LFBT     2
LFMAX    7
FMASS  .014  .0014 .025  .045  .050  .0153 .0068 .0041
FAREA  .5    .5    .5    .5    .5    .5    .5    .5
FHIGH  .25   .25   .25   .25   .25   .25   .25   .25
FTIME      20.   20.   50.   50.  100.  100.  400.
```

In this example, the specified fire is constrained with a limiting oxygen index of 1%. Since LFBO is not given, the default compartment (1) is used, and the position of the fire is in the center of the room. The default heat of combustion of 50000000 kJ/kg is used.

6.8 Species Production

Species production rates are specified in the manner similar to the fire, entering the rates as a series of points with respect to time. The species which are followed by FAST are

- Carbon Dioxide
- Carbon Monoxide
- Concentration-Time Product
- Hydrogen Cyanide
- Hydrogen Chloride
- Nitrogen
- Oxygen
- Soot (Smoke Density)
- Total Unburned Hydrocarbons
- Water

For a type one (LFBT=1) fire, only the concentration-time product of pyrolysate(ct), hydrogen cyanide(hcn) and hydrogen chloride(hcl) can be specified. No other species are followed. For a type two (LFBT=2) fire, nitrogen, oxygen, carbon dioxide, carbon monoxide, soot, unburned fuel and water are followed. In all cases, the unit of the production rates is

kg/kg. However, the meaning of the production rates is different for the several types of species. For either fire, the production rates for ct, hcn and hcl are with respect to the pyrolysis rate of the fuel. For the others, carbon monoxide, water, etc., the production rate is specified with respect to the basic carbon production in the form of a ratio with carbon dioxide. For carbon monoxide, for example, the specification will be CO/CO_2. Thus we can not consider a pure hydrogen flame, but this is unlikely in the situations of interest.

Label	Parameter	Comments	Units
SPECIES	(LFMAX+1)	For each species desired a series of production rates are specified for each of the time points input for the specified fire. The program performs a linear interpolation between these points to determine the time of interest.	
HCN, HCL and CT	Production Rate	Units are kilogram of species produced per kilogram of fuel burned. The input for CT is the kilograms of "toxic" combustion products produced per kilogram of fuel burned.	kg/kg
HCR	Production Rate of the Fuel	The mass ratio of hydrogen to carbon as it becomes available from the fuel. This parameter affects primarily the rate of production of water.	kg/kg
OD	Yield	The ratio of the mass of carbon to carbon dioxide produced by the oxidation of the fuel.	kg/kg
CO	Yield	The ratio of the mass of carbon monoxide to carbon dioxide produced by the oxidation of the fuel.	kg/kg

6.9 Files

There are several files which FAST uses to communicate with its environment. They are 1) a configuration file, 2) the thermal database, 3) a "dump" file, and 4) a restart file. The output of the simulation may be written to a disk file for further processing by programs such as FASTplot or to restart FAST. At each interval of time as specified by the dump interval in the TIMES label, the output is written to the file specified. For efficient disk storage and optimum speed, the data is stored in an internal format and cannot be read directly with a text editor.

Label	Parameter	Comments	Units
DUMPR	**Dump File**	The name specifies a file (up to 17 characters) to which the program outputs for plotting are written. **Dump file** is an optional input. If omitted, the file will not be generated. Note that in order to obtain a history of the variables, this parameter must be specified and also the dumper interval (under TIMES) must be set to a non-zero value.	
RESTR	**Restart File**	The name specifies a file (up to 17 characters) from which the program reads data to restart the model. This data must have been generated (written) previously with the dump parameter discussed earlier. A time step is given after the name of the file and specifies at what time the restart should occur.	
THRMF	**Thermal Database**	The name specifies a file (up to 20 characters) from which the program reads thermophysical data. If this parameter is not specified, then either the default (THERMAL.DAT) is used, for the name is read from the configuration file.	
DEFCG	**Configuration File**	The name specifies a file (up to 20 characters) from which the program reads configuration information data.	

Example:

```
DUMPR FAST1.DAT
RESTR filename n
THRMF thermal.tpf
```

where "filename" was created in a previous run using the DUMP parameter. "n" specifies the starting time and must be one of the times at which a dump was generated. As an example, if a data set were run with

```
VERSN   18 title...
TIMES   360 60 10 0 0


DUMPR   MYFILE
```

then every 10 seconds a snap shot of the time histories of all variables would be generated. So a restart might be done at 300 seconds with the following

```
VERSN   18 new title
TIMES   900 60 0 0 0


RESTRT  MYFILE 300
```

with no requirement that the restart must be at the last dump point. The only caveat is to check the listings to be sure that a dump was generated at the desired point. For those cases where too many dump intervals are requested, the interval is recalculated, and a message is written to the output device.

6.10 Graphics Specification

A graphics specification can be added to the data file. Details of the meaning of some of the parameters is best left to the discussion of the device independent graphics software used by FAST [2]. However, the information necessary to use it is straightforward. The general structure is similar to that used for the building and fire specification. One must tell the program "what to plot," "how it should appear," and "where to put it."

The key words for "where to put it" are

DEVICE	where to plot it
BAR	bar charts
GRAPH	specify an x-y plot
TABLE	put the data into a table
PALETTE	specify the legend for CAD views
VIEW	show a perspective picture of the structure
WINDOW	the size of the window in "user" space.

The complete key word is required. That is, for the "where to put it" terms, no abbreviations are allowed. Then one must specify the variables to be plotted. They are

VENT, HEAT, PRESSUR, WALL, TEMPERA, INTERFA,
H_2O, CO_2, CO, OD, O_2, TUHC, HCN, HCL, CT

As might be expected, these are the similar key words to those used in the plotting program, FASTplot. In this case, we have a reduced set. The application and use of FAST and FASTplot are different.

For each key word there are parameters to specify the location of the graph, the colors and finally titles as appropriate. For the variables, there is a corresponding pointer to the graph of interest.

The form of each "where to put it" variable is described below

Label	Parameter	Comments
DEVICE	**Plotting Device**	The **Plotting Device** specifies the hardware device where the graphics is to be displayed. For the PC version, this key word should be omitted. If it must be included for compatibility reasons, set it to 4. For other computers, it is installation dependent. In general it specifies which device will receive the output.
WINDOW	(6)	The window label specifies the **user space** for placement of graphs, views,...
	Xl	left hand side of the graph in any user desired units.
	Yb	bottom of the graph in any user desired units.
	Zf	forward edge of the 3D block in any user desired units.
	Xr	right hand side of the graph in any user desired units.
	Yt	top of the graph in any user desired units.
	Zb	rear edge of the 3D block in any user desired units. These definitions refer to the 3D plotting block that can be seen. The most common values (which are also the default) are Xl = 0. Yb = 0. Zf = 0. Xr = 1279. Yt = 1023. Zb = 10.

This is not a required parameter; however, it is often convenient to define graphs in terms of the units that are used. For example, if one wished to display a house in terms of a blueprint, the more natural units might be feet. In that case, the parameters might have the values

Xl = 0.
Yb = 0.
Zf = 0.
Xr = 50.
Yt = 25.
Zb = 30.

GRAPH (10)

Up to five graphs may be displayed at one time on the graphics display. Each graph is identified by a unique number (1-5) and placed in the window at a specified location. Xl,Yb,Zf,Xr,Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the graph.

Graph Number The number to identify the graph. Allowable values are from 1 to 5. The graphs must be numbered consecutively, although they do not have to be given in order. It is acceptable to define graph 4 before graph 2 but if graph 4 is to be used, then graphs 1 through 3 must also be defined.

Xl Left hand side of the graph within the window in the same units as that of the window.

Yb Bottom of the graph within the window in the same units as that of the window.

Zf Forward edge of the 3D (three dimensional) block within the window in the same units as that of the window.

Xr Right hand side of the graph within the window in the same units as that of the window.

	Yt	Top of the graph within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.
	Color	The color of the graph and labels which is specified as an integer from 1 to 15. Refer to DEVICE (NBSIR 85-3235) for the colors corresponding to the values for the color.
	Abscissa Title	Title for the abscissa (horizontal axis). To have blanks in the title, use the underscore character "_".
	Ordinate Title	Title for the ordinate (vertical axis). To have blanks in the title, use the underscore character "_".
TABLE	(7)	Up to five tables may be displayed at one time on the graphics display. Each table is identified by a unique number and placed in the window at a specified location. Xl,Yb,Zf,Xr,Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the table.
	Table Number	The table number is the number to identify the table. Allowable values are from 1 to 5. The tables must be numbered consecutively, although they do not have to be given in order. It is acceptable to define table 4 before table 2 but if table 4 is to be used, then tables 1 through 3 must also be defined.
	Xl	Left hand side of the table within the window in the same units as that of the window.
	Yb	Bottom of the table within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.

	Xr	Right hand side of the table within the window in the same units as that of the window.
	Yt	Top of the table within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.
VIEW	(24)	Up to five views may be displayed at one time on the graphics display. Each view is identified by a unique number and placed in the window at a specified location. Xl,Yb,Zf,Xr,Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the view.
	View Number	View number is the number to identify the view. Allowable values are from 1 to 5. The views must be numbered consecutively, although they do not have to be given in order. It is acceptable to define view 4 before view 2 but if view 4 is to be used, then views 1 through 3 must also be defined.
	Xl	Left hand side of the view within the window in the same units as that of the window.
	Yb	Bottom of the view within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.
	Xr	Right hand side of the view within the window in the same units as that of the window.
	Yt	Top of the view within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.

	File	**File** is the filename of a compatible "BUILD" file, as discussed later.
	Transform Matrix	The **Transform Matrix** is a 16 number matrix which allows dynamic positioning of the view within the window. The matrix (1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1) would show the image as it would appear in a display from BUILD.
PALETTE	(15)	The PALETTE label performs a specialized function for showing colors on the views. A four entry table is created and used for each type of filling polygon used in a view. Up to five palettes may be defined. Each palette is identified by a unique number and placed in the window at a specified location. Xl, Yb, Zf, Xr, Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the palette.
	Palette Number	Palette number is the number to identify the palette. Allowable values are from 1 to 5.
	Xl	Left hand side of the palette within the window in the same units as that of the window.
	Yb	Bottom of the palette within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.
	Xr	Right hand side of the palette within the window in the same units as that of the window.
	Yt	Top of the palette within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.

	Color and Label	There are four pairs of color/text combinations, each corresponding to an entry in the palette. The color number is an integer from 1 to 15 and the text can be up to 50 characters (but remember the 128 character maximum). As before, spaces are indicated with an underscore character "_".
BAR	(9)	Up to five bar charts may be displayed at one time on the graphics display. Each bar chart is identified by a unique number and placed in the window at a specified location. Xl,Yb,Zf,Xr,Yt and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the bar chart.
	Bar Chart Number	The number to identify the bar chart. Allowable values are from 1 to 5.
	Xl	Left hand side of the bar chart within the window in the same units as that of the window.
	Yb	Bottom of the bar chart within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.
	Xr	Right hand side of the bar chart within the window in the same units as that of the window.
	Yt	Top of the bar chart within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.
	Abscissa Title	Title for the abscissa (horizontal axis). To have blanks in the title, use the underscore character "_".

	Ordinate Title	Title for the ordinate (vertical axis). To have blanks in the title, use the underscore character "_".
LABEL	(10)	Up to five labels may be displayed at one time on the graphics display. Each label is identified by a unique number and placed in the window at a specified location. Xl, Yb, Zf, Xr, Yt, and Zb have a meaning similar to WINDOW. However, here they specify where in the window to put the label. It is assumed that time is always to be displayed if any labels are present. To this end, label 1 is always used for the time in the units HH:MM:SS.
	Label Number	Label number is the number to identify the label. Allowable values are from 1 to 5.
	Xl	Left hand side of the label within the window in the same units as that of the window.
	Yb	Bottom of the label within the window in the same units as that of the window.
	Zf	Forward edge of the 3D block within the window in the same units as that of the window.
	Xr	Right hand side of the label within the window in the same units as that of the window.
	Yt	Top of the label within the window in the same units as that of the window.
	Zb	Back edge of the 3D block within the window in the same units as that of the window.
	Text	The text to be displayed within the label. To have blanks in the title, use the underscore character "_".

Angle1, Angle2	Angles for display of the label in a right cylindrical coordinate space. At present only the first angle is used and represents a positive counterclockwise rotation; set the second angle to zero. Both angles are in radians.

In order to see the variables, they must be assigned to one of the above displays. This is accomplished with the variable pointers as

```
(Variable) (nmopq) (Compartment) (Layer).
            12345
```

Variable is one of the available variables VENT, HEAT, PRESSUR, WALL, TEMPERA, INTERFA, N_2, O_2, CO_2, CO, HCN, HCL, TUHC, H_2O, OD, CT used as a label for the line. The species listed correspond to the variable "SPECIES" in FASTplot. In the variable list of FAST, all are contained in the variable TOXICT. **(nmopqr)** is a vector which points to

index	display in
(1)	n -> bar chart
(2)	m -> table
(3)	o -> view
(4)	p -> label
(5)	q -> graph

respectively. These numbers vary from 1 to 5 and correspond to the value of "n" in the "where to put it" specification. **Compartment** is the compartment number of the variable and **Layer** is "U" or "L" for upper and lower layer, respectively.

Examples:

```
WINDOW     0   0 -100  1280  1024   1100
GRAPH 1  250. 170.  0. 1220. 900.   10.  5 TIME  CELSIUS
LABEL 1  970. 960.  0. 1231. 1005.  10. 15 00:00:00                  0.  0.
LABEL 2  690. 960.  0.  987. 1005.  10. 13 TIME_[S]                  0.  0.
LABEL 3  90.  920.  0.  730. 1020.  10. 4 Single_Compartment_demo   0.  0.
LABEL 4  400. 610.  0.  687. 660.   10. 1 U_layer_temperature      .1   0.
LABEL 5  400. 270.  0.  687. 320.   10. 1 1_layer_temperature      .0   0.
TEMPERA 0 0 0 0 1   1 U
TEMPERA 0 0 0 0 1   1 L
```

In this case, a new window is defined, along with one graph and five labels. Both temperature variables are assigned to graph 1. One quirk is not obvious. It is assumed that time is always to be displayed if any labels are present. To this end, label 1 is always used for the time in

the units HH:MM:SS. Graph 1 has the label "TIME" on the abscissa and "CELSIUS" on the ordinate.

```
WINDOW       0     0  -100  1280  1024   1100
GRAPH   1  120.  300.    0.  600.  920.   10.  3 TIME  PPM
GRAPH   2  740.  300.    0.  1220. 920.   10.  3 TIME  CELSIUS
LABEL   1  970.  960.    0. 1231. 1005.   10. 15 00:00:00        0.      0.
LABEL   2  690.  960.    0.  987. 1005.   10. 13 TIME_[S]        0.      0.
LABEL   3  200.  050.    0.  520.  125.   10.   14 CO¦D2¦O_CONCENTRATION 0. 0.
CO      0 0 0 0 1   1 U
TEMPERA 0 0 0 0 2   1 U
TEMPERA 0 0 0 0 2   1 L
```

This file sets up two graphs with the CO data from the upper layer of compartment (1) in the first graph and both the upper and lower layer temperatures displayed on the second graph.

```
WINDOW       0     0  -100  1280  1024   1100
GRAPH   1  150.  300.    0.  620.  920.   10.  3 TIME  PPM
LABEL   1  390.  960.    0.  651. 1005.   10. 15 00:00:00        0.      0.
LABEL   2  110.  960.    0.  407. 1005.   10. 13 TIME_[S]        0.      0.
LABEL   3  200.  050.    0.  520.  125.   10.   14 O¦D2¦O_CONCENTRATION 0. 0.
TABLE   1  700.  300.    0. 1200.  920.   10.
HEAT    0 1 0 0 0   1 U
O2      0 1 0 0 1   1 U
TEMPERA 0 1 0 0 0   1 U
TEMPERA 0 1 0 0 0   1 L
```

Here the four variables HEAT, O2, and TEMPERATURE are displayed in table 1 and O2 is shown in graph 1.

```
WINDOW       0     0  -100  1280  1024   1100
VIEW    1  800.  390.  150. 1200.  900.  200. DEMOFA.DAT 1.41 .48 1.33 0....
VIEW  2  420.  200.   50.  720.  500.  100. DEMOFA.DAT 1.53 -.46 1.21 0. ...
GRAPH   1   50.  290.    0.  300.  490.   10. 13 TIME  PPM
GRAPH   2  150.  650.    0.  500.  850.   10. 13 TIME  m¦U-1
GRAPH   3  510.  690.    0.  740.  890.   10. 13 TIME  CELSIUS
GRAPH   4  810.  120.    0. 1160.  320.   10. 13 TIME  HEIGHT
LABEL   1  760.  960.    0. 1021. 1005.   10. 14 00:00:00        0.      0.
LABEL   2   50.   10.    0.  250.   70.   10.  2 TEST_IN_ONE_ROOM   0.57079 0.
LABEL   3   70.  960.    0.  367. 1005.   10. 13 FIRE_[W]        0.      0.
LABEL   4  480.  960.    0.  777. 1005.   10. 13 TIME_[S]        0.      0.
LABEL   5  300.  960.    0.  475. 1005.   10. 14 _______         0.      0.
TABLE   1  220.   50.    0.  520.  250.   10.
HEAT    0 0 0 5 0   1 U
OD      0 1 1 0 0   1 U
OD      0 0 2 0 2   1 U
CO      0 1 1 0 1   1 U
CO      0 0 2 0 0   1 U
TEMPERA 0 1 1 0 3   1 U
TEMPERA 0 0 2 0 0   1 U
INTERFA 0 1 1 0 4   1 U
INTERFA 0 0 2 0 0   1 U
```

Two views are specified, both emanating from the file "demofa.dat" with different transforms. Four graphs, three labels and one table will be displayed. All variables will be taken from the

upper layer in compartment (1), and they will go to both views, in determining the hazard calculation. The variables will also be shown in table 1 and in the four graphs, respectively.

7. FASTplot

The FAST model predicts the environment produced by a fire in one of several compartments, or rooms, and follows smoke and toxic gases from one compartment to another, separately predicting values for each of the variables in both the upper and lower layers. The results for "FAST" are written to a special data file (the "dump" file) after each prescribed time step. FASTplot is intended to provide a post processing visual interface to generate graphs and tables from the time histories saved by the model. FASTplot has the capability to form a list of variables, read in their values at each time interval, list the values in tabular form, plot the values, and save the variables in a formatted file for use with other software. In addition, it has the capability to read dump files created by other programs to plot along with FAST data.

For the FAST dump files, the variables currently available are

boundary surface temperature (ceiling, floor)	WALL	°C
entrained mass flow in the plume	ENTRAIN	kg/s
hcl wall surface concentration	HCL	kg/m^2
heat release in lower layer	LPLUME	kW
heat release in upper layer	UPLUME	kW
heat release in flame out a vent	VFIRE	kW
heat release rate of the fire	HEAT RELEASE	kW
layer height	INTERFACE	m
layer temperature	TEMPERATURE	°C
mass flux from the plume into the upper layer	PLUME	kg/s
pyrolysis rate of the fuel	PYROLYSIS	kg/s
pressure	PRESSURE	Pa
radiation field to a target	TARGET	W/m^2
species density[5]	SPECIES	%,ppm
total radiative heat flux into the layer	RADIATION	W
total convective heat flux into the layer	CONVECTION	W
vent flow	VENT	kg/s
vent entrainment	JET	kg/s
volume of the upper layer	VOLUME	m^3

The command for starting the program is simply FASTPLOT. After identifying information, a "command prompt" appears and commands to direct the generation of the tables and graphs may be entered.

[5] For nitrogen, oxygen, carbon dioxide, fuel (tuhc) and water, the units are percent. For carbon monoxide and hydrogen cyanide, the units are parts per million. For optical depth the unit is inverse meters, and CT is gram-minutes per cubic meter.

Commands available at the "command prompt" are

ADD	LIST
ASCII	PLOT
AGAIN	RAPID
CLEAR	READ
DEFAULT	REVIEW
DELETE	SAVE
END	SHIFT
HELP	TENAB
FILE	VARIABLE

These commands can be broken into five major groups that describe the process used to generate tabular or graphical output with FASTplot. The following is a description of each of the commands. At least three characters must be used to identify a command.

7.1 Entering Data Into FASTplot

FASTplot can currently read three types of data files:

- data created by the FAST model (FAST dump files),
- data created by the TENAB model[6] (TENAB dump files), and
- data created in specially formatted ASCII text files from other programs including RAPID, a program developed by CFR for analysis of large-scale fire tests.

Several commands are available within FASTplot to read these data files. They are FILE, AGAIN, and ADD (for FAST files), ASCII and RAPID (for ASCII text files), and TENAB (for TENAB files). In addition, several commands provide ancillary functions to support data entry.

[6] Hazard I Technical Reference Guide, NIST Handbook.

7.1.1 Commands for Reading Data

ADD

This command is used to build a list of FAST variables to be read into the active list. When an option is requested, ADD may be entered by itself or together with a list of variables that are to be added. If it is entered alone, there will be a request for the variables that are to be added to the list. For example:

```
> ADD
- INPUT VARIABLES TO BE ADDED>
        or
> ADD TEMP,PRES,.....
```

For each variable selected there is a series of questions that will be asked to identify the type of that variable wanted. A question asked about all variables is:

```
WHICH COMPARTMENT? ->
```

For layer dependent variables, the user is asked to input the layer (U for upper or L for lower):

```
WHICH LAYER? ->
```

If VENTFLOW is chosen the compartment origin and destination will be requested as will the vent number; if SPECIES is selected the species name (O_2, CO_2,...) will be requested.

The maximum number of variables allowed in the active list at any one time is 20. If the list is full or the variable is presently in the active list the addition will be disallowed and another option requested.

ASCII

Read a file in columnar ASCII format. The next query will be for the columns to read. In order for this to work, there must be a column which corresponds to the default column as selected the "DEFAULT" command. Normally this will be time, but can be any other column as desired.

FILE

The FILE command allows the user to specify the FAST dump file name for subsequent ADD commands. FILE applies only to FAST dump files.

RAPID — Read a file in the RAPID format. The next query will be for the channels to read. In order for this to work, there must be a channel which corresponds to the default channel as selected the "DEFAULT" command. Normally this will be the time channel, but can be any other channel as desired.

TENAB — Read a file in the TENAB format. The TENAB program produces estimates for a number of tenability criteria for persons exposed to a fire environment predicted by the FAST model. The user must enter the "person number" and the desired criteria to be read from the file. The possibilities are:

Tenab Variable List
1. Fractional Effective Dose Due to Gases - Bukowski
2. Fractional Effective Dose Due to Gases - Purser
3. Fractional Effective Dose Due to CO2 - Purser
4. Temperature - Deg C
5. Fractional Effective Dose Due to Convective Heat
6. CT (G-MIN/M3)
7. Flux (KW-MIN/M2)
8. Derksen Curve

7.1.2 Support Commands for Data Entry

The AGAIN, CLEAR, DELETE, READ, and REVIEW commands allow the user to view and manipulate the list of variables read with the data entry commands.

AGAIN — This will repeat the input of a list of variables for a new file. The program maintains a list of the most recently acquired FAST variables. First, get a file with "FILE," then get a set of variables. Once again using "FILE," get a new file and then use AGAIN to get the same list of variables on this new file. This function simplifies direct comparisons between runs of FAST.

CLEAR — This command empties the current variable list.

DELETE — When this option is entered the present list of variables will be printed to the screen and the user will be asked to input the variables to delete by the number associated with them on the list. They must be entered on a single line separated by commas or blanks. If the variable number that is input does not correspond to one that is currently on the list it will be skipped. After the deletions have been processed a new list is presented and another option requested. If the list is presently empty then that fact will be stated in an error message. One caution is in order. The variables are deleted by the number in the list, rather then by rank ordering within a group. This is important in conjunction with use of the AGAIN command.

READ — READ is used to force a read of the data files. This is most useful for script files which can be processed automatically to display data. It is equivalent to pressing an <enter> at the "read prompt" in the interactive mode.

REVIEW — At times the user may wish to see what is presently on his list before entering a command. This may be done with the REVIEW command. It will print out the current list along with the compartment number, species, and layer of each of the variables. After the printing of the entire list, the option request is again displayed.

7.2 Generating Tables and Graphs With FASTplot

The commands LIST and PLOT allow the user to generate a table of values of selected variables or a graph of selected variables. The SHIFT command allows the user to shift the abscissa or ordinate axis of a variable.

LIST — List the values of any of the variables on the list to the screen. The variables to be listed and the time range of the list is entered. On PC versions, the list can be printed with the PRINT SCREEN key once it appears on the screen,.

PLOT — After entering the PLOT command, the current list of variables will be displayed along with their numbers. They should be entered in a string separated by commas or blank spaces. For example:

```
ENTER VARIABLES TO BE PLOTTED ->1,2,3,4
            or
ENTER VARIABLE TO BE PLOTTED ->1 2 3 4
```

Variables to be plotted together on a single graph are grouped in parenthesis. For example:

```
ENTER VARIABLES TO BE PLOTTED -> (1,2,3,4)
```

Normally, the program will scale the axes automatically. However, if the automatic formatting option has been turned off, then before the graph is drawn, the user is given the opportunity to change the range of the X and Y axes and the graph legends. The maximum and minimum value of the X and Y axes will be displayed, followed by a request for a change in each. If no change is desired simply enter an <enter> and the next axis change will be displayed:

```
 The Min/Max for Temperature  are

   X =        0.00 TO    2000.00
   Y =        0.00 TO    1000.00

 <enter> If no changes are desired.

   Xmin =       0.00, Change to =
   Xmax =    2000.00, Change to =
   Ymin =       0.00, Change to =
   Ymax =    1000.00, Change to =
```

Similar prompts are made for the legends for each graph. The user is allowed to change the text for each curve label and the position. If no changes are desired, the <enter> key may be pressed to accept the suggested values for the legend text and position:

```
Legend for  1 (Temperature  1 U  ) is |R 1 U|. :
<enter> For no change:
Legend for  2 (Temperature  2 U  ) is |R 2 U|. :
<enter> For no change:

Legend for graph 1 is at X=  40.00, Y= 945.49
<enter> If no changes are desired.
      X =      40.00, Change to =
      Y =     945.49, Change to =
```

When all the changes (if any) have been made the graph of that particular variable will be plotted. After the graph has been completed the option request will be displayed and a new option may be entered.

SHIFT

SHIFT is used to adjust the variable axes. The required input is a selection of the axis to shift, the amount of shift, and a list of channels. Please note that shifting the time axis for a single variable will shift the time axis for all variables associated with that particular file. Such an effect occurs because only one vector of values is kept for the time line for each file.

7.3 Saving Data With FASTplot

The save command allows the user to create an ASCII text file in one of two formats. These files may be used for future FASTplot runs or for exporting FAST or TENAB data to other programs.

SAVE

A command to save the values of the variables in the list into a file. The format used will depend on the option chosen in "DEFAULT," columnar data for spreadsheet and charting programs, or row data for making the data directly compatible with our data processing program (RAPID) designed for the reduction of experimental data in the Center for Fire Research.

The user will be asked for the name to be used for the file. A check will be made to see whether that file presently exists or not. If it does, the user will be asked if he wants to write over the old file with this new data. If his answer is NO, nothing will be placed in the file and other option requested. If, however, he does want the file rewritten, or the file does not already exist, the new file will be created and the data stored in it.

Columnar data is straightforward, with each variable listed. The time channel will be the first column. For files in the row format, each variable in the list will be saved with the following line at the beginning of each block of data:

```
I6,I6,A6,*----------COMMENT----------
```

The first I6 will be for the number of data points for that variable, the next I6 is for the number given to that variable on the list, and the A6 is the actual variable name. Everything after the * is a comment block and will be filled with information relevant to that particular variable, such as species number, compartment number, layer, etc. The actual numerical data will be written using the format 7E11.5.

7.4 Changing the Default Parameters in FASTplot

The DEFAULTs command allows the user to change a number of default parameters within FASTplot. These defaults specify the format of the graphical output and assumed values for some of the input parameters (ones where the user may simply press the <enter> key).

DEFAULT

This enables the user to set default parameters for the following, with the system default show to the right in parenthesis:

COMPARTMENT NUMBER	(1)
VENTFLOW DESTINATION	(2)
LAYER (U)	
CHARACTER SET	(4)
OUTPUT (not appropriate for PC versions)	
GRAPHICS DEVICE (" ") - will be implemented in the future	
AUTO SCALING	(Y)
CHANNEL FOR ABSCISSA	(999)
FACTOR FOR ABSCISSA	(1)

The purpose of this option is to change the defaults available for other commands and data input. Output and Graphics Device should not be reset on the PC versions. Channel for abscissa refers to the RAPID data reduction program, NBS Special Publication 722 (1986). Factor for abscissa refers to the column used when reading ASCII data files.

7.5 Getting Online Help in FASTplot

The HELP and VARIABLES command provides some simple online help for using FASTplot.

HELP — This command may be entered at any time that the user is asked for an option. Its purpose is to list to the screen, the available commands and a brief explanation, after which another option will be asked for.

VARIABLES — Show the list of variables which are available. This list is identical to the one shown at the beginning of section 7.

7.6 Exiting FASTplot

The END command terminates the execution of FASTplot. If desired, any data which has been read into FASTplot should be saved prior to entering this command. Any data not saved will be lost upon exiting the program and must be reentered if it is to be used again.

8. FAST_in

FAST_in is an interactive interface (front end) for the FAST model. As such, it is designed to guide a user through the creation and modification of a data file which can be used in running the model. FAST_in is not a general purpose fire growth and smoke transport model, although it does have limited capability for doing calculations and estimates. Rather, it is a text oriented editor used to create FAST data files while FAST is a general purpose model with graphics display. While some of the more intricate inputs available with the FAST model are not available from within FAST_in, basic data files can be created with FAST_in and further edited with any general purpose text editor.

The user interface is organized into a series of screens, each of which addresses a general area of the process of modeling a fire. General and key word help is always available except within the key word help section itself. The top of the screen shows which section is active. These names are shown below and are roughly descriptive of the area which is covered. These correspond to sections in the data file discussed in section 5. The bottom of the screen shows what special keys are active, or indicates what action is expected. If data can be entered, then the range and units will be shown if appropriate. For example, room width will be in units of length, whereas a title has no dimensions.

The "screens" are

0	Initialization	only at the beginning
1	Overview	primary sections
2	Ambient Conditions	
3	Geometry	
4	Thermal Properties	
5	Thermal Database	
6	Fire Specification	
7	Calculations,...	
8	Results	show results of calculation
9	Information and Settings	show the current version numbers and make permanent changes in the colors ans units

Note that the Initialization screen (screen 0) and the output screens (screens 7-9) do not correspond to sections of the data file. Rather, they are used to retrieve and save the data

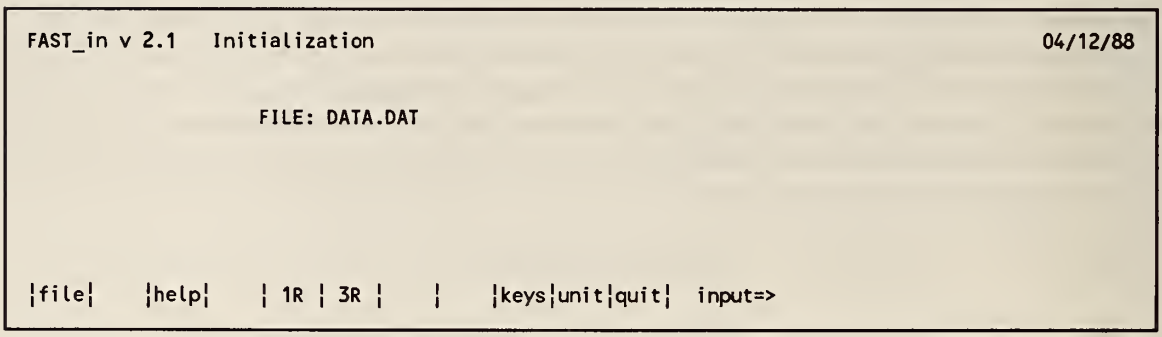
file created with FAST_in or to run the model with the current data set. Refer to section 6 for the details of the data entered on each screen.

1. Overview	Title and time specifications from section 6.1 and 6.2
2. Ambient Conditions	Ambient conditions from section 6.3
3. Geometry	Floor plan data and connections from sections 6.4 and 6.5
4. Thermal Properties	Thermophysical properties of enclosing
5. Thermal Database	surfaces from section 6.6
6. Fire Specification	Fire specifications from sections 6.7 and 6.8

In general, the program requests either data from the keyboard, or selection information from the function keys (or mouse if present). Any active function keys will be shown at the bottom of the screen. If the meaning is not clear, the **show keys** function key, **f9**, will give further explanation. Otherwise, there will be directions as to what further actions are possible. If alphanumeric input (data) is being requested, the entry must always be completed by pressing the **<enter>** key. For function keys, only a single keystroke is required. Some of the function keys are active throughout FAST_in; others are specific to certain screens. Those specific to individual screens are described in more detail on the following pages. Those active throughout the program are presented below.

key	key label	function
f1	go to page	Allows you to move directly from one screen to another within FAST_in. From any screen, pressing **<f1>** brings up a menu listing all the screens in FAST_in. Using the mouse or the arrow keys, select the screen of interest and press **<enter>** or the left mouse button.
f2	return	Allows you to move directly from the current screen to the previous screen within FAST_in. As an example, if you are on the thermal properties screen and press **<Page Down>** to move to the thermal database screen, pressing **<f2>** will return you to the thermal properties screen. Pressing **<f2>** again will take you again to the thermal database screen. This switching may be continued as long as desired.
f3	help	You may press the HELP key, **f3**, at any time to receive context sensitive help describing the current screen or current quantity being entered. Pressing **<f3>** a second time brings up a list of keywords for which more detailed help is available.
f8	change units	You may temporarily change the working engineering units displayed by FAST_in and used for data entry at any time by pressing **<f8>** and selecting the quantity to be changed with the

		up and down arrow keys. Pressing the right or left arrow keys changes the working units of the currently selected quantity. To change the units permanently, you must modify the installation parameters.
f9	show keys	provides a brief description of the function keys currently active and can be used to provide a quick reference of the current function of each of the keys.
f10	quit	is used to end the program.



On the Initialization screen, the FAST input file to be edited with FAST_in is selected. The name of any DOS file may be entered by typing in the name of the file or the user may press the select file key, f1, to see a list of files in the current working directory. By default, all files with an extension of `.DAT` are presented in the list. If desired, one may type a file matching pattern (such as `*.*` to see all files in the subdirectory) before pressing **<f1>**.

In addition to showing the name of the current screen, "Initializtion" in this case, the name of the module, its version number and the current date are shown. The latter two can change, as the program is enhanced, and when it run on dates different than shown in the figure.

If a completely new data file is to be created, two generic data sets are built into the program. Key **<f5>** may be pressed to use a single room case and key **<f6>** may be pressed to use a three room case.

```
FAST_in v 2.1 Overview                                              04/12/88

File: DATA.DAT      Title:    demo #1 a single compartment

Geometry                      Time              AmbientConditions
_________                     _________         _________________
Compartments        1   Simulation     180      Temperature    26.9
    Vents...        1        Print       0         Pressure 1.0E+05
HVAC connect        0         Dump       5      Station elv.     0.0
                             Display     5       Wind speed      0.0
                                                Scale height    10.0
                                                   Power law  0.1600
Fire Specification
_________
              Type Specified fire(constrained)
   Species tracked    O2  CO2   CO TUHC  H2O   OD   CT



Range: Alphanumeric ( 50)     Units: Name or Title
|goto|rtrn|help|    |    |    |    |unit|keys|quit|  input=> single compartment
```

The Overview screen presents a summary of the FAST data file. The title, simulation time, print interval, dump interval, and display interval may be changed on the screen. See sections 5.1 and 5.2 for detailed information on the parameters. All other information presented is changed on other screens of the program and is included here (in the "protected text" color) to provide a summary of the data set.

```
FAST_in v 2.1 Ambient conditions                                    04/12/88

             (internal)  (external)

   Temperature    26.9        26.9
      Pressure 1.0E+05     1.0E+05
  Station elv.     0.0         0.0

    Wind speed                 0.0
  Scale height                10.0
     Power law               0.1600

  Compartments       1      Maximum pressure differential      0.0
      Vents...       1           Maximum elevation change      2.30
  HVAC connect       0              Total internal volume      32.6



Range:    -73.1 to     76.9   Units: Temperature in CELSIUS
|goto|rtrn|help|    |    |    |    |unit|keys|quit|  input=>
```

On the Ambient Conditions screen, the internal and external ambient temperature, pressure, and station elevation along with information on external wind may be changed. Ambient conditions are detailed in section 5.3. The wind speed, scale height, and power law are used to calculate the wind coefficient for each vent connected to the outside. The wind velocity is specified at some reference height. The power law then provides a lapse rate for the wind speed. An assumption is that the wind velocity vanishes at the surface. The formula used to calculate the wind speed at the height of any vent is (wind speed) · ((vent height)/(scale height))$^{(\text{power law})}$. The wind is applied to each external opening as a change in pressure outside of the vent. It is further modified by the wind coefficient used for the openings.

```
FAST_in v 2.1 Geometry                                                    04/12/88

          Dimensions

 Compartment Number:        1
             Width:     3.30
             Depth:     4.30
            Height:     2.30
    Floor elevation:     0.0

        Vents(doors...)

      with respect to first room      wrt second room    - absolute -
  #  width   sill  soffit  wind     #   sill  soffit    a_sil  a_sof Vent(1->4)
  1   1.07    0.0    2.0    0.0     2    0.0    2.0      0.0    2.0      1




Range:      0.0 to    150.0   Units: Distance in METER
|goto|rtrn|help|ADD |DEL |O/C |SWPG|unit|keys|quit|  input=>
```

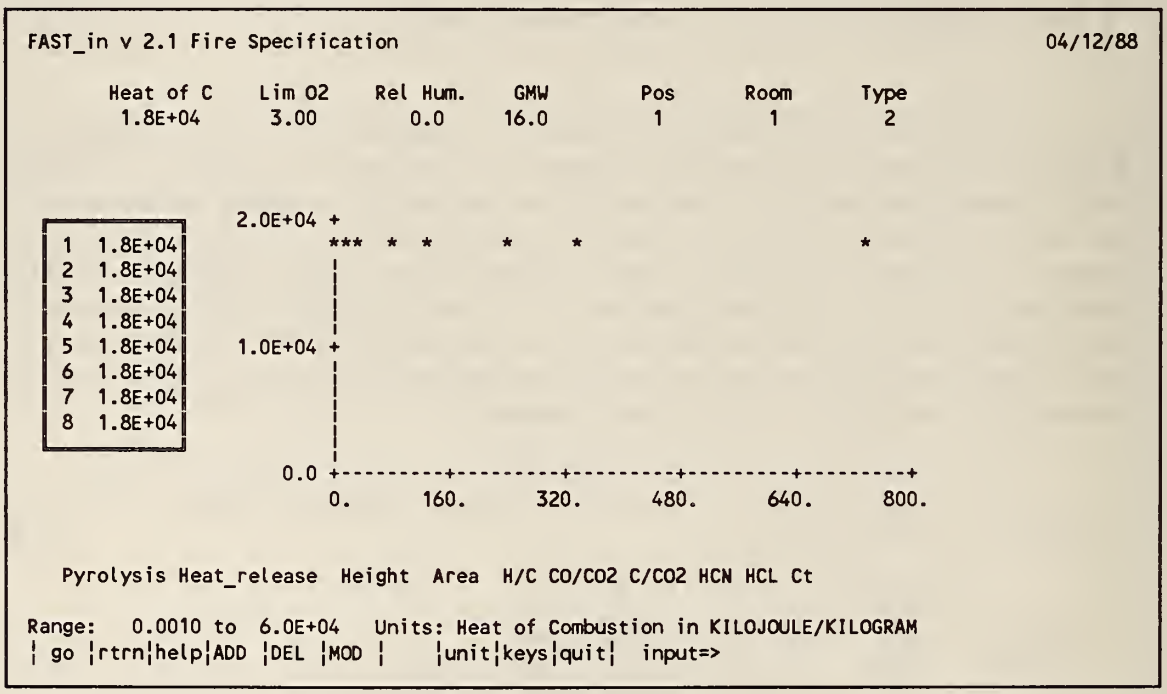
On the Geometry screen, information on the sizes of all of the rooms and vents are entered. Sections 5.4 and 5.5 provide details. The screen is divided into an upper and lower "page," one for the room dimensions and one for the vent information. The SWITCH PAGE key, f7, toggles between the two pages. A room or vent may be added or deleted using the ADD key, f4 or the DELETE key, f5. The OPEN/CLOSE key, f6, allows specification of vent position over the course of the fire as detailed by the CVENT parameter in FAST.

```
FAST_in v 2.1 Thermal properties                                    04/12/88

 Compartment Number       1

 Ceiling properties:      OFF
   Floor properties:      OFF
    Wall properties:      OFF




Range: Alphanumeric ( 8)     Units: Name or Title
| go |rtrn|help|ADD |DEL |    |    |unit|keys|quit|  input=>
```

The Thermal Properties screen details the materials used for the ceilings, walls, and floors of all of the rooms as detailed in section 5.6. The name of a material contained in the FAST Thermal Database may be entered by first positioning the highlighted selection bar over the entry of interest and typing the material name exactly as it appears in the FAST thermal database. To make the process easier, a material name may be selected on the Thermal Database screen below, and designated for the currently selected surface by pressing the ADD PICKED key, f4. To specify an adiabatic surface, press the DELETE key, f5, to turn OFF the heat transfer calculation for that surface. If the word NONE appears, it means that the name entered does not appear in the Thermal Database.

```
FAST_in v 2.1 Thermal Database                                      04/12/88

           Conduct Specifi Density Thickne Emissiv     * CODES *
DFIR30      0.0002  0.9000   790.0  0.0160  0.9000
PINEWOOD    0.0001    2.50   540.0  0.0160  0.8000
CONCRETE    0.0018    1.00  2200.0  0.1500  0.9400
REDOAK      0.0002    1.30   640.0  0.0160  0.9000
FIBER          0.0    1.25   240.0  0.0160  0.9000
GYPSUM      0.0002  0.9000   800.0  0.0160  0.9000
WOOD           0.0    1.00   250.0  0.0160  0.9800
DFIR0       0.0001    1.40   510.0  0.0127    1.00
DFIR10      0.0002    1.50   560.0  0.0160  0.9000
GLASS       0.0014  0.7600  2500.0  0.0160  0.9500
GLASFIBR       0.0  0.7200    32.0  0.0160  0.9000
KAOWOOL     0.0002    1.05   128.0  0.1160  0.9700
GYP1        0.0001  0.9000   800.0  0.0250  0.9000
GYP2        0.0001  0.9000   800.0  0.0500  0.9000
BRICK1      0.0002  0.9000   790.0  0.0160  0.9000
WB          0.0001    1.17  4050.0  0.0250  0.8000


Range:      0.0 to   0.0900   Units: Conductivity in KILOJOULE/SECOND/METER/CELS
| go |rtrn|help|ADD |DEL |PICK|    |unit|keys|quit|  input=>
```

The contents of the FAST thermal database may be examined or changed on the Thermal Database screen. A new material may be added by pressing the ADD key, **f4**, or an existing one deleted by pressing the DELETE key, **f5**. A material can be chosen (and later added in the Thermal Properties screen) by positioning the highlighted selection bar over the material and pressing the PICK MATERIAL key, **f6**. The thermophysical data file can not be changed (saved after editing) by FAST_in, although it will shown as changed on the "save files" screen if changes have been made at this point.



All data pertaining to the combustion properties are entered on this screen. The heat of combustion, mass loss rate, and species yields are entered, along with selection of the fire room and fire type as described in the data file format section. Note that fire chemistry is only allowed for constrained (type 2) fires.

A species may be added or deleted from the calculation using the ADD key (**f4**) or the DELETE key, f5. The time intervals may be modified by pressing the MODIFY TIME key, **f6**.

```
FAST_in v 2.1 Calculate,...                                          04/12/88

     run this data set          <f4> time       0  maximum     180 (seconds)

     quick estimates            <f5> asks for a time interval

     run time graphics (FAST)   <f6> no

     save data file(s)          <f7>

     write to log file          <f8> no




| go |rtrn|help|    |    |    |    |    |    |quit|
```

Once data for a test case has been entered or modified using FAST_in, you may run the data set using a version of the FAST model, or save the data to disk to run with the complete version of FAST. To run the model, press **<f4>**. To save the data to a disk file, press **<f7>**. You may also append a simple graphics descriptor to the FAST data file by pressing **<f6>**. The resulting display will show selected variables in a simple X-Y plot on the screen as the model calculates the results. If problems are encountered with FAST_in, you can document the problem by generating a log file with the **<f8>** function key and repeating the sequence of commands which generates the problem.

```
FAST_in v 2.1 Results - temp..                                          04/12/88

              Time:      0.0

 Compartment Number:       1

   Upper layer temp:     26.9
   Lower layer temp:     26.9
       Upper volume:   0.0326
        Layer depth:   0.0023
      Ceiling temp:     26.9
    Upper wall temp:     26.9
         Floor temp:     26.9
     Plume flow rate:      0.0
      Pyrolysis rate:      0.0
           Fire size:      0.0
           Vent fire:      0.0     0.0
            Pressure:      0.0



                              Units: Temperature in CELSIUS
| go |rtrn|help| FF |    |    |    |unit|keys|quit|
```

When the installation program is run, the default units are set. However, during a run of FAST_in, it is possible to change the units, for that session. The key to set units is <f8> when it is shown as active. This will allow a change for the current session. To change the units permanently, rerun the installation program. The screen for the units section looks like

```
FAST_in v 2.1 Set Units                                                 04/20/89

  Base Unit      Current Units  Possible Units

  Temperature    KELVIN         KELVIN      CELSIUS     RANKINE     FAHRENHEIT

  Pressure       PASCAL
  Length         METER
  Energy         JOULE
  Mass           KILOGRAM
  Time           SECOND
  Time           SECOND

   To change units, highlight the basic unit to be changed, then point to the
   unit desired.  Pointing is done either with the cursor keys or the mouse.

<esc> to exit,  <f3> for help
```

The time scale for most phenomena is set with the first entry. This refers to rates such as mass per unit time. The second is to accommodate English units in a natural way. In these units, conductivity is in BTU/hour/... as opposed to Joules/second/... In most cases, they will be set to the same unit, but if the "English" option is used, then they will be different. Of course, they can be set to different values manually.

For the most part, the remaining screens follow the same type of format. When the function keys are active, one can move through the "screens" with the "go" command, or by using **<PgUp>** and **<PgDn>**. The "Home" key moves the program to the "Overview" section and the **<End>** key will go to the "Calculate,..." section.

After one has become familiar with FAST_in, it is desirable to use some additional features which are available. They include making permanent changes to units and colors within FAST_in itself rather than returning to the installation procedure. Also, one can run the model directly, as long as "run time" graphics are not desired. To activate these features, run the installation module and exit with the **<f9>** key instead of **<f10>**.

9. ANNOTATED REFERENCES

[1] Jones, W.W., A Multicompartment Model for the Spread of Fire, Smoke and Toxic Gases. Fire Safety Journal 9, 55 (1985).

The papers by Jones [1], and Jones and Peacock [10] are the most complete descriptions of the use of differential equations in the problem of modeling fire growth and smoke transport. The original work on multicompartment models was written by T. Tanaka, A Mathematical Model of a Compartment Fire, BRI (Japan) No. 70 (1977). It is somewhat difficult to follow, partly due to language and partly to notation.

[2] Jones, W.W. and Fadell, A.B., A Device Independent Graphics Kernel, NBSIR 85-3235 National Bureau of Standards (USA) (1988).

[5] Siegal, R. and Howell, J.R., Thermal Radiation Heat Transfer, McGraw Hill Book Co., New York (1981).

[6] Schlichting, H., Boundary Layer Theory, translated by J. Kestin, Pergammon Press, New York (1955).

Schlichting is the most complete of the works on boundary layer theory especially the 7th edition, but somewhat difficult to read due to its completeness. An alternative which is much easier to follow is by Pitts, D.R. and Sissom, L.E., Heat Transfer, McGraw Hill, New York (1977).

[7] McCaffrey, B.J., Momentum Implications for Buoyant Diffusion Flames, Combustion and Flame 52, 149 (1983).

There are several plume models for fires. The one that has proved to be most in agreement with experimental data is that of McCaffrey [7]. Cetegan et al. have studied the door jet entrainment phenomena in great detail and their virtual plume concept works very well when used with McCaffrey's correlation.

[8] Cetegan, B.M., Zukoski, E.E., and Kubota, T., Entrainment and Flame Geometry of Fire Plumes, Ph.D. Thesis of Cetegen, California Institute of Technology, Pasadena (1982).

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The papers by Babrauskas [12] and Huggett [13] deal with a very specific piece of the chemistry which is extant in fires. Their concept allows us to finesse the very difficult question of the composition of the fuel, by providing an experimental relation between the net oxygen used by the products of combustion and the heat released by the fire.

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10. NOMENCLATURE

The variables used in the formulae are listed here. There are a few exceptions for local variables which are used only in a section for expository purposes. In general, most of these variables can be indexed by compartment (single i) or by the layer in a given compartment (u or ℓ). The variables shown in the implementation section correspond roughly to the mathematical variables shown here. Due to the limitations of character sets for computers, there can not be an exact correspondence, but the crosswalk should be clear. The first list is for the earlier discussion. The next list is for the numerical model as it is currently implemented.

Variables used in the mathematical description of the model:

A area (m^2)

- A_{upper} - extended upper wall - ceiling plus wall contiguous to upper layer
- A_{lower} - extended lower wall - floor plus lower wall
- A_w - area of surfaces in contact with a zone (upper or lower)
- A_d - area of interface between the two layers (discontinuity)

B sill height of a vent (m)

C coefficient (dimensionless)

- C - flow coefficient $\simeq$ 0.72 for doorways (nominal value: range is 0.55 to 1.0)
- C_o - convective heat transfer coefficient (which depends on orientation)
- C_w - wind coefficient - dot product of the wind vector and vent direction

c heat capacity

- c_p - heat capacity of a gas at constant pressure
- c_v - heat capacity of a gas at constant volume
- c - heat capacity of a solid

D denominator in radiative heat balance matrix

$\dot{E}$ rate of change of total energy (Joules/s) - consists of enthalpy plus specific energy - E is used because we are really referring to a change in the internal energy density of the gas; $h = \dot{m} c_p$ is part of this term

- $\dot{E}_u$ - upper layer
- $\dot{E}_\ell$ - lower layer

e_i rate of entrainment in plume in region (i) - used for vitiated combustion - refer to p_i

F view factor (dimensionless)
F_f product of the fraction of fire which goes into radiation and a view factor

Gr Grashof number - see eq (13)

g gravitational constant (9.80 m/s^2)

H height (m)
H - soffit height of a vent
H_w - height at which the wind speed is measured - relative to H_r
H_r - station elevation
H_i - height at which to calculate the pressure (including wind effects)

h heat of combustion (J/kg) or convective heat coefficient ($J/m^2/K$)

I time interval in seconds

$\dot{m}$ time rate of change of mass (kg/s)
$\dot{m}_i$ - total (net) mass flow into compartment i
$\dot{m}_u$ - total (net) mass flow into the upper layer of a compartment
$\dot{m}_\ell$ - total (net) mass flow into the lower layer of a compartment
$\dot{m}^{in}_{i,j}$ - net flow from compartment j into compartment i
$\dot{m}^{out}_{i,j}$ - net flow from compartment i into compartment j
$\dot{m}_{i,j} = \dot{m}^{in}_{i,j} - \dot{m}^{out}_{i,j}$ - in eq (20), (21), i→o is used to indicate in to out
$\dot{m}_e$ - entrained mass
$\dot{m}_f$ - pyrolysis rate of the fire
$\dot{m}_b$ - burning rate of the fire ($\leq \dot{m}_f$)

m species mass density (kg/m^3)
m_{xx} where xx is H_2O,CO_2,CO,S(soot),H,O,C,O_2,THUC,HCL,HCN,N_2 and fuel

N species number density or molar density ($\#/m^3$)
N_{xx} where xx is H_2O,CO_2,CO,S(soot),H,O,C,O_2,THUC,HCL,HCN,N_2 and fuel

N_U is the Nusselt number, a function of Gr and Pr. It is not used explicity in any calculation, but is to show the relationship with standard heat and mass transfer theory.

P pressure (Pa)
- P_u - upper layer
- P_ℓ - lower layer
- P_R - reference pressure (assumption $P_R = P_u = P_\ell$ for temperature and density calculations)
- P_i - pressure at the base of compartment i
- P_i - pyrolysis rate - used only in the explanation of the fire specification in figure 6
- P_a - ambient pressure at a given height H_r
- P_w - pressure at a height H_i including wind effects

p_i plume flow rate for the vitiated combustion calculation - subscript refers to the region (1,2 or 3), which are show in figure 3; corresponding term is e_i

p_w power for the pressure lapse rate in the equation for the pressure including wind

Pr Prandtl number (0.72)

$\dot{Q}$ heat release rate for a chemical or physical process - this does not include any enthalpy flux (Watts)
- $\dot{Q}_f$ - chemical heat release rate from a fire
- $\dot{Q}_r$ - radiation heating of a gas by a wall surface or other gas layer
- $\dot{Q}_c$ - convective heating of gas by a wall surface
- $\dot{Q}_k$ - from surface 'k'
- $\dot{Q}_g$ - net heating of a gas by all radiative processes

R "universal" gas constant (≈289 J/kg/K)

S surface area of a vent (m^2)

$\dot{s}$ rate of total energy change in a compartment (sum of $\dot{E}$'s)

T temperature (K)
- T_u - upper layer
- T_ℓ - lower layer
- T_{uw} - upper wall
- $T_{\ell w}$ - lower wall
- T_R - reference temperature - limit -> T_a
- T_a - ambient either inside or outside of the structure
- T_v - temperature of the volatiles (after gasification)

t time (s)

V total volume of a compartment (m^3)
- V_u - upper layer
- V_ℓ - lower layer
- V_w - wind speed (m/s) given at a height H_w above the terrain

v_p length of the virtual plume in vent flow calculations - used with the virtual offset z_p - both are in reduced units - see page 17ff

Z length (m) used for plume length, layer thickness and height of neutral plane(m)-
- z - same meaning as Z except used as an integration parameter
- Z_i - height of the hot layer interface (room height - layer thickness)

γ ratio of heat capacities $\approx$1.4 for air

σ Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4)

α absorption coefficient of the gas (m^{-1})

ϵ emissivity (dimensionless)
- ϵ_u - upper gas layer in a compartment
- ϵ_ℓ - lower gas layer in a compartment

κ thermal conductivity (J/m/s/K)

ν kinematic viscosity (m^2/s)

ρ mass density (kg/m^3)
- ρ_u - upper layer
- ρ_ℓ - lower layer
- ρ_i - i varies from 1 to 4 which represents upper and lower layers, as shown in figures 1 and 2

η condition number in the conduction equation - eq (39)

χ fraction of heat release rate which goes into some process
- χ_R fraction of heat release rate which goes into radiation
- χ_C fraction of heat release rate which goes into convective motion
- χ_e fraction of pyrolosate which burns

Π_u numerator of heat balance matrix for upper layer contribution

Π_{ℓ} numerator of heat balance matrix for lower layer contribution

In the flow calculation, the indices have a special meaning. The reference is from "i," the inside compartment, to "o" the outside compartment. In this case, the index is 1 for the upper layer of "i," 2 for the lower layer of "i," 3 for the upper layer of "o," and 4 for the lower layer in "o." This terminology applies to temperatures, densities and mass flow only for the flow calculation as done in section 4.4 The "i" and "o" are chosen by a selection rule discussed in section 6.4

Variables used by FAST in the common blocks moco1a, moco1c, moco1d and moco1e

AA(NR,NR,4)	flow from lower layer to lower layer (kg/s)
ACTIVS(NS)	logical switch to tell which species are active (interacts with "allowed")
AFIRED(NV)	area of fire (m^2)
AO(IFT)	area of simple fitting ift (m^2)
APS(NR)	current area of the specified fire (m^2)
AR(NR)	floor area of a compartment (in current version ceiling=floor)
AS(NR,NR,4)	flow from lower to upper layer (kg/s)
ASL(NR,NR,4)	entrainment from upper into lower layer (kg/s)
BFIRED(NV)	burning rate (kg/s)
BFLO(IB)	mass flow rate through branch ib (kg/s)
BR(NR)	breadth of a compartment (m)
BW(NR,NR,4)	width of vent (m) (modified by qcvent)
CCO2(NV)	net carbon production rate (fraction relative to co2)
CE(IB)	effective mass flow coefficient for resistance branch ib
CNAME(NWAL,NR)	name (pointer) of thermal property specied for a boundary
CO(IFT)	flow coefficient for simple fitting ift
COCO2(NV)	relative co/co2 production rate
CONFGFIL	name of a configuration file (not required)
CP	heat capacity of AIR at constant pressure (J/kg/K)
CRDATE(3)	creation date of the model (day, month and year)
CW(MXSLB,NWAL,NR)	specific heat of a thermal material
DA(ID)	area of duct id (m^2)
DE(ID)	effective diameter of duct id (m)
DELTAT	time step used by the model, currently 1.0 seconds
DFMAX(K)	derivative of fan curve at hmax(k)
DFMIN(K)	derivative of fan curve at hmin(k)
DL(ID)	length of duct id (m)
DPZ(I,K)	hydrostatic pressure difference between node i and kth node
DR(NR)	depth of a compartment (m)
DUCTAR(ID)	absolute roughness of duct walls
EME(NR)	plume entrainment rate (kg/s)
EMP(NR)	pyrolysis rate of the fire source (kg/s)

EMS(NR) plume flow rate into the upper layer (kg/s)
EPW(NWAL,NR) emissivity of the interior wall surface (non)
ERA(NR),EPA(NR),ETA(NR) exterior equivalents of ramb, pamb, and tamb: era,epa,eta
EXxx exterior equivalents of ta, pa and ra: exta, expa, exra
FKW(MXSLB,NWAL,NR) thermal conductivity of a material slab
FLW(MXSLB,NWAL,NR) thickness of a slab (m)
G gravity constant (9.806 m/s)
GAMMA cp/cv for air - 1.4
GMWF gram molecular weight (in grams, default ->16)
HCOMBA heat of combustion - initialization only
HCRATIO(NV) hydrogen/carbon ratio in the fuel - time dependent
HEATLP(NR) heat release rate in the plume in the lower layer (W)
HEATUP(NR) heat release rate in the plume in the upper layer (W)
HEATVF(NR) heat release in a vent (sum of all vents between two compartments 1->4)
HFIRED(NV) height of the base of the fire - time dependent (m)
HFLR(NR) absolute height of the floor of a compartment (m)
HH(NR,NR,4) top of vent (soffit) - distance from floor (m)
HHP(NR,NR,4) absolute height of the soffit (m)
HL(NR,NR,4) height of the sill relative to the floor (m)
HLP(NR,NR,4)absolute height of the sill (m)
HMAX(K),HMIN(K) max and min head pressure for fan(k)
HOCBMB(NV) heat of combustion of a specified fire (J/kg)
HR(NR) interior height of a compartment (m)
HRL(NR) absolute height of the floor (m)
HRP(NR) absolute height of the ceiling (m)
HVBCO(K,J) coefficients of fan curve polynomial
HVELXT(II) elevation of exterior nodes relative to station (m)
HVEXCN(MEXT,NS) species concentration at external the nodes
HVFLOW(I,J) mass flow rate to node i from the jth node to which it is connected
HVGHT(I) elevation of node i
HVNODE(I,J) mapping between external and internal nodes (2,MNODE)
HVP(I) relative pressure at node i
HWJ(NW,NR) hcl density on the wall (grams/m^2, initialized to 0)
IBRD(ID) pointer to resistive branch with duct id
IBRF(IFT) pointer to resistive branch with fitting ift
IC(I,K) pointer to kth resistive branch connected to node i
IDIAG not used
IFIRED current interpolation time for specified fire - integer pointer
IN(I,K) pointer to kth node connected to node i in hvac system
ITMMAX maximum number of time steps (#)
ITMSTP current time step (#)
IVERS current version
LCOPY number of "hard" copies for each graphics output - used for movies
LCW(MXSLB,NTHMX) local heat capacity

LDIAGO dump interval (#)
LDIAGP display (graphics) interval (#)
LEPW(NTHMX) local emissivity
LFBO compartment of origin (1 to nr-1)
LFBT type of fire (1, 2, ...)
LFKW(MXSLB,NTHMX) local conductivity
LFLW(MXSLB,NTHMX) local thickness (m)
LFMAX number of intervals in a fire specification
LFPOS position of the fire in a room (1 to 4) - affects entrainment only
LIMO2 limiting oxygen index in percent (default is 10%)
LNSLB(NTHMX) local number of slabs in a material (used in reading from the databasc)
LOGERR unit for error logging - set to zero if not to log erros
LPRINT print interval
LRW(MXSLB,NTHMX) local mass density of a material slab
MASS(2,NR,NS) mass in a layer of species ns (1 to ns)
MAXCT number of entries in the thermal database (max is 57 now)
MFIRET(NS) mass release rate of species ns - transient
MINMAS minimum mass in mass(...)
MPRODR(NV,NS) species production rate for specified fire - see tech ref for details
MPSDAT(3) date of this run
N number of compartments in use (including the outside)
N2,N3,N4 n+1,2n+1,3n+1
NA(IB) starting node for branch ib
NBR number of branches
NCNODE(I) number of branches coonnected to hvac node i
NCONFG 0 or 1 if a graphics descriptor is present
NDIV(MXSLB,NWAL,NR) number of interior nodes in a wall material (of mxslb slabs)
NDT number of ducts
NDUMPR 0 or 1 if a dump file specification is present
NE(IB) exit node number of branch ib
NEUTRAL(NR,NR) number of neutral planes for a vent - not very useful
NEXT number of exterior nodes
NF(IB) 0 if duct, fan number if a fan
NFAN number of fans
NFC(K) number of polynomial coefficients for fan k
NFT number of simple fittings
NLIST(NTHMX) list of thermal names used by the current thermal database
NLSPCT number of species in this run
NM1 actual number of compartments (N-1)
NNODE number of nodes in the hvac system
NOPNMX not used
NRESTR restart time (0 means no restart)
NRFLOW not used
NSLB(NWAL,NR) number of slabs in a particular wall

NSMAX maximum simulation time (seconds)
NW(NR,NR) switch for horizontal vents - coded for 1 to 4 by powers of 2
NWV(NR,NR) switch for vertical vents
ONTARGET(NR) absolute radiation from the upper layer to a target (less ambient)
P(NT) solution vector of pressure, upper temperature, lower temperature, volume
PA ambient pressure at the measured station
PAMB(NR) ambient pressure in a compartment prior to the fire
PMAX(NT),PMIN(NT) limits on the values in p
POFSET a pressure offset to help solve the stiffness problem
PPMDV(2,NR,NS) mass concentration (kg/m^3)
PREF default reference pressure (1.03 e+5)
QC(2,NR) net convective heat loss from a zone (Watts)
QF(2,NR) net heat generation rate of a fire into a zone (Watts)
QFIRED(NV) heat release rate for specified fire
QMAX(K),QMIN(K) flow rate at hmax(k) and hmin(k)
QR(2,NR) net radiative loss from a zone (Watts)
QRADRL fraction of heat which leaves a fire as radiation
RA default station ambient (inside) density (kg/m^3)
RAMB(NR) initial (ambient) mass density in a compartment
RELHUM initial relative humidity (default ->0%)
RGAS "universal" gas constant
ROHB(IB) density of gases in branch ib
RR(ID) relative roughness of walls of duct id
RW(MXSLB,NWAL,NR) material density of a boundary slab (kg/m^3)
SA(NR,NR,4) flow field upper to lower (kg/s)
SAL station elevation (m) - default to zero
SAU(NR,NR,4) entrainment rate into the upper layer
SIGM Stefan-Boltzmann constant (5.67×10^{-8} W/m^2/K^4)
SS(NR,NR,4) flow field from upper to upper layer (kg/s)
STIME current simulation time (s) - corresponds to itmstp
SWITCH(NWAL,NR) logical switch for wall conduction - switch...,nr) is used for output
TA station ambient temperature (K)
TAMB(NR) ambient temperature in a compartment (K)
TBR(IB) absolute temperature of gases in branch ib
TE pyrolysis temperature of the fuel
TERRORS(NTHMX) code for errors in the thermal database
TFIRED(NV) time interval specification
TFIRET current time for interpolation
TFMAXT maximum time for the specified fire
TGIGNT ignition temperature for a well stirred gas - limits fires in vents
THDEF(NTHMX) logical for whether thermal name is correctly defined
THRMFILE*20 name of the thermal database
TOXICT(2,NR,NS) conglomeration of stuff for output - see Tech Ref.
TREF default reference temperature

TWE(NWAL,NR) temperature of the gas external to a compartment boundary
TWJ(NWAL,NR,NN) temperature profile in the boundaries (ceiling, floor, upper/lower wall)
VOL(IBR) volume of branch ibr
VR(NR) volume of a compartment
VVAREA(NR,NR) area of a vertical vent
WINDC(NR) wind coefficient for a vent facing the outside
WINDPW wind power law coefficient
WINDRF wind reference height (m)
WINDV wind reference velocity at windrf

PARAMETERS:

MBR maximum number of branches
MCON maximum number of connections to a node
MDT maximum number of ducts
MEXT maximum number of exterior nodes
MFAN maximum number of fans
MFCOE maximum number of fan coefficients
MFT maximum number of simple fittings
MNODE maximum number of nodes
MOPT maximum number of options allowed on the command line
NR maximum number of compartments
NN maximum number of nodes in a boundary (walls, ceilings and floor)
NT maximum number of equations to be solved (4*nr+2*nr*ns)
NTHMX maximum number of thermal definitions
NV maximum number of time intervals
NS maximum number of species to be tracked
NWAL number of discrete wall surfaces (ceiling, upper wall ...) currently 4
MXSLB maximum number of different materials in a wall (now 3)
UPPER,LOWER upper, lower layer pointers (=1,2)

APPENDIX A: SAMPLE INPUT

The first four examples are included in the distribution as demo-fn.dat where n=1->4. The fifth file is simply another example and is the file 3R in FAST_in.

The first example is for a single compartment. This is also the 1R data file referred to in FAST_in. In the latter case the graphics descriptors are not included.

```
VERSN   18 demo #1 a single compartment
TIMES   180  0  0   5   0
TAMB    300.
HI/F    0.
WIDTH   3.3
DEPTH   4.3
HEIGH   2.3
HVENT   1    2   1   1.07  2.0  0.0
CEILI   GYPSUM
FLOOR   WOOD
LFBO    1
LFBT    2
LFMAX   7
CHEMI   0.0  0.0  1.0  18100000 300.
FMASS   .0014 .0014 .025 .045 .050 .0153 .0068 .0041
FAREA   .5   .5   .5   .5   .5   .5   .5 .5
FHIGH   .25   .25   .25   .25   .25   .25   .25 .25
FTIME   20. 20. 50. 50. 100. 100. 400.
OD      02 .02  .02  .02  .02  .02  .02  .02
CO      02 .02  .02  .02  .02  .02  .02  .02
WINDOW      0     0  -100  1280  1024   1100
GRAPH   1  120.  300.    0.  600.  920.   10.  5 TIME  PPM
GRAPH   2  740.  300.    0.  1220. 920.   10.  5 TIME  CELSIUS
LABEL   1  970.  960.    0. 1231. 1005.   10. 15 00:00:00        0.      0.
LABEL   2  690.  960.    0.  987. 1005.   10. 13 TIME_[S]        0.      0.
LABEL   3  200.  050.    0.  520.  125.   10.  2 CO¦D2¦O_CONCENTRATION 0. 0.
CO      0 0 0 0 1   1 U
TEMPERA 0 0 0 0 2   1 U
TEMPERA 0 0 0 0 2   1 L
```

Demonstration #2 is a similar run, but showing other types of displays which are available.

```
VERSN   18 demo #2 a single compartment but plot other stuff
TIMES   180 0  0  5  0
TAMB    300.
HI/F    0.
WIDTH   3.3
DEPTH   4.3
HEIGH   2.3
HVENT   1    2   1   1.07  2.0  0.0
CEILI   KAOWOOL
FLOOR   CONCRETE
```

```
LFBO    1
LFBT    1
LFMAX   7
LFPOS   1
CHEMI   0.0  0.0  6.00  18100000 300.
FMASS   .014 .0014 .025 .045 .050 .0153 .0068 .0041
FAREA   .5   .5   .5   .5   .5   .5   .5 .5
FHIGH   .25   .25   .25   .25   .25   .25   .25 .25
FTIME   20. 20. 50. 50. 100. 100. 400.
WINDOW       0     0  -100  1280  1024   1100
GRAPH   1  150.  300.    0.  620.  920.   10.  3 TIME  PPM
LABEL   1  390.  960.    0.  651. 1005.   10. 15 00:00:00        0.      0.
LABEL   2  110.  960.    0.  407. 1005.   10. 13 TIME_[S]        0.      0.
LABEL   3  200.  050.    0.  520.  125.   10.   14 O¦D2¦O_CONCENTRATION 0. 0.
TABLE   1  700.  300.    0. 1200.  920.   10.
HEAT    0 1 0 0 0   1 U
O2      0 1 0 0 1   1 U
TEMPERA 0 1 0 0 0   1 U
TEMPERA 0 1 0 0 0   1 L
```

This is the data set which produces the NIKE site evaluation scenario.

```
VERSN   18  demo #3 the original nike site evaluation
TIMES  180  0  0   5    0
TAMB   300.
HI/F   0.0  0.0  0.0  0.0  0.0  0.0
WIDTH  3.3  2.4  2.9  2.4  3.3  2.4
DEPTH  4.3 18.8  9.9  9.9  4.3  4.3
HEIGH  2.3  2.3  2.3  2.3  2.3  2.3
HVENT    1    2   1  1.07  2.0  0.0
HVENT    2    3   1  1.07  2.0  0.0
HVENT    3    7   1  0.95  .15  0.0
HVENT    2    4   1  1.07  2.0  0.0
HVENT    4    7   1   .95  .10  0.0
HVENT    2    5   1  1.07  2.0  0.0
HVENT    2    6   1  0.10  2.0  0.0
CEILI    GYPSUM GYPSUM GYPSUM GYPSUM GYPSUM GYPSUM
LFBO     1 ROOM OF FIRE ORIGIN
LFBT     1 TYPE OF FIRE (GAS BURNER)
LFMAX    7 NUMBER OF INTERVALS OF FIRE GROWTH
LFPOS    1 POSITION OF THE FIRE (CENTER)
CHEMI   .0  0.0       1.0     18100000 300.
FMASS   .0014 .0014 .025 .045 .050 .0153 .0068 .0041
FAREA   .5   .5   .5   .5   .5   .5   .5 .5
FHIGH   .25   .25   .25   .25   .25   .25   .25 .25
FTIME   100. 100. 50. 50. 100. 100. 400.
CO      0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
WINDOW       0     0     0  1280  1024   1100
VIEW    1 300 600 150 1200 900 200 DEMO-F3T.PIC 1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1
VIEW    2 300 300 150 1200 600 200 DEMO-F3B.PIC 1 0 0 0 0 0 -1 0 0 1 0 0 0 572 572 1
LABEL   1  820.  960.    0. 1081. 1005.   10. 14 _______         0.      0.
LABEL   2   50.   50.    0. 1080.  100.   10. 10 ¦Nike_Site_evaluation 1.57 0
LABEL   3   70.  960.    0.  367. 1005.   10. 03 FIRE_[kW]       0.      0.
LABEL   4  640.  960.    0.  937. 1005.   10. 03 TIME____        0.      0.
LABEL   5  360.  960.    0.  635. 1005.   10. 14 _______         0.      0.
TABLE    1  200.   20.    0.  950.  250.   10.
HEAT     0 0 0 5 0 1 U
TEMPE    0 1 1 0 0 1 U
INTER    0 1 1 0 0 1 U
CO       0 1 1 0 0 1 U
```

```
TEMPE   0 0 2 0 0 1 U
INTER   0 0 2 0 0 1 U
CO      0 0 2 0 0 1 U
```

The fourth demonstration data file is used to generate a dump file for trying FASTplot.

```
VERSN   18  demo # 4 a five compartment calculation with save's
TIMES   180  0  15   5    0
TAMB    300.
HI/F    0.0  0.0  0.0  0.0  0.0
WIDTH   3.3  2.4  2.9  2.4  3.3
DEPTH   4.3 18.8  9.9  9.9  4.3
HEIGH   2.3  2.3  2.3  2.3  2.3
HVENT    1    2  1    1.07  2.0  0.0
HVENT    2    3  1    1.07  2.0  0.0
HVENT    3    6  1    0.95  .15  0.0
HVENT    2    4  1    1.07  2.0  0.0
HVENT    2    5  1    1.07  2.0   0.0
HVENT    4    6  1    0.10  2.0   0.0
CEILING  GYPSUM   GYPSUM   GYPSUM   GYPSUM   GYPSUM
FLOOR    READOAK  READOAK  READOAK  READOAK  READOAK
LFBT     2
LFMAX    7
LFPOS    1
CHEMI    0.0  0.0  6.00  18100000 300.
FMASS   .0014 .0014 .025 .045 .050 .0153 .0068 .0041
FAREA   .5   .5   .5   .5   .5   .5   .5 .5
FHIGH   .25   .25   .25   .25   .25   .25   .25 .25
FTIME   100. 100. 50. 50. 100. 100. 400.
CO      0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
DUMPR demo-f4.dmp
WINDOW       0     0  -100  1280  1024   1100
GRAPH   1  120.  300.    0.  600.  920.   10.  7 TIME  PPM
GRAPH   2  740.  300.    0.  1220. 920.   10.  7 TIME  CELSIUS
LABEL   1  970.  960.    0. 1231. 1005.   10. 15 00:00:00        0.      0.
LABEL   2  690.  960.    0.  987. 1005.   10. 13 TIME_[S]        0.      0.
LABEL   3  200.  050.    0.  520.  125.   10.   14 CO¦D2¦O_CONCENTRATION 0. 0.
CO      0 0 0 0 1   1 U
CO      0 0 0 0 1   2 U
CO      0 0 0 0 1   3 U
CO      0 0 0 0 1   4 U
CO      0 0 0 0 1   5 U
TEMPERA 0 0 0 0 2   1 U
TEMPERA 0 0 0 0 2   2 U
TEMPERA 0 0 0 0 2   3 U
TEMPERA 0 0 0 0 2   4 U
TEMPERA 0 0 0 0 2   5 U
```

The fifth example is a three compartment scenario, and referenced in the interactive program as 3R. The results obtained by running this data set are shown in Appendix B.

```
VERSN   18  An example of a constrained fire
TIMES   180    10   0   0   0
TAMB    300.  101300.     0.
HI/F    0.00     0.00     0.00
WIDTH   2.34     2.44     2.84
DEPTH   2.34    13.19     2.34
HEIGH   2.16     2.44     2.44
```

```
CEILI   KAOWOOL  GYPSUM   GYPSUM
WALLS   KAOWOOL  GYPSUM   GYPSUM
FLOOR   CONCRETE CONCRETE CONCRETE
HVENT   1  2  1  0.81    1.60    0.00
HVENT   2  3  1  0.79    2.00    0.00
HVENT   2  4  1  1.02    2.00    0.00
CHEMI   0.0 0.0 6.  50026000. 300.
LFBO    1
LFBT    2
LFPOS   1
LFMAX   2
FMASS   0.0000   0.0018     0.0019
FHIGH   0.50     0.50       0.50
FTIME          30.      1000.
```

The corresponding thermal data file for these examples is

```
CONCRETE  1.75    1000.  2200.    .15      .94  CONCRETE,NORMAL WEIGHT
REDOAK     .15    1300.   640.    .016     .9   RED OAK
GYPSUM     .16     900.   800.    .016     .9   GYPSUM BOARD (PLASTERBOARD)
WOOD       .07    1000.   250.    .016     .98  WOOD,CHARRED,DRY
KAOWOOL    .22    1047.   128.    .116     .97  Glass fiber insulation
```

APPENDIX B: SAMPLE OUTPUT

The output of the FAST program consists of two major parts. The first is a summary of the input data and the initial conditions. The second consists of the calculated results at the end of each print interval. A sample of the program output is shown in Appendix B. The particular example comes from the three compartment data file (3R) shown in Appendix A. Due to the effect of the computer's internal precision on the solution of the equations, it is possible that the results from other computers will differ slightly from those found in Appendix B. The output is labeled and most of it is self explanatory. There are however, a number of abbreviations used which are explained in the following sections along with a general description of the output. The output pertaining to each of the compartments is listed across the page beginning with compartment one in the left most column and proceeding to the right to the highest number compartment.

B.1 Summary of Input Data

The summary of input data is divided into three sections. These are geometrical data, thermophysical properties, and the fire specifications. A title precedes these sections and lists the version number and any title which was in the data file.

B.1.1 Title

```
FAST version 18.2 - created May 16, 1988   An example of a constrained fire
```

B.1.2 Geometrical Data

This section lists the run title, the total number of compartments, depth, height, area, and volume for each compartment. It also gives the ceiling and floor height with respect to the reference datum. This is followed by the connections between the compartments. Each compartment is listed vertically down the page and horizontally across the page and the connections between compartments are given at the intersection of the vertical and horizontal lists. The final compartment in the horizontal list is the exterior space. The parenthetical numbers in the vertical compartment list are the number of openings for each compartment. For example, if the maximum number of openings between any two compartments is three, there would be three parts for each compartment in the vertical list. Each part consists of the following:

1) opening width (BW) (m)
2) height of top of opening above floor (HH) (m)
3) height of bottom of opening above floor (HL) (m)
4) height of top of opening above reference datum (HHP) (m)
5) height of bottom of opening above reference datum (HLP) (m)

```
Total compartments =                3

 FLOOR PLAN

          Width        2.3    2.4    2.8
          Depth        2.3   13.2    2.3
          Height       2.2    2.4    2.4
          Area         5.5   32.2    6.6
          Volume      11.8   78.5   16.2
          Ceiling      2.2    2.4    2.4
          Floor        0.0    0.0    0.0

 CONNECTIONS

  1 ( 1)  Width        0.00   0.81   0.00   0.00
          Soffit       0.00   1.60   0.00   0.00
          Sill         0.00   0.00   0.00   0.00
          a.Soffit     0.00   1.60   0.00   0.00
          a.Sill       0.00   0.00   0.00   0.00
  2 ( 1)  Width        0.81   0.00   0.79   1.02
          Soffit       1.60   0.00   2.00   2.00
          Sill         0.00   0.00   0.00   0.00
          a.Soffit     1.60   0.00   2.00   2.00
          a.Sill       0.00   0.00   0.00   0.00
  3 ( 1)  Width        0.00   0.79   0.00   0.00
          Soffit       0.00   2.00   0.00   0.00
          Sill         0.00   0.00   0.00   0.00
          a.Soffit     0.00   2.00   0.00   0.00
          a.Sill       0.00   0.00   0.00   0.00
```

B.1.3 Thermophysical Properties

This section lists the thermophysical properties of the ceiling, floor, upper and lower walls respectively for each compartment. Although the thermophysical properties of the upper and lower walls are the same, they are presented separately to correspond to the temperature of the upper and lower temperature layers of the compartment. The information first shown are the names as given in the data file. Following this is a listing of the conductivity, specific heat, density, thickness and emissivity obtained for each of the thermophysical items which can be found. If the program was unable to find all names, it will quit at this point.

```
 MATERIAL NAMES

  Ceiling:   KAOWOOL   GYPSUM    GYPSUM
  Walls:     KAOWOOL   GYPSUM    GYPSUM
```

```
 Floor:     CONCRETE  CONCRETE  CONCRETE

THERMAL DATA BASE USED:       THERMAL.DAT

 Name       Conductivity Specific heat   Density       Thickness   Emissi

 CONCRETE       1.75        1.000E+03    2.200E+03     0.150        0.940
 GYPSUM        0.160         900.         800.         1.600E-02    0.900
 KAOWOOL       0.220        1.047E+03     128.         0.116        0.970
```

B.1.4 Fire Specifications

This section consists of three parts. The first part lists the compartment number of the room of fire origin, the time step used in calculating the results, how often output is to be printed, the number of intervals for which the mass loss rate is specified, the total time over which the results will be printed, the fire location within the room of origin, and the fire type.

```
Compartment of origin is                          1
Print interval (seconds)                        900
Number of fire specification intervals is         2
Total time (seconds)                            900
Fire position                                     1
Limiting oxygen index (%) =                     6.0
Initial relative humidity (%) =                 0.0
Fire type is a SPECIFIED (CONSTRAINED)
```

The second part lists the initial fuel temperature, the ambient air temperature, and the ambient sea level reference pressure for the interior and exterior.

```
Pyrolysis  temperature (K) =                    300.
Ambient air temperature (K) =                   300.
Ambient reference pressure (Pa) =            101300.
Reference elevation (m) =                        0.
External ambient temperature (K) =              300.
External reference pressure (Pa) =           101300.
Reference elevation (m) =                        0.
```

The third part lists for each specified point of the fire, the mass loss rate of the burning fuel, the height of the base of the fire with respect to the floor, the heat of combustion and the fractional production rates of the species. Also listed is the duration of each time interval.

```
Fmass=   0.00      1.80E-03  1.90E-03
Hcomb=   5.00E+07  5.00E+07  5.00E+07
Fqdot=   0.00      9.00E+04  9.50E+04
Fhigh=   0.50      0.50      0.50
C/CO2=   0.00      0.00      0.00
CO/CO2=  0.00      0.00      0.00
H/C=     0.33      0.33      0.33
Ftime=    30.      1.00E+03
```

B.1.5 Initial Conditions

This section shows the conditions in the structure at the beginning. If this is a restart, then the conditions will be at the time step used for the restart.

```
 Time =    0.0 seconds.

   Upper temp(K)       300.0       300.0       300.0
   Lower temp(K)       300.0       300.0       300.0       300.0
 Upper vol(m**3)         0.0         0.1         0.0
  Layer depth(m)         0.0         0.0         0.0
 Ceiling temp(K)       300.0       300.0       300.0
 Up wall temp(K)       300.0       300.0       300.0
Low wall temp(K)       300.0       300.0       300.0
   Floor temp(K)       300.0       300.0       300.0

Plume flow(kg/s)   0.000E+00   0.000E+00   0.000E+00
Pyrol rate(kg/s)   0.000E+00   0.000E+00   0.000E+00
    Fire size(W)   0.000E+00   0.000E+00   0.000E+00
                   0.000E+00   0.000E+00   0.000E+00
  Plume in ul(W)   0.000E+00   0.000E+00   0.000E+00
  Plume in ll(W)   0.000E+00   0.000E+00   0.000E+00
    Vent fire(W)   0.000E+00   0.000E+00   0.000E+00   0.000E+00
 Radiant(W/m^2)    0.000E+00   0.000E+00   0.000E+00
                   0.000E+00   0.000E+00   0.000E+00
On target(W/m^2)   0.000E+00   0.000E+00   0.000E+00
 Convect(W/m^2)    0.000E+00   0.000E+00   0.000E+00
                   0.000E+00   0.000E+00   0.000E+00
                   0.000E+00   0.000E+00   0.000E+00
                   0.000E+00   0.000E+00   0.000E+00
    Pressure(Pa)   0.000E+00   0.000E+00   0.000E+00

                  Upper layer species

      N2   %  |     79.3        79.3        79.3
      O2   %  |     20.7        20.7        20.7
     CO2   %  |    0.000       0.000       0.000
      CO ppm  |    0.000       0.000       0.000
    TUHC   %  |    0.000       0.000       0.000
     H2O   %  |    0.000       0.000       0.000
      OD 1/m  |    0.000       0.000       0.000

                  Lower layer species

      N2   %  |     79.3        79.3        79.3
      O2   %  |     20.7        20.7        20.7
     CO2   %  |    0.000       0.000       0.000
      CO ppm  |    0.000       0.000       0.000
    TUHC   %  |    0.000       0.000       0.000
     H2O   %  |    0.000       0.000       0.000
      OD 1/m  |    0.000       0.000       0.000
```

B.2 Results of Calculations

The final part of the output consists of the calculated results at the end of each print interval. The first line of the output is the simulation time. In this example the results have only been listed for 900 seconds (see the data file in Appendix A). Following the time are the temperatures of the upper and lower layers, the upper layer volume and thickness, and the temperatures of the ceiling, upper (UW.TEMP) (K) and lower walls, and the floor.

```
Time =  900.0 seconds.

   Upper temp(K)       633.5       404.0       338.8
   Lower temp(K)       327.1       307.7       305.8       300.0
Upper vol(m**3)          5.3        32.0         9.1
   Layer depth(m)        1.0         1.0         1.4
Ceiling temp(K)       502.8       345.5       315.1
Up wall temp(K)       466.2       333.4       311.0
Low wall temp(K)      396.3       310.8       303.4
   Floor temp(K)       313.2       301.9       300.2
```

Next is the flow rate of combustion products and entrained air into the upper layer from the plume, the pyrolysis rate of the fuel, the enthalpy release rate of the fire, the total radiant heat transfer to the upper layer, the total convective heat transfer from the surfaces surrounding the layers to the upper and lower layers respectively, and the difference between the current pressure and the initial pressure at the floor.

```
Plume flow(kg/s)   2.202E-01  0.000E+00  0.000E+00
Pyrol rate(kg/s)   1.887E-03  0.000E+00  0.000E+00
    Fire size(W)   9.440E+04  0.000E+00  0.000E+00
                   0.000E+00  0.000E+00  0.000E+00
  Plume in ul(W)   0.000E+00  0.000E+00  0.000E+00
  Plume in ll(W)   9.440E+04  0.000E+00  0.000E+00
    Vent fire(W)   0.000E+00  0.000E+00  0.000E+00  0.000E+00
  Radiant(W/m^2)  -1.886E+02 -5.015E+01 -2.953E+00
                   9.011E+02  1.388E+02  3.524E+01
On target(W/m^2)   6.978E+02  6.610E+00  1.272E-01
  Convect(W/m^2)   1.031E+03  4.779E+02  1.596E+02
                   8.980E+02  3.824E+02  1.225E+02
                  -4.021E+02 -6.817E+00  5.125E+00
                   4.546E+00  1.485E+00  1.445E+00
    Pressure(Pa)  -1.152E+00 -4.932E-01 -4.514E-01
```

The final part of the results consists of the species concentration for each compartment. The total mass of each specie in the upper layer is given for each compartment (kg). Depending on the species, a concentration (ppm) or opacity (m^{-1}) is also given. For CT, the concentration-time product, only the time integrated (from time=0) concentration (mg-min/l) for the upper layer in each compartment is given. The use of this time integrated concentration is discussed in reference [8].

Upper layer species

N2	%	77.4	78.4	78.4
O2	%	16.1	18.5	18.5
CO2	%	2.17	1.06	1.02
CO	ppm	0.000	0.000	0.000
TUHC	%	0.000	0.000	0.000
H2O	%	4.33	2.11	2.05
OD	1/m	0.000	0.000	0.000

Lower layer species

N2	%	79.2	79.2	79.0
O2	%	20.6	20.6	20.1
CO2	%	7.921E-02	7.783E-02	0.302
CO	ppm	0.000	0.000	0.000
TUHC	%	0.000	0.000	0.000
H2O	%	0.158	0.156	0.603
OD	1/m	0.000	0.000	0.000

APPENDIX C: DISTRIBUTION AND INSTALLATION

The installation process which is described applies to the PC version of the model. For mainframe applications, the installation is somewhat more complex, and the authors need to be contacted directly.

For the PC version, the model is distributed on various media, such as 3 1/2 or 5 1/4 disks. All files should be copied to a single directory on a hard disk. Then look at the readme.doc file (if present) for instructions. The following files shown below should be present:

BUILD.EXE		build graphics descriptions
COLORTST.EXE		diagnostic
DATA.DAT		standard data file
DEMO.BAT		run FAST with demonstration data files
DEMO-F1.*	(4)	data files for demonstration (see appendix a)
DEMO-F3B.PIC		graphics data files for demo #3
DEMO-F3T.PIC		" " " "
DEVFONT.*	(2)	data file for stroke (non filled) characters
FAST.EXE		FAST model
FAST_IN.EXE		interactive input program
FASTPLOT.EXE		interactive output program
HLPTXT.V18		help text for FAST_in
INSTALL.EXE		program to set colors, file names and units (FAST_in)
LISTTHRM.EXE		list the contents of the thermal database
RELEASE.DOC		overview and version history
SWU8*.*		another demonstration, showing the stack effect
SYSTEM*.*	(13)	bit mapped font files[7]
TEQUIPT.EXE		diagnostic
TESTGA.EXE		find out what the graphics adaptor is - returns an integer
THERMAL.TPF		default thermal database

The purpose of each program is

BUILD - generate 3D pictorial representations for display by FAST
COLORTST - show the color palette used by FAST (not FAST_in)

[7] These files are to be replaced by a filled stroke (vector) font, at which time there will be only a single file.

FAST - the main model of fire growth and smoke transport
FASTplot - post processing of FAST dump files for tables and graphs
FAST_in - interactive program to generate FAST data files
INSTALL - defined colors, units and default path names for the models
LISTTHRM - list the properties in the thermal database
TEQUIPT - check for available equipment: math coprocessor and display
TESTGA - find out what we think the graphics adaptor is - diagnostic only

The command line arguments for the executable tasks are

BUILD [/Gnnn]
COLORTST - no arguments
FAST [/N] [/L] [/Gnnn] [input or configuration file] [output file]
FASTplot [/N] [/L] [/Gnnn] [script file]
FAST_in [/N] [/L] [/Gnnn] [configuration file]
INSTALL - no arguments
LISTTHRM - no arguments
TEQUIPT - no arguments
TESTGA - no arguments

The options are

/L turn on the log feature - writes to a xxx.log file
/N turn off the header/copyright notice
/Gnnn where nnn is an alternative graphics adaptor

It is necessary to run the installation program before doing anything else. The important settings are the name of the thermal database and the path to the data files. Even if the name is to remain the same, the model(s) will need the configuration file which is generated by running the installation program. The name of the default configuration file is "DEFAULTS.FCG" and must reside in the same directory as the models. To leave the defaults in place, simply exit each section of the program. The colors and units which are set in this program apply only to the interactive interface, FAST_in. It is essential that this file not be modified. All information in the file can be modified by the installation program. The subsequent programs do not check for integrity of this file and if it is not in the correct form they will most likely terminate in an unpredictable way.

The first test should be to run the demonstration files. Enter the command "DEMO" - it should run a sequence of four calculations. If nothing appears then use the two diagnostic programs to check for the presence of the proper equipment. This set of programs requires a minimum of 490K bytes and a graphics adaptor. Note that the 490K is free memory, so generally, 640K of memory (RAM) is required since the operating system takes between 80 and 120K.

Both FAST and FAST_in use a configuration file. They will attempt to find the default file DEFAULTS.FCG unless the configuration file is specified on the command line. FAST also requires a data file. If this is given on the command line, it is used, otherwise the model will look in the configuration file (default or specified) to find the file last edited with FAST_in. There are two conditions which will cause FAST to quit. The first is if it cannot find a data file, and the second is if there are thermophysical properties which are not defined.

The /L option will turn on an error logging feature which describes what each program is doing. It is an ASCII file, so it can be examined. However, it is really only useful if there appears to be a "bug" and help is requested. In this case, we will require a copy of the log file, which was generated when the failure occurred. If a problem arises, rerun the particular program with this feature turned on, duplicate the problem, and send a copy of the appropriate data file(s) together with this log file.

The /G option is used to specify an alternative display adaptor. If the model does not seem to be picking the correct adaptor, then this will be useful. The only case we have found is the Compaq portable which use a high resolution plasma display, but which has the capability for CGA output. When using the CGA output, the option /GC:4 needs to be used to override the default and force the model to use the CGA driver.

APPENDIX D: THERMAL DATABASE

Thermal data is read from a file which is in an ASCII format. The default name used is THERMAL.TPF. Another name can be used by selecting it during installation, or by using the key word THRMF in the FAST datafile. The relationship is by the name used in specifying the boundary. The example shown in section 6.6 was for concrete, brick and redoak. Any name can be used so long as it is in the thermal database. If a name is used which is not in the database, then FAST_in will turn off the conduction calculation, and FAST will stop with an appropriate error message. The form of an entry in the database is

name conductivity specific heat density thickness emissivity

and the units are

name	1 to 8 alphanumeric characters
conductivity	Watts/meter/Kelvin
specific heat	Joules/kilogram/Kelvin
density	kilograms/cubic meter
thickness	meters
emissivity	dimensionless.

The default database that comes with FAST (THERMAL.TPF) is

Name	Conductivity	Specific heat	Density	Thickness	Emissivity
DFIR30	0.1800	900.0	790.0	0.0160	0.9000
PINEWOOD	0.1200	2500.0	540.0	0.0160	0.8000
CONCRETE	1.75	1000.0	2200.0	0.1500	0.9400
REDOAK	0.1500	1300.0	640.0	0.0160	0.9000
FIBER	0.0500	1250.0	240.0	0.0160	0.9000
GYPSUM	0.1600	900.0	800.0	0.0160	0.9000
WOOD	0.0700	1000.0	250.0	0.0160	0.9800
DFIR0	0.1300	1400.0	510.0	0.0127	1.00
DFIR10	0.1500	1500.0	560.0	0.0160	0.9000
GLASS	1.40	760.0	2500.0	0.0160	0.9500
GLASFIBR	0.0360	720.0	32.0	0.0160	0.9000
KAOWOOL	0.2200	1047.0	128.0	0.1160	0.9700
GYP1	0.1200	900.0	800.0	0.0250	0.9000
GYP2	0.1200	900.0	800.0	0.0500	0.9000
BRICK	0.1800	900.0	790.0	0.0160	0.9000

The output listing of FAST, and the thermal data base screen for FAST_in show a table of "codes." The code is an eight character string whose fields are

1-3 number of nodes if it exceeds 'NN' which is currently 48 (36 for the PC version)
4 always blank
5 too many slabs - greater than mxslb (S)
6 inconsistent number of slabs - all properties must have the same number of slabs (I)
7 duplicate names - the first in the list will be used (D)
8 used in the present calculation (U)

NBS-114A (REV. 2-8C)

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5. AUTHOR(S)

Walter W. Jones and Richard D. Peacock

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8. Type of Report & Period Covered

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9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Same as item #6

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

FAST (fire and smoke transport) is a zone model capable of predicting the environment in a multi-compartment structure subjected to a fire. This reference guide provides a detailed description of the source terms used in the model, data input requirements, and the output produced by version 18 of the model.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

compartment fires; fire growth; mathematical models; numerical models; room fires; smoke; toxicity

13. AVAILABILITY

☒ Unlimited

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