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CALCULATING FIRE PLUME CHARACTERISTICS IN A TWO LAYER ENVIRONMENT

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Abstract

Methods are developed to determine axial gas flow conditions within a weakly buoyant plume that passes from an ambient quiescent environment, in which the plume originates, to an upper layer at elevated temperatures. The methods are appropriate for inclusion in two layer analysis of enclosure fire. In particular, they are a first step in developing a prediction of actuation time for thermally activated automatic sprinklers exposed to an enclosure fire. Results obtained with various methods are compared with measurements in a 1.22 m diameter cylindrical enclosure.

Key words: Compartment fires; fire models; fire plumes; room fires; sprinkler systems.

1. INTRODUCTION

A primary objective of the suppression and extinguishment research group in the Center for Fire Research is to develop methods to predict the performance of fire suppression systems. Current research includes efforts focused on the study of light hazard automatic fire protection sprinkler systems.

To predict the fire suppression performance of a sprinkler system, it is necessary to construct models for the various phenomena which influence system performance. One must predict the time required for the system to respond to the fire, the characteristics of the water spray discharged from the sprinkler head, and the effects of this spray on the fire. This report is a contribution to the first of the objectives above, prediction of system actuation time.

In the case of a typical water sprinkler system, the response of the system is determined by the time required for the hot gases generated by the fire to heat parts in the sprinkler head linkage. For typical sprinkler heads in use today, actuation occurs after the rupture of either a frangible bulb or solder link at a predetermined elevated temperature. The rupture of these parts in the mechanical assembly of the sprinkler head allows water to flow through the head.

In previous work, methods were developed to characterize the thermal response of sprinkler heads to hot gas flow [1,2][1]. It has been found that the response of the sprinkler head can be characterized satisfactorily with a single time constant. The time constant for the sprinkler head is calculated from laboratory measurements of the time required to actuate the sprinkler head in a controlled hot gas flow. The value of the time constant is sensitive to changes in the resistance to heat transfer from the hot gases to the sprinkler head. For heat transfer dominated by convection from fire gases, the product of the time constant and the square root of gas flow speed past the sprinkler head is constant [2].

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[1] Numbers in brackets indicate the literature references at the end of the paper.

Using existing models of the thermal response of sprinkler heads, the actuation time for the head could be predicted if it were possible to predict the gas temperature and velocity histories at the sprinkler head generated by specified fires. For enclosures large enough that accumulation of gases from the fire into the quiescent hot gas layer under the ceiling is not significant, Alpert [3] has developed methods to determine the response of thermal detectors to slowly varying fires using quasisteady approximations. Heskestad and Delichatsios [4] have modeled the initial transient convective flows under large flat ceilings.

Common light hazard fire protection sprinkler systems are often installed to protect areas that are much smaller than the compartments for which the results of the above two studies apply. In these small enclosures hot combustion products from a fire can quickly accumulate in the upper portion of the enclosure after ignition, influencing the temperature of gases flowing near the ceiling and walls of the enclosure. Therefore, for small enclosures engineering methods must be developed to include the effects of an accumulated hot gas layer in the prediction of gas flow temperatures and velocities near ceilings and wall surfaces where sprinkler heads may be located. This is currently an active area of fire research. As light hazard sprinklers have activation temperatures in the range of 57°C to 77°C, it is important to predict the initial gas flow temperatures accurately, to provide good estimates of actuation times.

Difficulties exist in applying the present field equation models like those of Baum et al. [5] and Liu and Yang [6], and global zone models like those of Mitler and Emmons [7], and Pape et al. [8] to predict the fire driven

gas flow temperatures and velocities within enclosures. The present field equation models have the potential to calculate gas temperatures and velocities anywhere within an enclosure, but present codes require large computer storage for execution and are generally not accurate near wall and ceiling surfaces. The global zone fire models do not supply detailed information about flow conditions at any particular location within a zone, but simply the average conditions for the zone. Without some means to include the effects of boundary flows, zonal analysis is not capable of providing the detailed flow information necessary for calculating sprinkler actuation times.

The simplest model that will yield useful engineering predictions for actuation times of sprinkler heads in enclosures must contain a minimum of three regions. Two of these regions are currently dealt with in the two zone fire models - the lower or cold layer, and the upper or hot layer. The third region that must be added to the two layer arrangement is a ceiling and wall layer flow region that is driven by the fire plume. In this third region, gas temperature and velocity will be a function of position within the enclosure. This region would include the normal sites for ceiling and wall mounted sprinkler heads or other thermally actuated fire detection devices.

Although algorithms to treat special regions adjacent to enclosure boundaries have not yet been included in two zone enclosure fire models, Alpert [3], and Heskestad and Delichatsios [4] have studied the behavior of a fire plume and the induced flow under an unconfined ceiling. Useful predictive formulae for actuation time were found for heat detectors located in the

ceiling jet layer established by the fire plume. In Alpert's calculations, conditions of the plume flow near the ceiling, but prior to impingement on it, were used as boundary conditions for a calculation of the ceiling jet flow.

Following Alpert's work, a first approximation calculation of flow conditions in the ceiling jet layer within an enclosure may be performed, provided that conditions within the fire plume prior to ceiling impingement, including the effects of an accumulated hot gas layer, can be determined. However, it should be recognized that buoyant flow within an enclosure is more complex than flow under an unconfined ceiling. The walls of the enclosure that lead to the accumulation of a stagnant hot gas layer in the upper portion of the room may also affect the ceiling jet flow. As an example, Delichatsios [9] has studied abrupt changes in the ceiling jet flow resulting from ceiling beams.

In this report, methods are developed to determine axial gas flow conditions within a weakly buoyant plume that passes from an ambient quiescent environment, in which the plume originates, to an upper layer at elevated temperatures. The models should be appropriate for inclusion in two layer zonal analysis of enclosure fires. Results obtained using several methods to calculate axial temperatures in a plume are compared to measurements made in a 1.22 m cylindrical enclosure, which is also described.

2. BUOYANT PLUME IN A UNIFORM ENVIRONMENT

A commonly used model for describing the flow in a fire plume was developed by Morton, Taylor and Turner [10]. This model will be used to describe plume flow conditions in the cold lower layer of a two layer environment. In the model, the weakly buoyant plume is assumed to originate at a point source. Weakly buoyant plumes are those in which, everywhere, the fractional density change from the ambient environment is assumed to be small. These changes are small enough so that in writing conservation equations, density changes (or similarly, temperature in a constant pressure system) need only be considered explicitly in buoyancy terms (i.e. where $\Delta\rho$ appears in combination with g).

A fire plume is assumed to be axisymmetric with radial distribution of velocity in the vertical direction and density at any height, z, as follows:

$$u(z,r) = u(z,0)\ \exp(-r^2/b^2) \tag{1a}$$

$$\Delta\rho(z,r) = \Delta\rho(z,0)\ \exp[-r^2/(\lambda^2 b^2)] \tag{1b}$$

where $\Delta\rho = \rho_o - \rho$, ($\rho_o(z)$ is the ambient density at any height above the source), $b = b(z)$, and λ is a dimensionless constant.

Using these assumed Gaussian profiles, equations may be written for conservation of the flowing quantities mass, momentum, and density defect (energy) integrated across the plume at each height. These take the form

$$\frac{d}{dz}\left(b^2u(z,0)\right) = 2b\alpha u(z,0) \tag{2a}$$

$$\frac{d}{dz}\left(b^2u^2(z,0)\right) = 2\lambda^2b^2g\,\frac{\Delta\rho(z,0)}{\rho_1} \tag{2b}$$

$$\frac{d}{dz}\left(b^2u(z,0)g\,\frac{\Delta\rho(z,0)}{\rho_1}\right) = (1+1/\lambda^2)b^2u(z,0)\,\frac{g}{\rho_1}\,\frac{d\rho_o}{dz} \tag{2c}$$

where α is an entrainment constant and ρ_1 is the ambient density at the level of the heat source $z = 0$, i.e. $\rho_1 = \rho_o(z = 0)$.

With the substitutions

$$P = \Delta\rho(z,0)/\rho_1 \tag{3a}$$

$$U = u(z,0) \tag{3b}$$

$$V = bU \tag{3c}$$

$$W = b^2U \tag{3d}$$

$$F = \lambda^2WgP \tag{3e}$$

$$R = g\rho_o/\rho_1 \tag{3f}$$

the conservation equations become:

$$\frac{dW}{dz} = 2\alpha V \tag{4a}$$

$$\frac{dV^4}{dz} = 4FW \tag{4b}$$

$$\frac{dF}{dz} = (\lambda^2 + 1)W\,\frac{dR}{dz} \tag{4c}$$

The derivative of V^4 appearing in equation (4b), results from the substitution of dV^4/dz for the term $2V^2(dV^2/dz)$ which appears after the use of substitute variables.

The most widely used solution to the above equations is for a uniform ambient density ($dR/dz = 0$) and a source at the level $z = 0$ of positive buoyancy flux $\pi\rho_1 F_1/(\lambda^2+1) > 0$, with no momentum flux ($\pi\rho_1 V^2 = 0$), and no mass flux ($\pi\rho_1 W = 0$). A useful shorthand notation for boundary conditions is the form (F, V, W). The above conditions are written (F_1, 0, 0).

For the boundary condition (F_1, 0, 0), the equations (4a-c) may be solved directly to describe conditions within the plume rising through a uniform ambient density ($dR/dz = 0$). The solution is:

$$F = F_1 \tag{5a}$$

$$V = \left(\frac{9}{5} F_1 \alpha\right)^{1/3} z^{2/3} \tag{5b}$$

$$W = \frac{6}{5} \alpha \left(\frac{9}{5} F_1 \alpha\right)^{1/3} z^{5/3}. \tag{5c}$$

Using the definitions from equations (3a-f), the following are obtained:

$$b = \frac{6\alpha}{5} z \tag{6a}$$

$$U = \frac{5}{6\alpha} \left(\frac{9}{5} F_1 \alpha\right)^{1/3} z^{-1/3} \tag{6b}$$

$$P = \frac{5F_1}{6\alpha\lambda^2 g} \left(\frac{9}{5} F_1 \alpha\right)^{-1/3} z^{-5/3}. \tag{6c}$$

The buoyancy parameter F_1 for a weakly buoyant plume is related to the heat release rate of the fire source $\dot{Q}$ by

$$\dot{Q} \tilde{=} 2\pi C_p T_1 \int_0^\infty ru(z,r)\ \Delta\rho(z,r)dr, \tag{7a}$$

where use has been made of the approximation $T-T_1 \tilde{=} T_1\Delta\rho/\rho_1$ in the constant pressure ambient. With substitutions and integration equation (7a) becomes,

$$\dot{Q} = \pi\rho_1 T_1 C_p F_1/g(\lambda^2+1) \tag{7b}$$

$$\text{or} \quad F_1 = \dot{Q}\, g(\lambda^2+1)/\pi\rho_1 T_1 C_p \tag{7c}$$

It is interesting to note that the plume width (b) for a constant value of α, the entrainment coefficient, is simply proportional to height, z, above the source (Eq. (6a)). Also the buoyancy parameter F_1, equation (7c), is independent of changes in ambient density at the source in a constant pressure system, because density only enters through the constant product of density and temperature.

The equations (6a-c) are widely used to describe the plume above a fire source. With the proper selection of a height for the source point, these equations may be used to describe the plume in the cold or lower layer of a two layer room fire model. The above solution does not continue correctly across the sharp density change associated with the boundary between the upper and lower layers in a two zone room fire model.

3. DETERMINATION OF WEAKLY BUOYANT PLUME PARAMETERS

In recent publications, Zukoski [11,12] sets down several equations for temperature, density, and velocity in weakly buoyant plume flows. Values of several parameters used in the latter work [12], are refinements of estimates used in the early paper [11]. All calculations performed in this paper are based on the values of parameters given in the earlier work which differ only slightly from the refined values. In the earlier work [11], Zukoski draws on experiments performed by Yokoi [13] to obtain values for two empirical constants that determine entrainment rate and relative width between the temperature and velocity profiles. Values given in Zukoski's paper [11] of $C_\ell = 0.125$ and $C_{\ell t}/C_\ell = 1.15$ can be translated into parameters used in this paper of $\alpha = 0.1042$ and $\lambda = 1.15$. Using these two parameters, comparisons can be made between weakly buoyant plume model discussed in section 2 and Zukoski's formulae for plume centerline velocity and density.

Zukoski's expression for maximum velocity, U_{zuk}, is

$$U_{zuk} = C_v \, g^{1/3} \, \dot{Q}^{1/3} \, \rho_1^{-1/3} \, C_p^{-1/3} \, T_1^{-1/3} \, z^{-1/3} \tag{8}$$

From the analysis in the previous section a similar expression for maximum velocity, U, can be calculated

$$U = \left[\frac{5}{6\alpha}\left(\frac{9}{5}\,\frac{(\lambda^2+1)\alpha}{\pi}\right)^{1/3}\right] g^{1/3} \, \dot{Q}^{1/3} \, \rho_1^{-1/3} \, C_p^{-1/3} \, T_1^{-1/3} \, z^{-1/3} \tag{9}$$

To produce equivalent answers, C_v in Zukoski's work must be equal to the value in brackets, or $C_v = 4.14$. Zukoski suggests the use of a value in good agreement of $C_v = 3.8$, based on experimental work performed by Yokoi [13].

Similarly, identical expressions for density defect $\Delta\rho$ may be compared. From Zukoski's work

$$\Delta\rho_{zuk} = C_T\, g^{-1/3}\, \dot{Q}^{2/3}\, \rho_1^{1/3}\, T_1^{-2/3}\, C_p^{-2/3}\, z^{-5/3} \tag{10}$$

From this analysis

$$\Delta\rho = \left[\frac{5(\lambda^2+1)}{6\alpha\lambda^2\pi}\left(\frac{9(\lambda^2+1)\alpha}{5\pi}\right)^{-1/3}\right] g^{-1/3}\, \dot{Q}^{2/3}\, \rho_1^{1/3}\, T_1^{-2/3}\, C_p^{-2/3}\, z^{-5/3} \tag{11}$$

To produce equivalent expressions C_T must be equal to the value in brackets, or $C_T = 8.64$. This agrees well with the value of $C_T = 9.1$ obtained from Yokoi's experiments.

Using the above values for α and λ in the calculation presented here, and the corresponding calculated values for C_v and C_T in Zukoski's formulation, identical velocity and density distributions can be calculated. It should be noted, that with the assumption of the weakly buoyant plume in a constant pressure environment, density and temperature variables can be exchanged with the use of

$$\rho T = \rho_1 T_1 \tag{12}$$

Having examined the plume in the lower cold layer of gas, methods of continuing the solution across an interface between cold and hot layers will now be discussed.

4. TRANSITION ACROSS AN ABRUPT CHANGE IN AMBIENT DENSITY

In the usual room fire situation, shortly after a fire starts to grow, a complex flow of hot combustion gases and cooler room air is set into motion. The global features of this flow are modeled by dividing the room environment away from the fire plume into a hot upper and a cold lower layer by determining an interface height [8,9]. The height of the interface within the room is determined by the size of the fire, the temperature of the hot and cold layers and the geometry of openings in the room. Within each layer, temperature conditions are considered to be uniform.

The method described in section 2 enables one to determine density and velocity profiles for a fire plume in the lower, cold region of the room fire. This solution applies only up to the height of the interface between the upper and lower layers. This height may be assumed to be a known quantity, for this paper, as various methods are available to calculate this height.

Implicit in the use of radially integrated equations (2a-c) and assumed radial distribution (1a-b) is the requirement that the rate of change of conditions in the environment, at the radial plume boundaries in the direction of flow are slow with respect to rate of entrainment and mixing processes that equilibrate the plume velocity and temperature distributions to new ambient conditions. For slowly varying environmental conditions, the assumption that Gaussian distributions of velocity and density defect within the plume asymptote to the ambient conditions at every height is appropriate. However, the

presence of an abrupt change in ambient density presents special problems for the continuation of the solution found in the previous section to describe the plume flow in the lower layer.

At the location of a sharp interface between two gas layers of differing density, environmental conditions change rapidly. The radial distribution of velocity and density defect within the plume is not expected to maintain a simple Gaussian distribution in the radial direction. Cold gas from the lower layer will be forced into the upper layer by the momentum of the gas at the edge of the plume. This gas, being cooler than the ambient conditions in the hot upper layer, can be expected to slow down after crossing into the upper layer, and may then fall back towards the interface. These effects are discussed in more detail by Jaluria [14]. The distance required for a buoyant plume flow to recover a Gaussian distribution of density defect and velocity adjusted to an abrupt increase in ambient temperature has not been studied.

Considering these effects, an exact solution to this problem of a plume transition between the cold and hot layers would be prohibitively difficult and inappropriate for the intended engineering applications. However, several approximate solutions are possible, all of which retain the approximation of Gaussian density defect and velocity profiles in the plume flow on both sides of the interface. For example, a straight forward method to continue the solution of the plume flow in the lower layer into the upper layer is to solve equations (4a-c) in the upper layer using boundary conditions on F, V, and W determined from conditions in the plume flow in the cold layer at the interface height. All solutions to be considered in this report include the

assumption that the entire plume flow from the lower layer continues into the upper layer. This is a good assumption during the growth phase of the enclosure fire of interest for prediction of sprinkler actuation. Other cases, discussed by Jaluria [14], in which the entire lower layer plume flow may not penetrate far into the upper layer may be calculated by adjusting the F, V, and W boundary conditions at the interface.

In terms of conditions likely to be encountered in the growth stages of a room fire, the interface between the hot and cold layers in a compartment may be thought of as the limit of the mathematical processes by which relatively small changes in layer density occur over a vanishingly small change in elevation. Equations (4a-c) show that only two terms may vary greatly in such a region. Even though the overall change in the density between the cold and hot layers may be small, the rate of change in hydrostatic parameter, dR/dz in equation (4c), can be arbitrarily large. The only other term which may become large in response to the rapid change in hydrostatic parameter, is the derivative of the buoyancy parameter, dF/dz. Consistent with equations (4a-c), one may expect that changes in F will be as rapid as changes in layer gas density. Changes in W and V may not be rapid. In the limit of a discontinuous change in layer density, F will be discontinuous, but W and V will be continuous. Physically continuous W and V requires that the plume width parameter and velocity distribution be the same on both sides of a discontinuous change in layer density. For the weakly buoyant plume, this is equivalent to mass flux and momentum conservation across the interface.

From equation (4c), it is clear that within each layer of constant density ($dR/dz = 0$), the value of F does not change. Crossing the interface the value of F will change. The amount of change depends on the assumptions made to describe how the density defect profile adjusts to the abrupt change in ambient conditions.

Sargent [15] assumes that the plume flow equilibrates immediately to the Gaussian distribution of temperature adapted to the increased ambient temperature while maintaining the lower layer velocity distribution. Conservation of excess enthalpy flux with respect to the lower layer ambient temperature is assumed across the interface. This assumption results in an abrupt change in maximum plume temperature as the flow crosses the interface.

Using the assumed Gaussian density defect profile, equation (1b), a similar result may be obtained by requiring that the flux of excess density defect with respect to the lower layer ambient density, ρ_1, be conserved crossing the interface between the cold and hot layers. The expected abrupt change in centerline density defect at the interface is

$$[\rho_2 - \rho_{2,I}(z,0)]-[\rho_1 - \rho_{1,I}(z,0)] = (\rho_2 - \rho_1)\,(1 + 1/\lambda^2) \qquad (13)$$

where subscript I indicates values at the interface height, and subscripts 1 and 2 represent variables in the lower and upper layer, respectively. The value of F_2 may be calculated using equation (3c) with $\Delta\rho_{2,I}(z,0)$ from equation (13) and $W_{2,I} = W_{1,I}$.

Alternately the value of F_2 may be calculated assuming that the centerline density defect is continuous, $\rho_{2,I}(z,0) = \rho_{1,I}(z,0)$. Using equation (3c) the value for F_2 is calculated using either approximation for $\rho_{2,I}(z,0)$ as

$$F_2 = \lambda^2 W_I g \frac{\rho_2 - \rho_{2,I}(z,0)}{\rho_1} \tag{14}$$

In the following section, a solution will be constructed by the method used by Morton [16] that continues the plume into the upper layer using boundary conditions at the interface determined from calculated flow at the interface elevation in the lower layer and assumed transition conditions.

5. PLUME FLOW WITH INITIAL BUOYANCY AND MOMENTUM

Solutions to the weakly buoyant plume equations for boundary conditions other than (F_1, 0, 0) have been calculated by Morton [16]. The solution for the (F_2, V_I, 0) boundary condition must be obtained in order to solve the equations for the boundary condition (F_2, V_I, W_I) needed to continue the plume flow solution across the interface between the hot and cold gas layers. The (F_2, V_I, 0) boundary conditions requires that the plume have both initial buoyancy and momentum, but zero mass flux at the source.

With the change of coordinates $z_2 = z - z_I$ where z_I is the height of the interface above the source in the lower layer, equations 4a-c, to be solved in the upper layer $z_2 > 0$, become:

$$\frac{dW}{dz_2} = 2\alpha V \tag{15a}$$

$$\frac{dV^4}{dz_2} = 4FW \tag{15b}$$

$$\frac{dF}{dz_2} = 0 \tag{15c}$$

with the boundary condition $(F_2, V_I, 0)$ at $z_2 = 0$.

For this problem, explicit formulas cannot be written for V and W in terms of position z as found for the simple buoyant plume calculation with the $(F_1, 0, 0)$, boundary condition. Following Morton [16], the solution takes the form

$$F = F_2 \tag{16a}$$

$$W = \left(\frac{4\alpha}{5F_2}\right)^{1/2} \cdot \left(V^5 - V_I^5\right)^{1/2} \tag{16b}$$

$$z_2 = \left(\frac{4\alpha F_2}{5}\right)^{-1/2} V_I^{3/2} \int_1^{V/V_I} (x^5-1)^{-1/2}\, x^3 dx \tag{16c}$$

Equation (16a) is found by direct integration of equation (15c). Equation (16b) is found by eliminating variable z_2 using equations (15a) and (15b) before integration to determine the relationship between W and V. The relationship between z_2 and V in equation (16c) is found by eliminating the variable W using equations (15a) and (15b).

The integral of the type in equation (16c) can be evaluated numerically. Values are shown graphically in figure 1. For large values of the upper integration limit A in figure 1, the integral grows like $A^{3/2}$. To determine

flow conditions near the interface, and over a range of distances appropriate for hot layer depths in room fires, values of $A = V/\gamma V_I$ close to 1.0 must be considered.

6. PLUME FLOW WITH INITIAL BUOYANCY, MOMENTUM AND MASS FLUX

To continue the plume into the hot, upper layer of a two layer environment, the boundary conditions (F_2, V_I, W_I) must be satisfied by the plume in the hot layer at the interface with the cold layer, $z_2 = 0$. These boundary conditions represent the presence of buoyancy, momentum and mass flux at the interface $z_2 = 0$.

The solution to this problem has also been found by Morton [16]. In his solution, a source of the type (F_2, γV_I, 0) is placed at a position $z_2 = -\bar{z}_2$ below the interface, $z_2 = 0$. Then the unknown parameters $\bar{z}_2$ and γ are determined by requiring the flow from the virtual (F_2, γV_I, 0) source at $z_2 = -\bar{z}_2$ match the desired (F_2, V_I, W_I) conditions identically at $z_2 = 0$. This is the solution to the equations for the boundary conditions (F_2, V_I, W_I) for $z_2 > 0$ or $z > z_I$.

The solution developed in section 5 for the plume from a (F_2, γV_I, 0) source, can be used directly if a displaced coordinate system z_2 is introduced.

$$W' = \left(\frac{4\alpha}{5F_2}\right)^{1/2} (V'^5 - (\gamma V_I)^5)^{1/2} \tag{17a}$$

$$z_2' = \left(\frac{4\alpha F_2}{5}\right)^{-1/2} (\gamma V_I)^{3/2} \int_1^{V'/\gamma V_I} (x^5 - 1)^{-1/2} x^3 dx \tag{17b}$$

where $z_2' = z_2 + \bar{z}_2$ and W' and V' are variables with respect to the displaced coordinates. Applying the desired conditions at the interface

$$W' = W_I \text{ at } z_2' = \bar{z}_2 \tag{18a}$$

$$V' = V_I \text{ at } z_2' = \bar{z}_2 \tag{18b}$$

values for the parameters γ and $\bar{z}_2$ may be calculated as

$$\gamma = \left[1 - W_I^2 \left(\frac{5F_2}{4\alpha}\right) V_I^{-5}\right]^{1/5} \tag{19a}$$

$$\bar{z}_2 = \left(\frac{4\alpha F_2}{5}\right)^{-1/2} (\gamma V_I)^{3/2} \int_o^{1/\gamma} (x^5 - 1)^{-1/2} x^3 dx \tag{19b}$$

Substitution of $\bar{z}_2$ and γ into equations (17a) and (17b) yields the desired solution for the plume in the hot upper layer. This solution is awkward because the independent variable is $V' = V(z_2')$ instead of the distance z_2'. As with the solution for the point source solution (F_1, 0, 0) boundary conditions, values for plume width, velocity, and density may be calculated from the definitions of the F, V and W variables given in equations (3a-f). Crossing the interface between the lower and upper layer, the plume width and velocity distributions are preserved. Peak density defect may be preserved or may change abruptly depending on the assumptions used to calculate F_2 (see section 4). The distribution of density defect remains Gaussian but decays to the upper layer density far from the axis of the plume.

7. APPROXIMATIONS FOR ENGINEERING APPLICATION

Although the solution for plume flow in a two layer environment presented in the previous section may be a good closed form analytic solution possible, it is certainly not convenient to use. For engineering applications, simpler formulations may be desirable. However, the previous solution, although complex, is valuable because it provides a bench mark to which approximations may be compared.

The problem of determining approximations to continue the buoyant plume from the cold to the hot layer has been addressed recently by Cooper [17], in a study of heat transfer to ceilings. In that work, the integrated plume properties of mass flux and mass average temperature in the lower ambient environment are computed from Zukoski's [11] point source plume equations. The integrated plume properties in the upper hot layer are similarly described in terms of flow from a new point source located in a hot layer which, for the purpose of computation of plume conditions in the upper layer, is assumed to be extended below the interface in an imaginary manner. The strength and location of the new point source are chosen so that the mass flux and mass average temperature of the plume flow is continuous across the interface. While these two integrated plume properties are maintained continuous across the interface, the momentum flux, excess enthalpy flux referenced to the lower ambient temperature and the radial distribution of temperature and velocity are not modeled as being continuous. In particular, an abrupt change in centerline plume temperature is allowed as the flow crosses the interface.

For the purpose of determining sprinkler actuation times, it is important to make accurate estimates of gas flow temperatures and velocities near the ceiling. As shown by Alpert [18], gas temperatures and velocities in this flow are directly related to temperatures and velocities in the plume flow before ceiling impingement. It is probable that the ability to predict temperatures along the axis of a plume, particularly near the ceiling, will be an important step towards predicting sprinkler actuation in room fires.

The engineering approximations used by Cooper [17], as discussed above, to calculate heat transfer to ceilings, do not attempt to preserve the distribution of temperature and velocity in the region about the axis of the plume. Instead close attention is given to matching only integrated plume quantities. For the purpose of calculating heat transfer from fire plumes to enclosure ceilings, this approximation appears to be adequate [17]. For the calculation of sprinkler actuation times, where greater accuracy in the prediction of fire plume temperatures may be necessary, this approximation may not suffice.

Consistent with the discussion of plume flow across a rapid change in ambient density in section 4, it may be desirable to preserve the plume width b, and gas velocity on the plume axis across the interface between the lower and upper layers. This corresponds to continuous V and W variables. Note that preserving plume width and maximum velocity on the plume axis also preserves the entire velocity distribution for the flow.

To obtain useful engineering approximations to the plume flow in the upper layer, Cooper [17] has chosen to make changes in the plume source location and strength while maintaining fixed environmental boundary conditions. An alternate choice for approximate solutions, to be discussed below, is to maintain the plume source strength and location fixed and modify the environmental boundary conditions to account for the effects of the two layer environment on the plume flow. This method has the important advantage that the plume width and velocity profiles can easily be made continuous through the interface because the location of the source is not changed.

In general, for the prediction of sprinkler actuation in a room containing a two layer environment, one must account for the cumulative effect of entrained gases from the environment over the distance from the source to the ceiling. It should be observed that using the point source plume flow equations discussed in section 2, all the flow in the plume is entrained from the environment. Therefore, temperature and velocity distributions in the plume depend directly on the entrained mass. One way to replace the two layer environment with a suitable average environment is to determine an equivalent average value of environment density, ρ_m, through which the plume from the given fire source is imagined to pass. The environmental density ρ_m, is chosen such that, at any height above the source, the mass flow in the plume flowing through the two layer environment is equal to that in the plume flowing through the imaginary constant density environment. Thus the average environment density, ρ_m, becomes a function of height above the source at every elevation in the upper layer, but remains equal to the constant density of the lower layer at every elevation in the lower layer.

In order to determine a value for the equivalent average environment density, the plume mass flow at all heights in the two layer environment must be calculated. This can be done by integrating the entrained mass flow from the source to the elevation of interest. To do this, it must be assumed that entrainment at the interface and in the upper hot layer is characterized by the same process as in the lower layer. Using equation (2a) the rate of mass per unit height entrained into the plume is proportional to the product of $bu(z,0)$ and the local ambient density, $\rho_o(z)$.

Integrating the entrained mass flow from the source to any height, z in both the two layer environment and the equivalent average density environment and equating them at every height yields

$$\rho_m(z) = \frac{\int_o^z \rho_o(z) bu(z,0) dz}{\int_o^z bu(z,0) dz} = \frac{\left[\int_o^z \rho_o(z)\ V(z)\ dz\right]\ \text{two layer environment}}{\left[\int_o^z V(z)\ dz\right]\quad \text{average environment}} \qquad (20)$$

The product $bu(z,0)$ is by definition the variable V, (equation (3c)).

From equation (5b), for flow from a point source

$$V(z) = \left(\frac{9}{5} F_1\ \alpha\right)^{1/3}\ z^{2/3} \qquad (21)$$

As discussed in section 2, the value of F_1 is independent of changes in density in a constant pressure system. So, evaluating the mean density for elevations in the plume below the interface $z < z_I$, the values of V(z) in the two integrals will be equal and the mean density will equal the lower level density $\rho_m = \rho_1$.

The values of flow velocity and plume width reflected in V(z) above the interface $z > z_I$ will not be equal to those calculated in a uniform environment at the same distance above the source. In large part this is due to the choice of assumptions used to calculate the change in variable F crossing the interface as discussed in section 4.

Fortunately, for many practical enclosure fire growth problems the changes in the velocity and plume width parameter b, because of the change in ambient density associated with the initial stages of a fire may not be rapid. A suitable approximation for the purpose of calculating a mean density is simply to assume that the variable V(z) be equal to values calculated for a uniform environment. With this assumption, equation (21) can be used for all elevations and equation (20) simplifies to

$$\rho_m(z) = \rho_1 \qquad \text{for } z \leq z_I \qquad (22a)$$

$$\rho_m(z) = \rho_2 + (\rho_1 - \rho_2)\left(\frac{z_I}{z}\right)^{5/3} \qquad \text{for } z \geq z_I \qquad (22b)$$

Equations (22a-b) provide a convenient method to calculate approximate plume flow conditions in the upper and lower layer of the two layer environment using the solution of the flow from a weakly buoyant point source, equations (5a-c) or (6a-c) with variables defined in (3a-f). For flow in the lower layer, the calculation is straight forward, using the lower layer density ρ_1. For positions in the upper layer, the same solution may be used, except that ambient density is replaced by the mean values $\rho_m(z)$ given in equation (22b).

In practice, the above method may be used to calculate flow conditions on the axis of the plume at the ceiling elevation for room size fires. It is expected that the assumptions used in the development of the approximate method will not introduce great inaccuracies in the calculation of plume flow in the region close to the axis for fire sizes and layer depths encountered in room fire situations. Since the calculation may generally be used to determine conditions at only one elevation in the upper layer, the ceiling elevation, the fact that the mean density is a function of elevation in the upper layer does not add a significant burden to the calculation.

At present, testing is being conducted to measure impingement conditions in the flow over a range of fire sizes, ceiling elevations, and layer depths. These measurements are being made in a 1.22 m diameter cylindrical enclosure using a steady fire source. In the next section, the application of both the detailed solutions and various approximation to prediction of plume centerline temperatures are illustrated and comparison is made with one set of measurements collected in the cylindrical enclosure.

8. COMPARISON OF CALCULATION WITH EXPERIMENT

Measurement of the gas temperature along the axis of a plume flowing through both a uniform and quiescent cold and then hot layer environment would be the ideal test conditions for comparison with these calculations. Experimentally this is difficult to do. A less ideal comparison, but closer to conditions that would exist in room fires, would be to establish a hot gas layer in an enclosure, by containing the hot combustion products from the

plume flow. The upper layer, formed by the circulation of these hot gases before eventually flowing from the enclosure, will not be perfectly uniform or quiescent but may be thought of as such.

To study the axisymmetric plume, a particularly useful enclosure shape to maintain axisymmetric flow is a cylinder. A 1.22 m diameter enclosure formed by the 0.29 m deep PMMA curtain around a 13 mm thick ceramic fiber board ceiling was constructed as shown in figure 2. The 0.0365 m outlet of the burner is located 0.58 m directly under the center ceiling of the enclosure. Protective screening that shields the apparatus from room air drafts is not shown in figure 2.

A steady flow of laboratory gas premixed with air to minimize flame height was burned in the enclosure. Combustion products from the plume flow accumulated into an upper hot gas layer contained by the curtain. To compare various methods of calculating temperatures along the axis of the fire plume temperature measurements were made in the enclosure after steady conditions were established by a 0.62 kW total heat release rate (assuming complete combustion) methane fire. Measurements of gas temperatures along the plume axis and in the upper gas layer outside the plume flow are shown in figure 3. The range indicated by the bars attached to each data point for the centerline plume temperatures indicate the amount of signal fluctuation associated with the measurement at each position. Temperatures nearer the burner outlet show greater fluctuations than temperatures measured at positions further away. The average value for the upper layer temperatures used in calculations is shown in figure 3.

8.1 Point Source Solution for Lower Layer

For the purpose of calculation, the interface between the cold and hot layers is located at the bottom edge of the enclosed wall. For the configuration tested, this is at mid-height between the burner outlet and the ceiling, ($z'/H = 0.5$). The upper gas layer is imagined to be large enough so that a region of quiescent, uniform temperature gas at 30 K above the lower layer ambient can be said to exist far from the axis of the plume.

For the test conditions corresponding to the data in figure 3 parameters for the weakly buoyant plume flow model are as follows

$$\dot{Q} = 0.62 \text{ kW} \tag{23a}$$

$$g = 9.8 \text{ m/s}^2 \tag{23b}$$

$$T_l = 296 \text{ K} \tag{23c}$$

$$\rho_l = 1.1923 \text{ kg/m}^3 \tag{23d}$$

$$C_p = 1.0 \text{ kJ/kg K} \tag{23e}$$

$$\lambda = 1.15 \tag{23f}$$

$$\alpha = 0.1042 \tag{23g}$$

In order to calculate plume flow conditions in the lower cold layer region using the above parameters and the analysis of weakly buoyant plume flow from section 2, it is necessary to determine a location for the position of the imaginary point source that best represents the flaming heat source. In the absence of any data, one approximation to locate this position has been suggested by Alpert [18]. Using this approximation, a position for the virtual point source of heat below the burner face is calculated such that the diameter of the plume is equal to the burner diameter at the elevation of the burner surface above this virtual point source.

For the test conditions corresponding to the data in figure 3, a virtual point source located 0.09 m below the actual burner outlet reproduces well the centerline plume temperature data in the lower cold layer. This value differs from the 0.07 m distance that would be calculated by direct application of Alpert's formula [18]. In any event, the portion of the plume calculation that applies to the lower cold layer will be common to all methods of calculating conditions in the upper layer.

Using the above parameters for the heat source strength and conditions in the lower layer given in equations (23a-f), the value of the buoyancy parameter F_l in the lower layer can be calculated using equation (7c). The result is

$$F_l = 0.0127 \ m^4/s^3 \qquad (24)$$

Using this value of F_1, and a point source location 0.09 m below the burner outlet, conditions along the plume centerline anywhere in the lower layer can be calculated.

Besides the experimental data shown in figure 3, five separate calculations of plume centerline temperatures are shown. Each will be discussed in detail. For now, attention should be directed at the single curve corresponding to the predicted centerline temperature in the lower layer ($z'/H < 0.5$). This curve is based on calculated centerline densities from equation (6c) using the value of F_1 given in equation (24). Density and temperature variables are exchanged using equation (12).

At this point it is worth noting, that for this example calculation, plume conditions in the lower layer will be extending into an upper gas layer with an ambient temperature 30 K above the lower layer temperature. This temperature was determined from test data as discussed previously. In practice, application of these calculations will depend on temperatures for the upper and lower gas layers in the room and the elevation of the interface being established by separate calculations. It is assumed that this information can be supplied by developing two-zone models of room fire dynamics.

To make the transition from the lower layer to upper layer values of variables are needed at the elevation of the interface 0.29 m above the burner outlet ($z' = 0.29$ m) or 0.38 m above the point source ($z = 0.38$ m). Values of the key plume variables at the interface, indicated by subscript I, are calculated using equations (5a-c) and (6a-c). For the given test conditions these values are

$$V_I = 0.0701 \text{ m}^2/\text{s} \quad (25a)$$

$$W_I = 0.00333 \text{ m}^3/\text{s} \quad (25b)$$

$$b_I = 0.0475 \text{ m} \quad (25c)$$

$$U_I = 1.475 \text{ m/s} \quad (25d)$$

$$P_I = 0.2943 \quad (25e)$$

As a baseline to judge other methods of continuing the plume flow solution from the lower to the upper layer, the calculation performed in the lower layer can simply be extended to greater elevations completely ignoring the change in ambient temperature. The broken curve A in figure 2 shows the calculated plume centerline temperatures using this method. As would be expected the predicted results fall below measured values, with the difference increasing with increasing elevation in the upper layer.

8.2 Two Solutions for Sources with Initial Mass Flux

To continue the plume flow into the upper layer using solutions for plume flow from sources with initial mass flux, based on work by Morton [16] discussed in sections 5 and 6, values of additional parameters need to be determined. The upper hot gas layer is imagined to be at a uniform temperature of 326 K, 30 K above the lower layer temperature, with corresponding gas density $\rho_2 = 1.0826 \text{ kg/m}^3$. To calculate an estimated value for the buoyancy parameter in the upper layer, F_2, using equation (14), a value for the density

of the gas flowing along the centerline of the plume at the elevation of the interface in the upper layers, $\rho_{2,I}(z,0)$, is needed. This value may be calculated using either of the two methods discussed in section 4. If the plume centerline density is assumed to be preserved crossing the interface then this value of $\rho_{z,I}(z,0)$ is obtained directly from the analysis of flow in the lower layer. Using the definition of variable P, equation (3a), and the calculated value of P_I from equation (25e), the density of gas on the centerline of the plume flow entering the interface is

$$\rho_{2,I}(z,0) = 0.8414 \text{ kg/m}^3 \tag{26}$$

Using equation (14) and the above information, the buoyancy variable for the upper layer is found to be

$$F_2 = 0.008731 \text{ m}^4/\text{s}^2 \tag{27}$$

As found for the lower layer, this value of F is constant for all elevations in the upper layer.

Using values for the various variables and ambient properties in the lower layer, at the interface, and in the upper layer as given above, parameters to describe the source for plume flow in the upper layer, γ and $\bar{z}_2$ can be calculated using equations (19a) and (19b), respectively. For this example, they are

$$\gamma = 0.7931 \tag{28}$$

$$\bar{z}_2 = 0.258 \text{ m} \tag{29}$$

using a value of I = 0.53 for the integral in equation (19b) as read from the graph in figure 1, for A = $1/\gamma$ = 1.261

Using these two parameters, values for W' and V' (W and V variables in z_2' coordinates) can be calculated using equations (17a) and (17b). As discussed in section 6 the determination of W' and V' as a function of elevation is not straight forward because the independent variable in equation (17a) and (17b) is V'.

Corresponding values for z_2', W', and V' were calculated using equations (17a) and (17b) for various elevation in the upper gas layer. The variable dependence on elevation z_2' above the source for flow in the upper layer is changed to dependence on z' the elevation above the burner face with the relation

$$z' = z_2' - \bar{z}_2 + 0.29 \text{ m} \tag{30}$$

where 0.29 m is the distance of the burner face below the interface for the test condition calculated. Values of centerline flow density are calculated using the values of F_2, ρ_2 and W(z') in equations (3c) and (3a). Corresponding values of temperature are calculated using equation (12). The result of the calculation for centerline temperature in the plume flow in the upper layer is shown as curve B in figure 3.

Alternately, the value of F_2 may be calculated assuming that excess density defect flux is preserved across the interface (equation (13)). In this case

$$\rho_{2,I}(z,0) = 0.9243 \text{ kg/m}^3 \tag{31}$$

All other parameters would then be calculated as above. The relevant values are,

$$F_2 = 0.005730 \text{ m}^4/\text{s}^3 \tag{32}$$

$$\gamma = 0.8872 \tag{33}$$

$$\bar{z}_2 = 0.220 \text{ m} \tag{34}$$

$$I = 0.31 \text{ (with } A = 1/\gamma) \tag{35}$$

The result of this alternate calculation for centerline temperature in the plume flow in the upper layer is shown as curve C in figure 3.

The agreement of both curves B and C with the experimental data is good away from the interface. Just above the interface the solutions differ greatly, largely because of the abrupt change in density produced by the method conserving excess density defect flux. Predicted values are consistently higher than measured values for method B, which may in part be due to an increase in excess density defect flux introduced by preserving centerline

density defect and the velocity profile. Predicted values are consistently lower than measured values for method C, which reflects the continued influence of the abrupt decrease introduced at the interface.

8.3 Engineering Approximation - Average Density Environment

Considerable simplification over the method just described can be achieved by using the approximate, average environment method of calculating conditions in the upper layer as described in section 7. To apply the method a mean density $\rho_m(z)$ is determined for each elevation of interest in the upper layer using equation (22b). Each elevation z is measured from the location of the virtual point source for flow in the lower layer. For each location in the upper layer, the solution for the lower layer is continued exactly as described in section 8.1 except that the layer density ρ_1 is replaced by $\rho_m(z)$ in definition 3a. Notice that the change in mean density does not affect the functional form of the solution or the value of the buoyancy variable F_1 for the flow, if a mean temperature corresponding to $\rho_m(z)$ in the constant pressure system is used in equation (7c) replacing T_1. Therefore, values of P are taken for all elevations in the lower and upper level from equation (6c). Centerline density values are calculated using $\rho_m(z)$ in place of ρ_1 in equation (3a) for elevations in the upper layer. Corresponding values of centerline temperature are then calculated using equation (12).

The results of this procedure are shown in figure 3 as curve D. As with the more complex solution curve B, the predicted values of centerline temperature in the upper layer is continuous from the lower layer. The predicted values are close to, but consistently slightly below the previous solution B.

8.4 Engineering Approximation - Substitute Point Source

For completeness in this discussion, it is interesting to apply the method used by Cooper [17] as discussed in section 7 of this report, to predict centerline temperatures in the upper hot layer. Using this method the plume flow in the upper layer is imagined to originate at a point source at both an elevation and with a heat release rate differing from the point source used to predict conditions in the lower layer. For the test case being studied here, the 0.62 kW source located 0.38 m below the interface used to predict centerline plume flow conditions in the lower layer at 296 K must be replaced by a 0.246 kW source located 0.484 m below the interface in a uniform 326 K environment in order to calculate flow conditions above the interface. Again the solution to the weakly buoyant plume flow equations (5a-c), (6a-c), and (7c) apply.

Carrying out the calculation produces curve E as shown in figure 3. This calculation has features very similar to curve C, having an abrupt change in centerline above the interface. In this example, an abrupt decrease of 60 K in centerline temperature is predicted as the plume crosses the interface from cold lower layer to the hot upper layer. As a result of assumptions at the interface, a larger temperature decrease is predicted than for curve C in which density defect flux was preserved. The offset between curves C and E is maintained throughout the upper layer. This results in calculated values for curve E remaining significantly below measured values even near the ceiling elevation which is relatively far from the interface.

9. CONCLUSIONS

Various methods to calculate the continuation of plume flow across an abrupt change in ambient density characteristic of conditions that occur in the initial stages of fire growth in enclosures have been examined. An approximate method to calculate plume conditions both in the lower and upper layer of the two layer environment using the common solution to buoyant flow from a point source with a suitable average ambient has been shown to be at least as accurate as other methods for the single case examined. Accurate prediction of plume temperature is an important step toward prediction of sprinkler actuation times in response to the flow of hot combustion products generated by fires within small enclosures. Although the results of comparing calculations with experiment presented in this report are encouraging, the calculation method requires evaluation over a range of fire heat release rates and layer depths.

10. ACKNOWLEDGMENTS

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Notation

b	characteristic width of plume [m]
C_ℓ	proportionality constant from reference [11]
$C_{\ell t}/C_\ell$	rate of thermal to velocity profile width from reference [11]
C_p	heat capacity [kW•s/kgK]
C_v	constant from reference [11] (equation (8))
C_T	constant from reference [11] (equation (10))
F	buoyancy flux parameter (equation (3e)) [m^4/s^3]
g	gravitational acceleration [m/s^2]
H	ceiling height above burner outlet [m]
I	value of integral (figure 1)
P	density defect parameter (equation (3a))
$\dot{Q}$	convective heat release rate [kW]
u	velocity in plume [m/s]
U	centerline velocity u(z,0) [m/s]
V, V'	momentum flux parameter (equation (3c)) [m^2/s]
W, W'	mass flux parameter (equation (3d)) [m^3/s]
r	radial distance [m]
R	hydrostatic parameter (equation (3f)) [m/s^2]
T	temperature [K]
x	integration variable
z	axial distance above source [m]
z_I	height of interface above source [m]
z_2	distance above interface $z_2 = z - z_I$ [m]
$\bar{z}_2$	distance of plume source, for upper layer flow below the interface [m]
z_2'	displaced coordinate system $z_2' = z_2 + \bar{z}_2$ [m]

z'	axial distance above burner outlet [m]
α	entrainment constant (equation (2a))
γ	parameter for substitute plume modifying V_I
λ	ratio of thermal to velocity profile width
ρ	plume density [kg/m^3]
ρ_o	ambient density at any elevation
$\Delta\rho$	density defect ($\rho_o - \rho$)
ρ_m	mean density for approximate flow calculation (equation (22a-b))

Subscripts

I	interface conditions
1	conditions in lower layer
2	conditions in upper layer
zuk	taken from reference [11] (Zukoski)

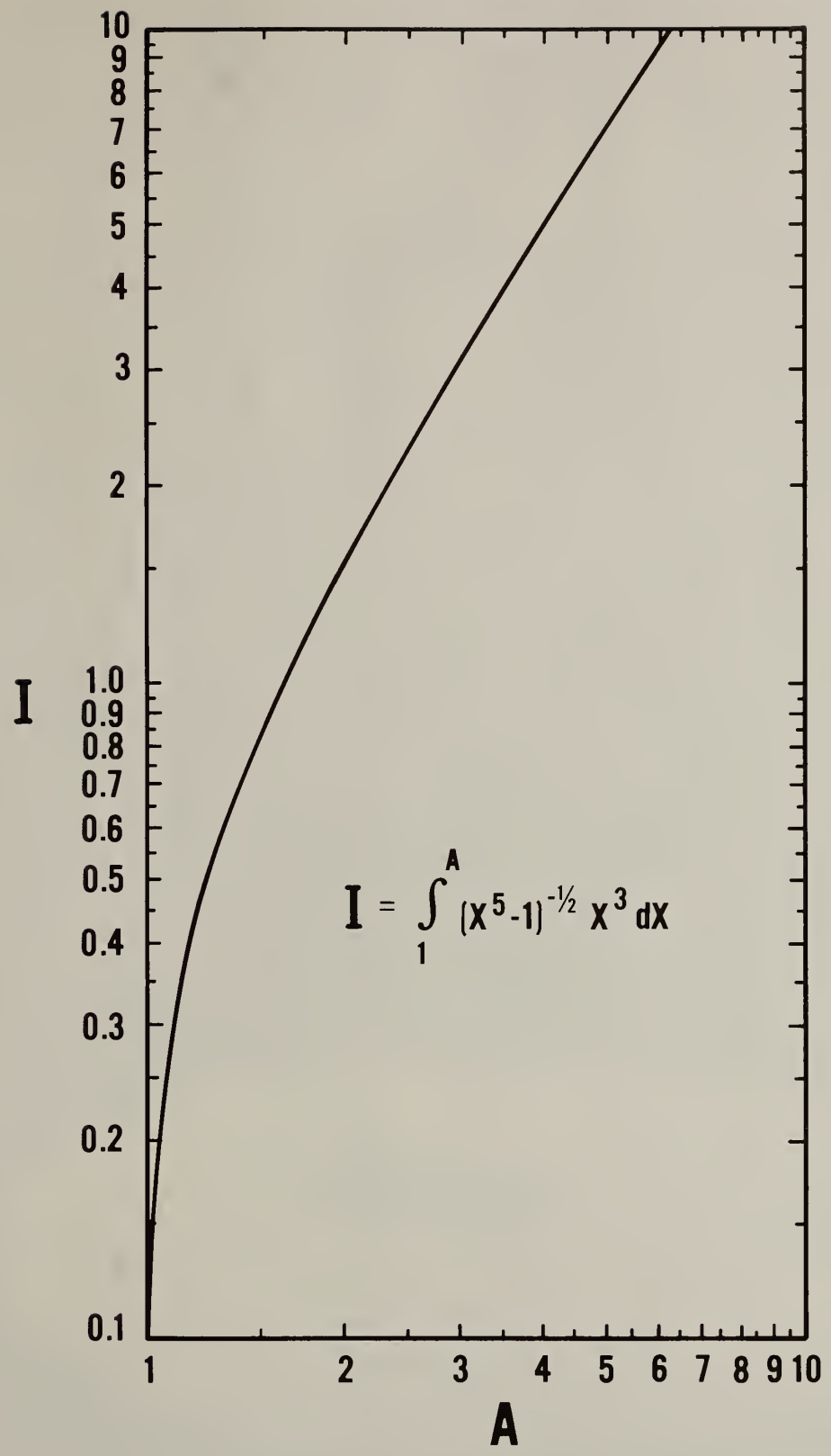

Figure 1. Evaluation of integral $I = \int_1^A (x^5-1)^{-1/2} x^3 dx$

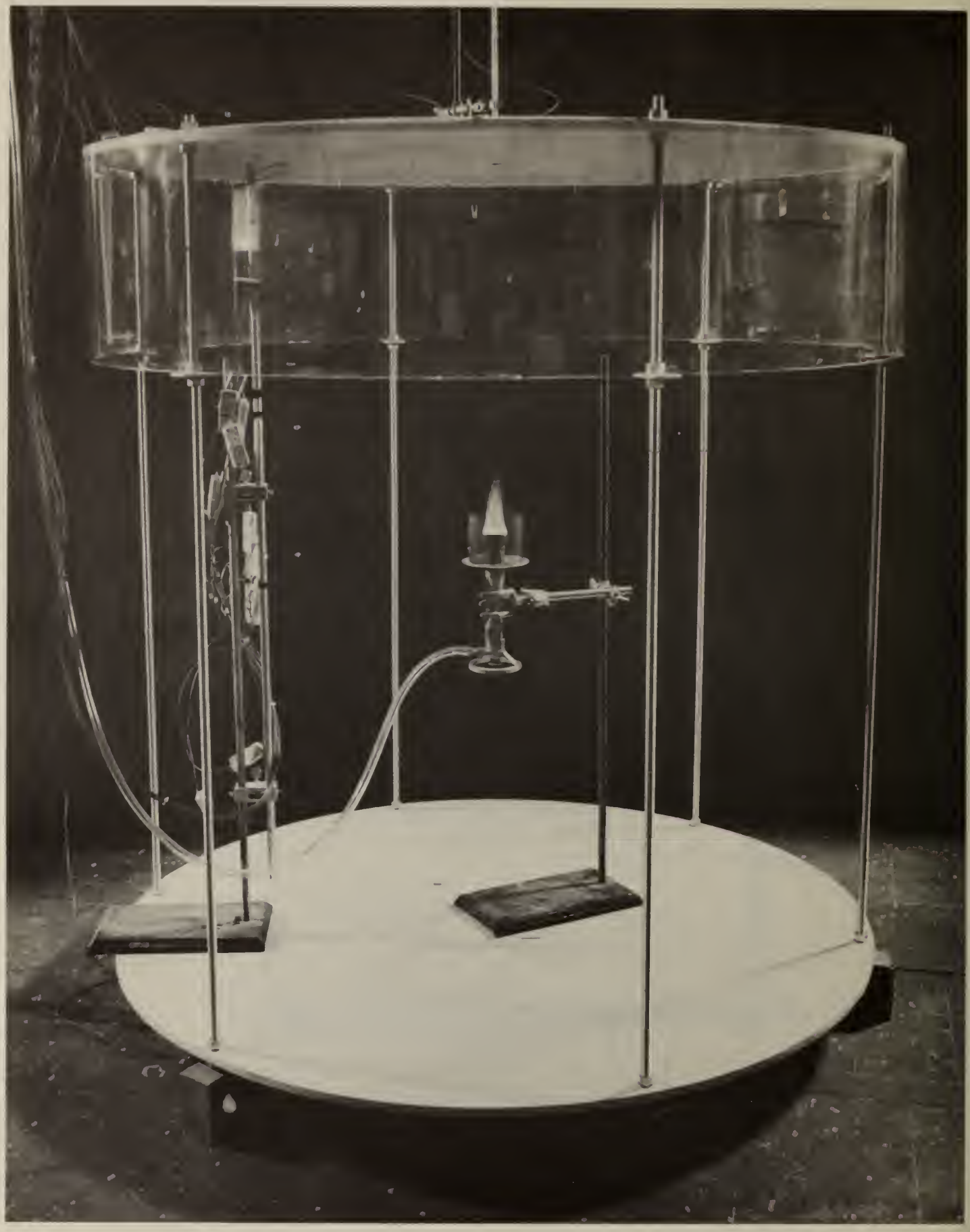

Figure 2. 1.22 m diameter cylindrical enclosure apparatus

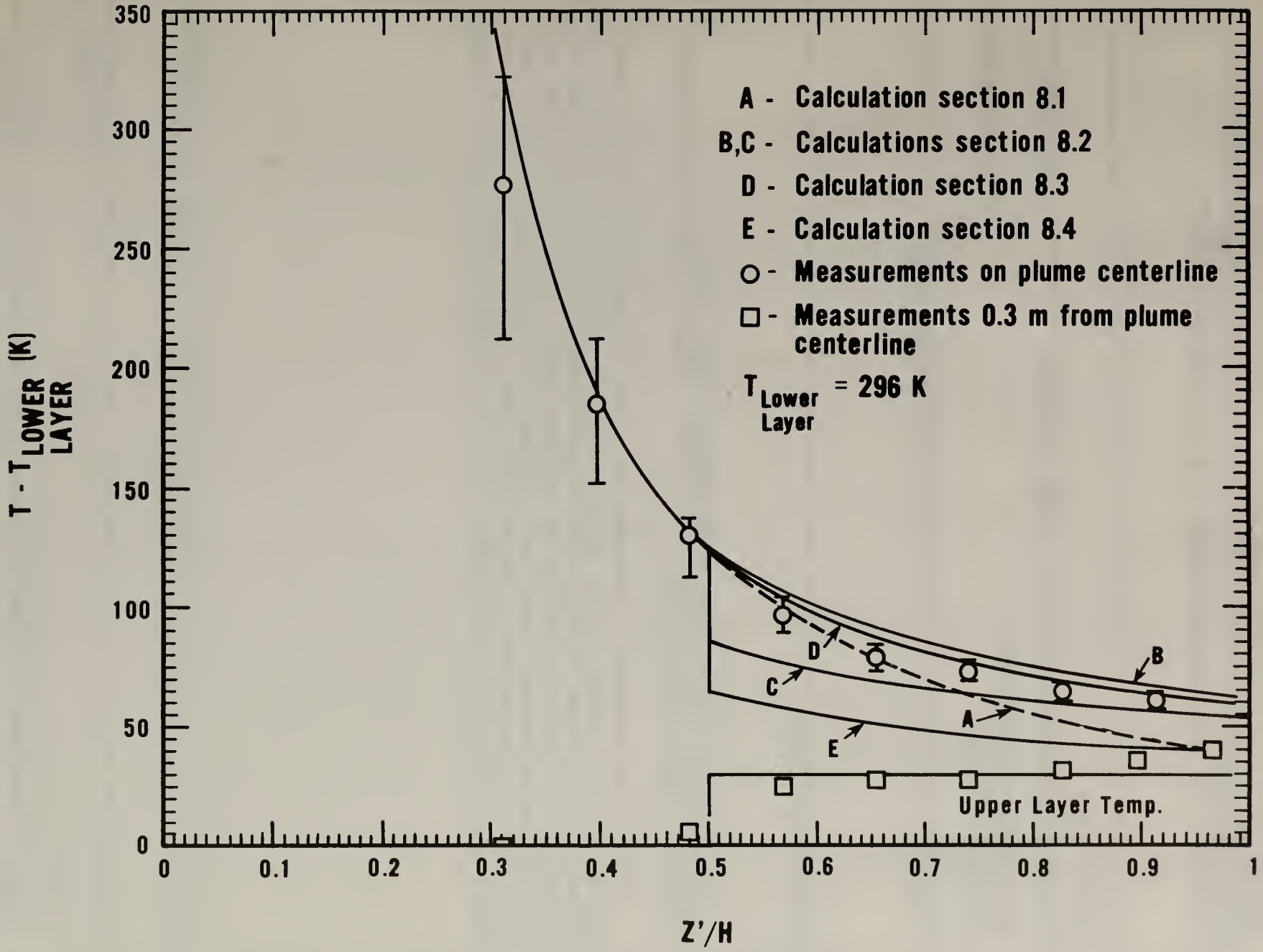

Figure 3. Calculated and measured plume centerline temperatures for a 0.62 kW source

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Methods are developed to determine axial gas flow conditions within a weakly buoyant plume that passes from an ambient quiescent environment, in which the plume originates, to an upper layer at elevated temperatures. The methods are appropriate for inclusion in two layer analysis of enclosure fire. In particular, they are a first step in developing a prediction of actuation time for thermally activated automatic sprinklers exposed to an enclosure fire. Results obtained with various methods are compared with measurements in a 1.22 m diameter cylindrical enclosure.

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

Compartment fires; fire models; fire plumes; room fires; sprinkler systems.

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