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Algorithm for the Mass-Loss Rate of Burning Wall

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ABSTRACT

A derivation is given for a simple algorithm which yields the quasi-steady
burning rate of a vertical panel of non-charring, non-melting material in an
enclosure with stratification of temperature and oxygen concentration. The
algorithm requires the solution of a transcendental equation; it is suggested
that this be done by successive approximations. Among the thermophysical data
which are needed, are the mean flame temperature and the height-dependent
absorption coefficient, $\kappa(z)$. It is found from experiment that $\kappa(z)$ is well
described for PMMA by a two-parameter expression linear in $1/z$. Comparison
with a transient experiment yields good agreement for the mass-loss rate, over
much of the range.

1. Introduction

There are a number of compartment fire models in existence now (see, for
example, [1-6]). Most of these lack an appropriate algorithm to describe a
wall fire. Of the above, only Smith's model [4] considers wall fires, and it
is tied directly to experimental output from a particular apparatus. A
general wall-fire model for burning in compartments must be able to predict
the ignition, and then the time-dependent burning and spread-rates (upward,
lateral, and downward) of a wall fire under conditions of temperature and

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oxygen concentration stratification. It should include the effects of external radiation, and of melting, charring, and burn-through. The present work is a step in that direction. So far, there have been three published models for the burning rate of turbulent wall fires [7-9]; several for upward spread [10-16].

The problem is to predict the mass-loss rate of a fire ignited on a vertical surface, given the dimensions of the pyrolyzing zone, some material parameters corresponding to the wall, any external heat fluxes, and some properties of the flame and plume. Although much of the physics involved in burning is well understood, the complexity of the processes is such, especially for turbulent diffusion flames in an enclosure, that modeling all aspects of it from first principles is as yet an impossible task. The k-ϵ-g approximation (which does not purport to describe the soot-formation process), has had some success in describing the flame and its radiation [8,9], but is very complex. It is demonstrated in this paper that by using some well-known relationships plus one new result, the mass-burning rate can nevertheless be fairly accurately predicted, with a quite simple integral model. Moreover, in distinction from earlier work, this is extended to the case where there is strong stratification in the enclosure. The key is the finding that the mean radiation absorption coefficient varies with height, and that it does so in a simple way. The present model is limited to yielding the steady-state mass-loss rate of non-charring solids.

2. The Pyrolysis Rate

The mass-loss rate can be calculated either point by point, or globally. Since we are principally interested in the total mass-loss rate, any calculations which are made point by point - - i.e., as a function of height, will be

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integrated. To begin, we assume that the ignited (and therefore pyrolyzing) region is rectangular, with the width w and height z_p. The pyrolysis rate, $\dot{m}''$, is proportional to the net heating flux at the surface of the wall: if we have incoming radiation flux ϕ_{in} and incoming convective heat flux ϕ_c, then a heat balance at any point of the surface yields

$$\dot{m}''L_v = \alpha_w \phi_{in} + \phi_c - \phi_{rr} + k \text{ grad } T \tag{1}$$

where α_w is the gray-body absorption coefficient of the wall material. Here ϕ_{rr} is the reradiation flux from the surface,

$$\phi_{rr} = \alpha_w \sigma T_s^4 \tag{2}$$

(the surface is at the temperature T_s. The radiation from the environment is to be included with any other incoming radiation flux). The radiation flux ϕ_{in} is the sum of the flame radiation ϕ_{rf} and that of any external heat fluxes:

$$\phi_{in} = \phi_{rf} + \phi_{ext} \tag{3}$$

The flux ϕ_{ext} explicitly includes the ambient radiation flux σT_a^4 and the "feedback" radiation flux from surrounding hot walls and/or hot gases. k grad T is the heat conduction flux into the solid, and L_v is the latent heat of gasification (i.e. of evaporation or pyrolysis) of the wall material. In experimental measurements of the heat of gasification, neither L_v nor k grad T are measured separately. Instead, an approximately steady state is achieved; then the energy required to vaporize a gram of material is that required to raise its temperature from T_a, its uniform initial temperature, to T_s, the surface temperature during its vaporization, plus its latent heat of vaporization:

$$H_v = L_v + \int_{T_a}^{T_s} c_p(T) \, dT \tag{4}$$

This is its *effective* heat of vaporization, and equation (1) becomes

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$$\dot{m}" = [\phi_r + \phi_c - \phi_{rr}]/H_v \tag{5}$$

for the steady state, where

$$\phi_r \equiv \alpha_w \phi_{in}$$

Note that radiation blocking [17-19] is ignored. In the sections to follow, the various fluxes on the right hand side of Eq.(5) will be calculated.

3. The Radiation Flux.

The external flux will depend entirely on the particular circumstances, configurations, etc. In a compartment within which there is a burning wall, it would consist of the radiation fluxes from the igniting flame, from the hot layer(s), from the hot walls, floor, and ceiling, and from any other fires. In a laboratory, it might be that produced by a radiant panel. Only the radiation flux ϕ_{rf} from the wall flame will be considered in this section. In order to calculate it, the flame temperature, thickness, and absorption coefficient must be known. As shown in the work of Orloff, Modak, and Alpert (ref [20], hereafter referred to as OMA), the thickness of the flame at the height z above the base of the flame, d(z), increases linearly with height up to the top of the pyrolysis region (see Fig. 1):

$$d(z) = \lambda z, \qquad\qquad 0 < z < z_p \tag{6}$$

where λ is the (constant) slope of the flame envelope. OMA found that $\lambda \approx 1/16$ for their PMMA fire; we shall assume it to be the same for all materials. Thus the flame profile is that of an inverted wedge, up to z_p. Although the flame width will explicitly be taken into account, it is here assumed that there are no variations in the fluxes or in the mass-loss rate across the pyrolyzing region, as if this were a two-dimensional calculation. A straight-forward calculation gives the radiation flux as a function of height, for the case where the temperature and the emission coefficient of the hot gases, κ,

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are uniform and constant. Simpler, however, is to use the approximation used

by OMA: they found the radiation flux from the hot flame gases at any point

on the contiguous wall surface by using an equivalent rectangular slab of the

same width and length, but of thickness equal to the local thickness of the

wedge. They then used the mean-beam-length approximation for that parallel-

epiped, for the local flux:

$$\phi_{rf}(z) = \sigma T_f^4 [1 - \exp(-\xi)] \tag{7}$$

where T_f is the (uniform) flame temperature, and ξ is given by

$$\xi(z) = 3.6\kappa V/A = 1.8 \ \kappa \left[\frac{1}{w} + \frac{1}{z_f} + \frac{1}{d(z)} \right]^{-1} \tag{8}$$

where V is the volume of the emitting gas mass and A its surface area. For

the wall flame, w is the width of the flame, z_f is the flame (and therefore

slab) length, and d(z) is the local thickness, given by Eq.(6). This

approximation underestimates the flux for $0 \leq z < z_p/2$, and overestimates it

for $z_p/2 < z \leq z_p$. OMA estimated that $\kappa = 1.4 \ m^{-1}$ and $T_f = 1367$ K, for the

PMMA flame; with these values, Eqs.(7) and (8) yield the flux shown by curve A

in Fig.2. On the other hand, their measurements yield a radiation flux which

is very well fitted by

$$\phi_{rf} = 1.10 + 0.7483 \ z - 0.01 \ z^2 \quad W/cm^2, \qquad 0.5 \leq z \leq 3.56 \tag{9}$$

(with z in meters). This is plotted as curve B in the same figure; it is

distinctly different from curve A. The most important difference is that the

value extrapolated to the origin is a significant fraction of the maximum

measured value. Choosing a smaller value for T_f (1250 K) yields curve C, with

a smaller slope, but does not change the important differences.

However, one need not assume that κ is constant; indeed, by working backward

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from the data, it is possible to infer an effective value for the absorption
coefficient and the gas temperature at each height. When this was done, the
values shown in Fig.3 were obtained, and it was found that T_f is remarkably
constant, at 1285 K. Note, incidentally, that Markstein found a similar
variation of κ with height for pool fires [21]. Since $d(z)$ is proportional to
z, it is clear from Eqs.(7) and (8) that as z approaches zero, ϕ_{rf} approaches
a value proportional to $z\kappa$. In order to obtain a non-zero value of ϕ_{rf} at the
origin, therefore, the expression for $\kappa(z)$ must approach const./z. It is
remarkable that the absorption coefficient shown in Fig.3 is in fact very well
fitted by a simple binomial, linear in 1/z:

$$\kappa(z) = \kappa_0 + \kappa_1/z, \tag{10}$$

with

$$\kappa_0 = 0.651 \text{ m}^{-1} \quad \text{and} \quad \kappa_1 = 0.562 \tag{11}$$

This expression is the key which permits one to properly obtain the
radiation as a function of height. Note that this is a new application of the
experimental results of OMA.

In the simplest approximation, we may take the mean flux to be that received
at the midpoint of the slab:

$$\overline{\phi}_{rf} \simeq \sigma T_f^4 (1 - \exp\text{-}\overline{\xi}) \tag{12}$$

with $\overline{\xi}$ obtained by using Eq.(8) with d given by

$$\overline{d} = \lambda z_p/2 = z_p/32 \tag{13}$$

and $\quad\quad\quad \overline{\kappa} = \kappa(z_p/2) \tag{14}$

In fact, according to Eq.(10), the volume-weighted average absorption coeff-
icient in the pyrolysis region is also given by the midpoint value; that is,

$$\kappa_{av} = \overline{\kappa} = \kappa_0 + 2\kappa_1/z_p \tag{15}$$

Note that κ_{av} is not a constant, so that different-sized slabs will

experience different radiation levels. It also follows that χ_R will not be constant; it also will vary with slab height.

4. The Convective Flux

The mass-loss rate of a burning object whose flame is small and non-luminous is given by the well-known expression [22]

$$\dot{m}'' = \frac{h}{c_p} \ln (1 + B) \tag{16}$$

where B is the Spalding mass-transfer number, h is the heat-transfer co-efficient, and c_p is the specific heat of the gas. B can be written as

$$B = [\nu y_o H_c + c_p (T_g - T_s)]/H_v \tag{17}$$

where ν is the stoichiometric fuel/oxygen mass ratio, y_o is the mass fraction of oxygen in the air, and T_g is the local gas temperature; the other symbols have already been defined. When combustion is incomplete, and there is energy loss from the combustion zone _via_ radiation as well, then the appropriate value for the heat of combustion that should be used in Eq.(17) is

$$H_c' = (\chi_A - \chi_R)H_c \tag{18}$$

where χ_A is the combustion efficiency and χ_R the fraction of energy lost to radiation. With that change, B becomes B', and is the value to be used in Eq.(16). When there is radiation impinging on the pyrolyzing surface, leading to additional heat deposition, there will evidently be an increased rate of pyrolysis. It has been shown [23,24] that for the case where the pyrolyzing gases do not themselves absorb any of the radiation, the radiation can be incorporated as a boundary condition; this permits one to continue to use Eq.(16), but with B' modified by using the "convective B-number"

$$B_c = \frac{B'}{1 - \dot{q}''/\dot{m}''H_v} \tag{19}$$

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in place of B′, where $\dot{q}''$ is the net radiative heat transfer flux (including reradiation). From the energy balance equation (5), the denominator in Eq.(19) can be expressed in terms of the convective heat flux; inserting that into Eq.(16), the latter can be rewritten as

$$\phi_c = \frac{\dot{m}''\ B'H_v}{\exp(\dot{m}''c_p/h)\ -\ 1} \tag{20}$$

This is the expression used by De Ris [25] and others [26,27]. In order to use it, h/c_p must be known; from the experiments of Orloff et al [28], the value

$$h/c_p\ =\ 7.943\ \ g/m^2\ sec \tag{21}$$

can be inferred.

5. Reradiation

If the material is a pure substance (such as water), then there will be a well-defined evaporation temperature T_{ev}, and the reradiation flux is given by Eq.(2), with $T_s \rightarrow T_{ev}$. For a substance such as PMMA, on the other hand, the (local or global) mass-loss rate depends on the surface temperature; for PMMA it can be expressed as an Arrhenius function:

$$\dot{m}''\ =\ A\ \exp(-E_A/RT) \tag{22}$$

Therefore (see OMA)

$$\phi_{rr}\ =\ \alpha_w\sigma T_{so}^4\ \left[1\ -\ \frac{T_{so}R}{E_A}\ \ell n\ \frac{\dot{m}''}{\dot{m}_o''}\right]^{-4} \tag{23}$$

where R is the universal gas constant (R=8.314 J/mole °C), E_A is the activation energy, α_w the grey absorption coefficient, $\dot{m}''$ the actual mass-loss rate, and $\dot{m}_o''$ the mass-loss rate at the reference temperature T_{so}. (For PMMA, OMA

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yields $\alpha_w = 0.927$, $T_{so} = 636$ K, and $E_A = 83.7$ kJ/mole; at $T = T_{so}$, the mass-
loss rate is $\dot{m}_o" = 8.316$ g/m^2 sec, and $\phi_{rro} = \alpha_w \sigma T_{so}^4 = 8.6$ kW/m^2).

6. Calculations for PMMA

   Measurements made by OMA show that for the 3.56 m slab, the average mass-
loss rate is $\dot{m}" = 12.38$ g/m^2 sec. The radiation loss fraction has been
measured by Tewarson and others [27] to be $\chi_R = 0.33 \pm .03$ for large PMMA
pool fires; also, $\chi_A = 0.94$. Although χ_R was not measured by OMA for their
wall fire, it has been observed [29] that the radiation fraction is generally
smaller for wall fires; we have assumed that $\chi_R = 0.30$. All the parameter
values chosen for PMMA are displayed in Table 1. Most of these values are
taken from the literature, or inferred from the OMA data. Using these

Table 1. Parameter values chosen for PMMA and its wall flame [8,20,26].		
$\chi_A = 0.94$	$\chi_R = 0.30$	$T_f = 1310$ K
$\kappa_0 = 0.651$ m^{-1}	$\kappa_1 = 0.562$	$\gamma_s = 8.268$
$H_v = 1.611$ kJ/g	$H_c = 25.2$ kJ/g	$h/c_p = 7.943$ g/m^2 sec
$c_p = 1.0$ J/g °C	$T_{so} = 636$ K	$E_A = 83.7$ kJ/mole
$\alpha_w = 0.927$		

values, a calculation can be made for the mass-loss rate for any other ver-
tical PMMA sample. The calculation proceeds as follows: Eq.(5), with
Eqs.(12) for ϕ_{rf}, (20) for ϕ_c, and (23) for ϕ_{rr}, is a transcendental equation
for $\dot{m}"$. A simple method for solving it is to choose an initial value for the
mass-loss rate, $\dot{m}_1"$, and calculate ϕ_{rf}, ϕ_c, and ϕ_{rr} with $\dot{m}_1"$; then Eq.(5)
yields a resulting $\dot{m}"$. A second choice is then made for the mass-loss rate
on the basis of this first result, and the process repeated. Generally, half

a dozen iterations suffice to yield an answer to four or five significant figures. $\dot{m}''$ is involved in the calculation of ϕ_{rf} through the flame height z_f in Eq.(8). This height is calculated according to

$$z_f = 0.06 \ (\dot{Q}')^{2/3} \quad m \tag{24}$$

(see [16]) where $\dot{Q}'$ is the total power output of the fire per unit width, in kW/m. On the other hand, the calculated value of $\dot{m}''$ is insensitive to the exact choice for z_f; for simplicity one may take $z_f \simeq 1.8 \ z_p$ in order to speed the calculation, if desired. Some experiments [5] made earlier than that of OMA used slabs with a width of 41 cm and height 1.57 m. Proceed-ing as described above, the value $\dot{m}'' = 8.65 \ g/m^2 \ sec$ was calculated. This is only 2% smaller than the measured value, $8.84 \ g/m^2 \ sec$.

The values chosen in Table 1 are all approximate; undoubtedly a set could be chosen (still within the experimental bounds) which would precisely yield the measured value of $\dot{m}''$ for the 1.57-meter slab as accurately as for the 3.56-meter slab. Such precision would be spurious, however.

7. Comparison With Data

A more challenging test of the algorithm is to see whether it will yield reasonable results for cases where there is an external flux, and where the local temperatures and oxygen concentrations vary. This is the situation for a wall burning in a compartment. There, indeed, the fluxes, temperatures, and $Y(O_2)$ all vary with position. Since the algorithm has been developed for the case of <u>uniform</u> conditions, it must be generalized. The simplest approximation is to use area-weighted values of $Y(O_2)$ and T_g in Eq.(17), and assume that $\chi_A - \chi_R$ remains unchanged in Eq.(18). (This is nearly identical

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to summing the contributions from each zone). In a two-zone model, this is particularly easy to do, and that is the procedure used in the following.

Steckler [30] has carried out a series of wall-fire burns on a reduced scale; the floor of the compartment was 1 m x 1 m, and it was 75 cm high; a doorway 55 cm high provided the only ventilation. A 1"-thick slab of PMMA, 28.25" high and 7.31" = 18.57 cm wide was attached to the rear wall. A line burner ignited the PMMA; when the latter was fully involved, the burner was turned off, and the fire allowed to develop. This development was sufficiently slow that the quasi-steady approximation is probably valid throughout most of the experiment. Sensors measured the various temperatures, fluxes, and oxygen concentrations. A load cell measured the mass of the slab, and therefore the mass-loss rate can be calculated. That is shown, for his run #9 (with the doorway width at 33 cm), by the solid curve in Fig.4. The algorithm described above was used to calculate $\dot{m}''$ (and therefore $\dot{m}$) at several times; those results are shown by the open circles, which have been joined by a smooth dashed curve. It is seen that the agreement is quite good from t = 468 sec (when the igniting flame, which gives an extra, unmeasured, flux, was extinguished) to t $\simeq$ 1300 sec. It is increasingly poor from there to t $\simeq$ 1500 sec; after that time, comparisons cease to be meaningful, as the slab buckled and collapsed starting then.

As of this writing, the method has been tested against only one of Steckler's trials; further testing remains to be done.

8. Discussion

The agreement with the Steckler experiment in the region 468 ≤ t ≤ 1309 is surprisingly good, in view of the crudity of the approximations. On the other

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hand, one may ask why then there is a significant disagreement in the region
t > 1309. There are five possible explanations for this disagreement:

a. Radiation blocking, which has been ignored, will reduce the flux absorbed
   by the PMMA, and the effect will be strongest at high mass-loss rates.

b. The calculation assumes that a steady state existed, whereas the
   experimental conditions were transient.

c. The PMMA melts, as well as pyrolyzing, and this will

   i) uncover lower-temperature material in the upper regions, and

   ii) cover (and thereby inhibit the pyrolysis of) material in the lower
       regions.

d. The radiation from a flame burning with vitiated air is weaker than that
   from the usual flame.

e. The oxygen concentration in the upper layer may be too low to support
   combustion there, in the late stages ("oxygen starvation").

These phenomena are subjects for future investigations. Note, however, that
the contribution to the disagreement from items d and e must be small in this
case, since the data shows that [according to Eq.(5)], the external flux
alone, without _any_ contributions from the flame, should still yield a mass-
loss rate in excess of the measured value, for t > 1350.

The method described in this paper is easy to use, and is quite accurate for
PMMA. However, it requires extensive knowledge of material and flame proper-
ties. For the flame emission coefficient, indeed, it requires information
(κ_0, κ_1) which is not generally available. This may be viewed as an experi-
mental challenge; in order to obtain results immediately, however, the obvious
procedure is to ignore κ_1. Alternatively, one can speculate that since κ =
1.5 m^{-1} when it is measured for a pool fire [31], then

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$$\kappa_0 \simeq 0.651 \ \kappa/1.5 = 0.434 \ \kappa$$

and $\kappa_1 \simeq 0.562 \ \kappa/1.5 = 0.375 \ \kappa$.

Another calculational alternative which has been examined is to use an integral (global) approach, without using averages. However, that presents an analogous difficulty: it requires that one know what fraction of the total energy released falls on the pyrolyzing portion of the slab; indeed, it requires knowing it accurately, as the calculation is very sensitive to that fraction. For the 3.56 m case, this fraction is 8.22%; this is just as unknown a number, generally, as are κ_0 and κ_1. Moreover, it is not constant: for the 1.57-meter slab, the figure is 7.45%.

An interesting question is the sensitivity of the results to the parameter values which are chosen. For example, suppose that χ_R had been taken to be $\chi_R = 0.26$ rather than 0.30, above. In order to get the same value of ϕ_c for the large slab, h/c_p would then have to be chosen to be 7.949 g/m^2 sec (rather than 7.943), and the mass-loss rate calculated for the smaller slab would then be 8.649 g/m^2 sec (rather than 8.645). Thus, the results are insensitive to the precise value chosen for χ_R.

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A   Surface area of flame; proportionality constant [Eq.(22)]

B   Spalding mass-transfer number

c_p Specific heat of air

d, d(z)   Thickness of flame, at height z

E_A Activation energy for pyrolysis reaction

h   Heat-transfer coefficient

H_c (Lower) heat of combustion

H_v Effective heat of vaporization

H_c' Heat of combustion, modified for combustion efficiency
             and radiation

k   Thermal conductivity

L_v Latent heat of vaporization

$\dot{m}''$ Pyrolysis (mass-loss) rate

$\dot{q}''$ Net radiative heat transfer flux

$\dot{Q}'$ Power output per unit width

R   Universal gas constant

t   Time

T   (Absolute) temperature

V   Volume of the flame

w   Width of the flame

$y_o = Y(O_2)$ Mass fraction of oxygen

z   Height above base of slab (and of flame)

Greek symbols

α Absorption coefficient

γ_s Stoichiometric air/fuel mass ratio; $= 1/\nu Y(O_2)$

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κ	Emission coefficient of flame gases
κ_0, κ_1	Terms in the expansion of $\kappa(z)$ [see Eq.(10)]
λ	Slope of flame envelope
ν	Stoichiometric fuel/oxygen mass ratio
ϕ	Heat flux
σ	Stefan-Bolzmann constant
ξ	Dimensionless optical depth
χ_A	Burning efficiency
χ_R	Fraction of energy produced going into radiation

Subscripts

a	Ambient
c	Combustion; convection
ev	Evaporation
ext	External
f	Flame
g	(Hot) gas
in	Inward
o	Reference value
p	Pyrolysis
r	Radiation
rf	Radiation from flame
rr	Reradiation (from surface)
s	Surface; stoichiometric
v	Vaporization
w	Wall

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Other Symbols

$\bar{a}$ Mean value of a

$\dot{a}$ Time derivative of a: da/dt

$'$ Per unit length; modified quantity
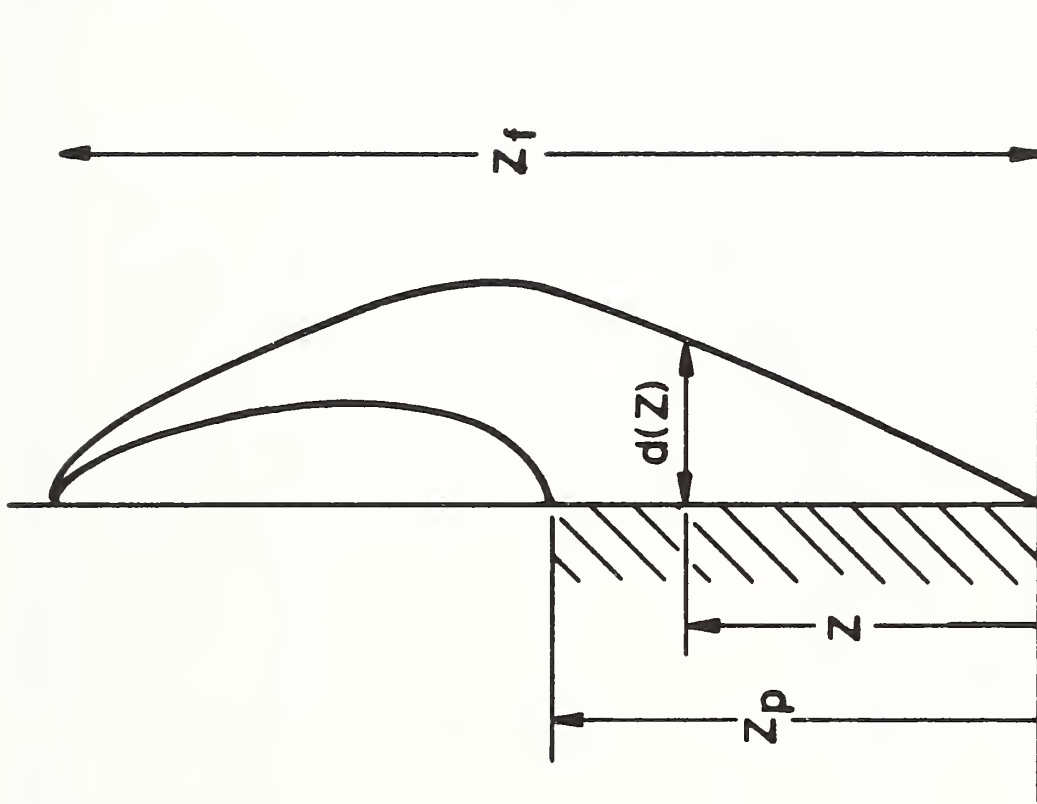
$''$ Per unit area

Figure 1. Schematic of the appearance of a wall flame. The shaded region is where pyrolysis is taking place.
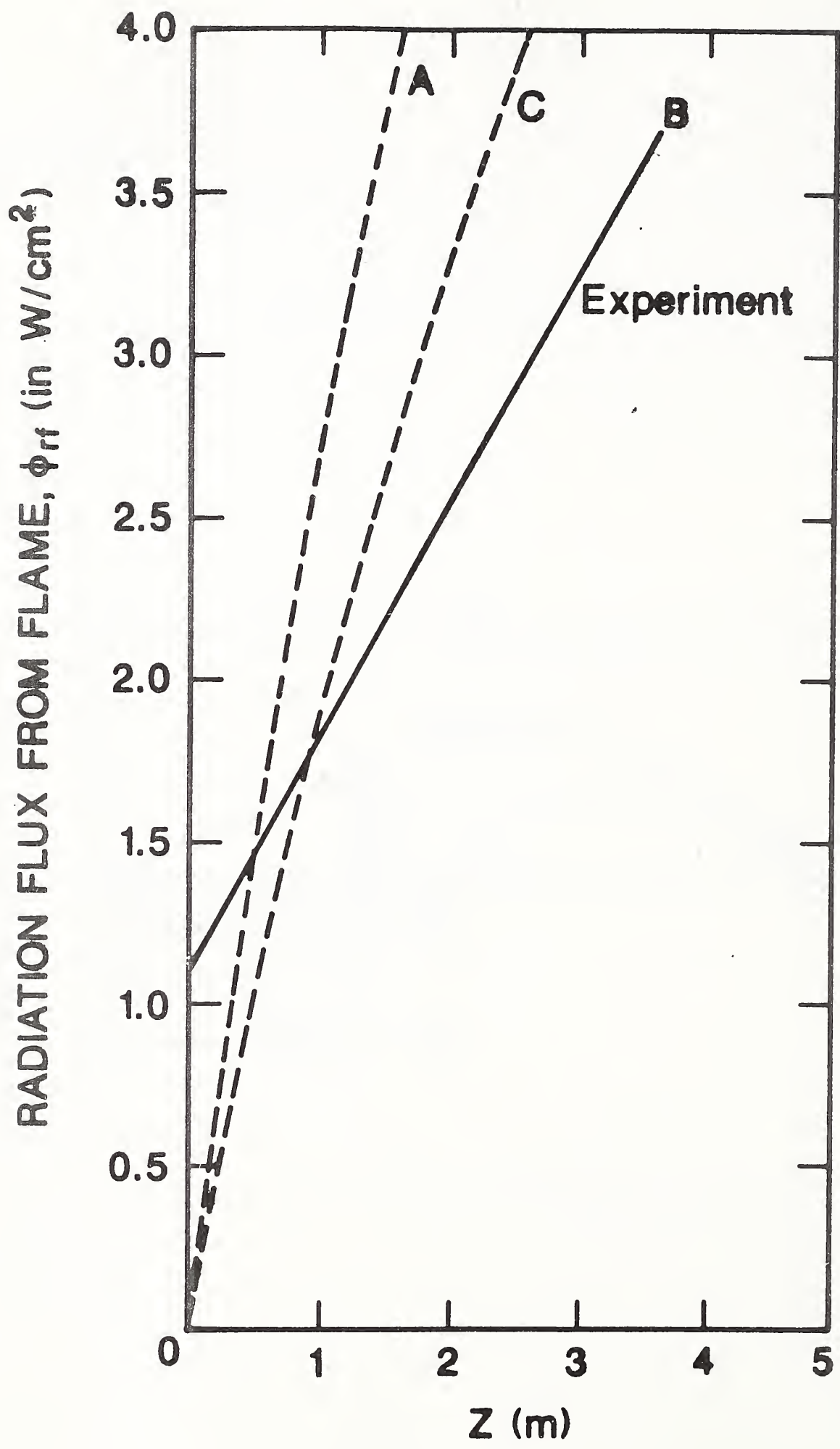
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Figure 2. Curve B is the experimentally measured radiation flux from the flame, as measured by OMA. Curves A and C are the results of calculation with a fixed κ and two different assumed flame temperatures.
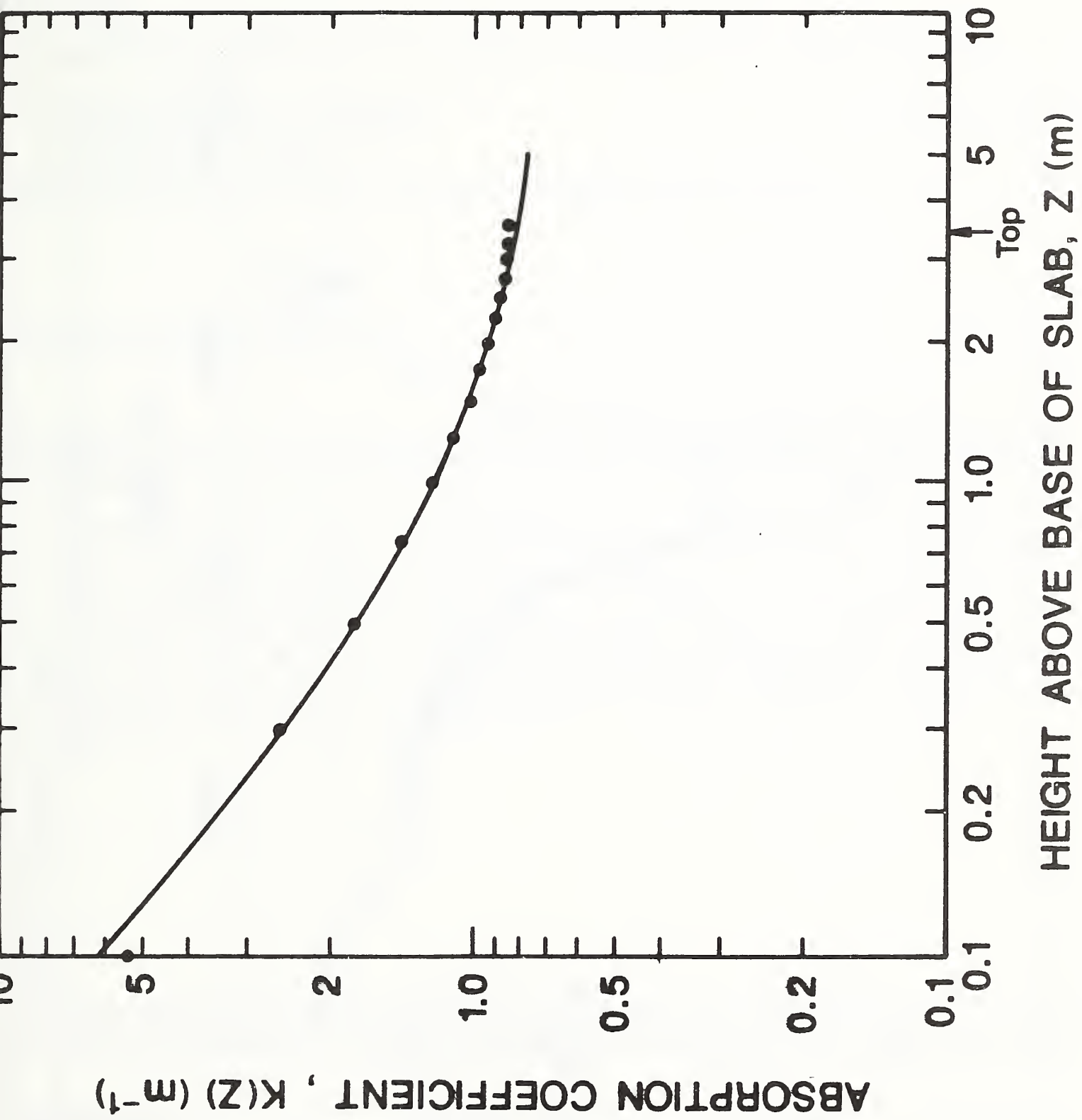
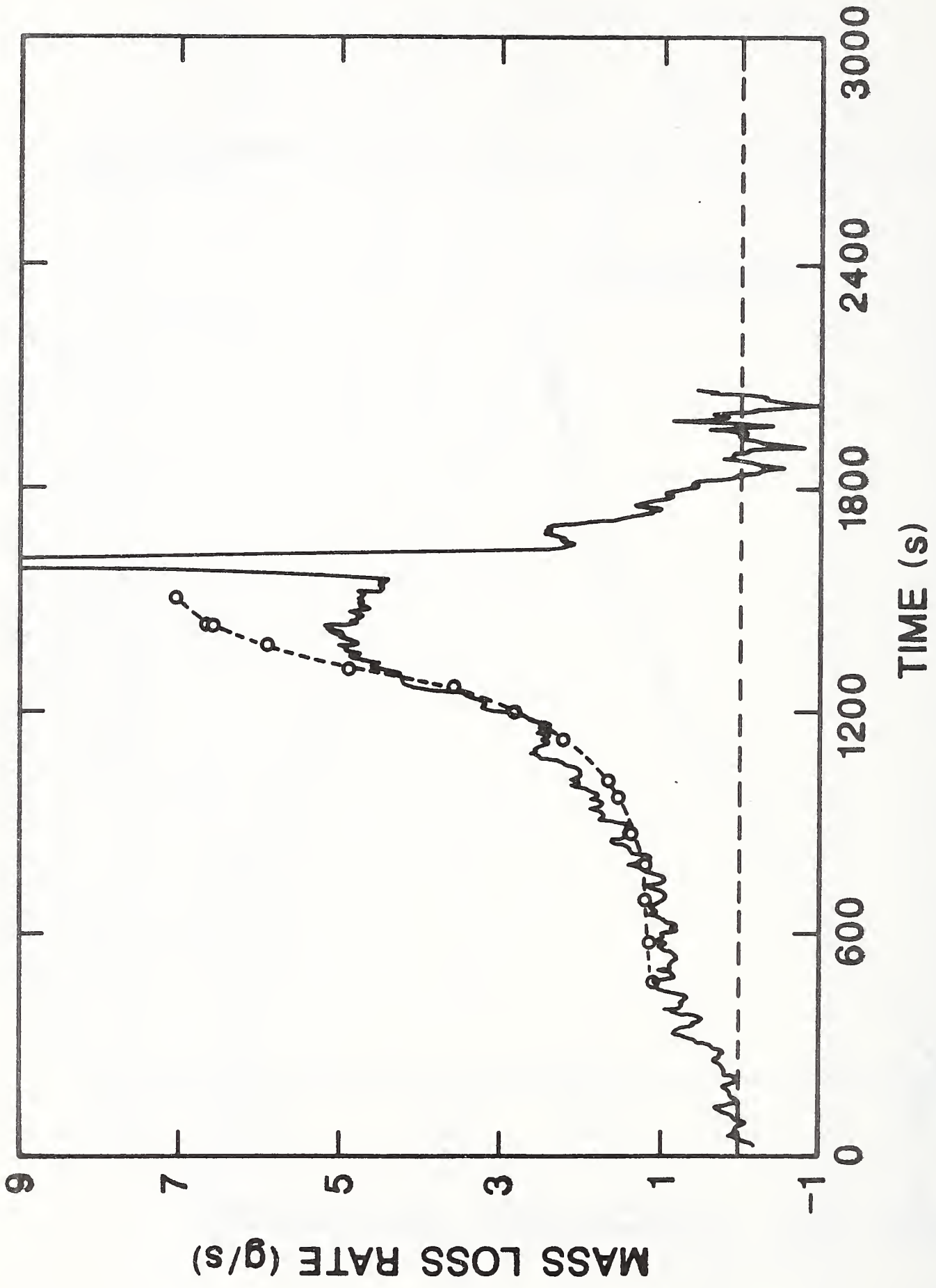Figure 3. Absorption coefficient of large PMMA wall flame, as a function of height above base of slab.

Figure 4. Mass-loss rate of PMMA slab in Steckler's experiment number 9 (with a vent width of 33 cm).

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☐ 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)

A derivation is given for a simple algorithm which yields the quasi-steady burning rate of a vertical panel of non-charring, non-melting material in an enclosure with stratification of temperature and oxygen concentration. The algorithm requires the solution of a transcendental equation; it is suggested that this be done by successive approximations. Among the thermophysical data which are needed, are the mean flame temperature and the height-dependent absorption coefficient, $K(Z)$. It is found from experiment that $K(Z)$ is well described for PMMA by a two-parameter expression linear in $1/Z$. Comparison with a transient experiment yields good agreement over much of the ranges.

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

algorithms; burning rate; computer models; fire models; pyrolysis rate; wall fires

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