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MODELING OF ENCLOSURE FIRES*

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16. Abstract (Limit: 200 words) A proposal was made for an approximate modeling technique for enclosure fires based on the hypothesis that the combustion of a fuel pile in an enclosure depended on associated differences in the fluid mechanical properties and the chemical composition of the gas supply to the fire. Earlier work concerning unconfined fires of wood cribs was reviewed. Under the assumption of large Grashof numbers for the convective flow, application of the modeling hypothesis resulted in the following sufficiency conditions for predicting fire properties on one enclosure scale from experiments on another scale: the enclosures must be geometrically similar; unconfined burning rates of the fuel piles in the two enclosures must be in the ratio of the linear scale ratio to the 5/2 power; porosities of the fuel piles must be conserved from one scale to the other; and the thermal properties of the walls must be modeled for proper thermal response. The third and fourth conditions were not satisfied by experiments available for testing the modeling technique. However, data on burning rates, selected gas species and overall fire behavior conformed well with the modeling hypothesis. Probably due to the fact that wall properties had not been modeled, temperatures did not conform.

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SUMMARY

An approximate modeling technique for enclosure fires is proposed and partially tested. The technique is based on the hypothesis that the combustion of a fuel pile in an enclosure, relative to the combustion of the same pile in open space (unconfined), depends on associated differences in the fluid-mechanical properties and the chemical composition of the gas supply to the fire.

Previous work on unconfined fires of wood cribs is reviewed and consolidated in a form which relates the burning rate per unit exposed surface area to stick thickness and a function of a porosity factor. This factor differs in a small but significant way from a porosity factor proposed previously by Gross(10). Application of the modeling hypothesis, under the assumption of large Grashof numbers for the convective flow, then leads to the following sufficiency conditions for predicting fire properties on one enclosure scale from experiments on another scale: 1) the enclosures must be geometrically similar; 2) unconfined burning rates of the fuel piles in the two enclosures must be in the ratio of the linear-scale ratio to the 5/2 - power; 3) porosities of the fuel piles (defined under equation (10)) must be conserved from one scale to the other; and 4) the thermal properties of the walls must be modeled for proper thermal response (equations (17)).

Experiments available for testing the modeling technique did not satisfy the third and fourth conditions. Nevertheless, data on burning rates, selected gas species (oxygen, carbon monoxide, carbon dioxide), and overall fire behavior conformed well with the modeling hypothesis. Temperatures did not conform, evidently because wall properties had not been modeled. No discernable effects of fuel porosity were observed, but the scope of the experiments was too limited to allow a firm conclusion on porosity effects.

INTRODUCTION

It may eventually be possible to accurately model, on a small scale, a complete fire history for an arbitrary set of governing variables. However, major advances in fundamental fire research are needed before this possibility can be realized. While precise modeling techniques are not currently available, approximate methods do appear feasible and may satisfy many modeling needs. This paper describes recent advances in the development and testing of an approximate modeling method.

Factory Mutual Research Corporation has conducted a large number of enclosure fires to study the evolution of toxic products in ventilation-controlled fires. Two enclosure sizes were used, one being twice the linear size of the other. Various fuels were investigated, including wood cribs, alcohol, paraffin oil, and plastics. Experimental data and general observations from the wood crib fires have already been reported and discussed by Tewarson(1). The wood crib data will be analyzed in this paper for consistency with the proposed modeling method. The experimental program was not designed to prove or disprove ideas expressed here; consequently, only part of the data available is applicable to the current purpose.

Kawagoe(2) made one of the first important discoveries related to fire modeling. He found that the burning of piles of wood pieces in inert, ventilated enclosures was approximately proportional to the theoretical flow rate of cold air through the vent. Except for light fire loads, the burning rate was found largely independent of the fire load. The theoretical air flow rate derived by Kawagoe is closely proportional to the ventilation parameter $Ah^{1/2}$, where A is the vent area and h is the vent height. The enclosure temperature has an effect, but only a minor one.

Subsequent work by Thomas(3) and Simms et al.(4) seemed to confirm Kawagoe's findings on proportionality between burning rate and ventilation parameter, but cautioned that an effect of the fuel surface area may exist. Later, Gross and Robertson(5) found marked deviations from proportionality both at large and small ventilation parameters; beyond a limiting ventilation parameter, the burning rate remained nearly constant and was governed by the fuel bed, rather than the vent. Thomas and Heselden(6) have since discussed in detail the upper bound on the ventilation parameter.

Gross and Robertson(5) attempted to correlate their data on burning rate, temperature, and fire gas composition from differently sized enclosures in terms of the ventilation parameter in ratio to the square of a linear-scale ratio, but the outcome was inconclusive. Heselden(7), who later found effects of the fire load contrary to earlier indications, sought to account for this effect by correlating burning rate per unit fire load with the ventilation parameter per unit fire load. Rasbash and Stark(8) measured fire gas compositions in variously sized enclosures and also found effects of the fire load; these investigators tried as well to correlate their data in terms of the ventilation parameter per unit fire load. Robertson and Gross(9), in a comprehensive review of related investigations, have pointed out that the geometry and arrangement of the fuel may exert a strong influence on fire behavior.

Success in accounting for effects of scale and fuel particulars would, together with Kawagoe's original findings(2), imply that the basic ingredients of a modeling procedure were at hand. However, the attempts made have been sporadic, of only modest success, and of insufficient generality. A rational method of approximate modeling still remains unavailable.

EXPERIMENTS

Only a brief description of the apparatus and experimental method used in the present study is given here; further details are found elsewhere(1).

Two enclosures differing in linear size by a factor of two, and geometrically similar in overall proportions, were employed. Figure 1 indicates the geometric proportions. Width:length:height were in the ratios 1:2:1. The smaller enclosure was 48 cm high and the larger enclosure was 98 cm high (interior dimensions). Each enclosure consisted of a sheet steel box of 0.19 cm wall thickness with an interior lining of insulating asbestos millboard. The thickness of the lining was 1.27 cm in the smaller enclosure and 0.95 cm in the larger enclosure. Each enclosure was vented symmetrically through horizontal vents running the full width of the enclosure at both ends.

The fuel consisted of <u>geometrically similar</u> cribs of Northern White Pine. The number of (square) sticks per layer in the crib was 7, the number of layers was 9, and the length-to-width ratio of the sticks was 13. Stick size was varied to produce cribs with nominal weights of 0.4 kg, 0.7 kg, 1.1 kg, 2.7 kg, 4.7 kg, 9.8 kg, and 14.3 kg. Prior to each experiment, the crib was conditioned overnight at about 100°C. Ignition was by acetone-soaked cotton balls uniformly distributed among crevices in the bottom layer of the crib which were touched off by a match. The cribs were placed in a cradle suspended from an overhead load cell which recorded the weight-loss history.

Many sampling locations for temperature and fire gas composition were distributed throughout the enclosure. Results to be used here were obtained at the sampling point under the ceiling indicated in Fig. 1. Continuous records of temperature and concentrations of selected gas components (carbon monoxide, carbon dioxide, and oxygen) were obtained in each fire. Instantaneous sampling for other products was also made, but the results are not suitable for inclusion here. Temperatures were measured with bare chromel-alumel thermocouples. The sampling flow was through stainless steel tubing to an infrared analyzer (CO and CO_2) and a paramagnetic analyzer (O_2) via traps, filters and dryers.

The various burning modes observed may be described in conjunction with a series of burns of 2.7 kg cribs for different degrees of ventilation in the smaller enclosure. For a relative window height $h/H = 0.32$, where h is the vent height and H is the enclosure height, the burning rate increased to a maximum and then decayed with time in a fashion similar to unconfined burning, a decrease in crib weight to 55 percent of original weight being attained in about 4 minutes. A reduction in vent height to $h/H = 0.20$ had no apparent qualitative effect on the burn, but the 55 percent weight was now reached in about 8 minutes from ignition. For the smaller vent height of $h/H = 0.10$, however, the character of the fire changed. Subsequent to an orderly rise to maximum burning rate, the flames moved to one of the vents, then returned to the crib, and this was followed by several similar cycles. The 55 percent weight was reached in about 13 minutes. For a still smaller vent height, $h/H = 0.06$, the burning rate remained practically constant after the initial rise, accompanied by flames floating above the floor between the crib and one of the vents which gave way to smoldering combustion after 27 minutes from ignition. The 55 percent weight was not reached until about 46 minutes from ignition.

For the purpose of this paper, the burning rate is represented by the time average between 80 percent and 55 percent of original crib weight. In most cases, this interval bracketed the maximum burning rate wherever a clear maximum was indicated. Associated concentrations of CO, CO_2 and O_2 have been averaged over the same time intervals.

MODELING HYPOTHESIS

Initial Approach

The view is first taken that the combustion of a given fuel configuration in an enclosure relative to that in open space (unconfined) depends primarily on associated differences in 1) the fluid-mechanical properties and 2) the chemical composition of the gas supplying the fire. For the burning rate, this dependence can be expressed functionally as:

$$R/R_r = f\ (G,\ \dot{m}_a\ /R) \qquad (1)$$

where R is the (mass) burning rate in the enclosure, R_r is the unconfined burning rate, G is the relative geometry of the enclosure, and $\dot{m}_a$ is the mass flow rate of air into the enclosure. It is here assumed that the Grashof Number of the natural convection is so high that variations in its magnitude are of no consequence (turbulent flow).

The relative geometry of the enclosure, G, refers to ratios such as length:height, width:height, and vent-height:height. But it also includes the relative dispostion of the fuel within the enclosure and the relative gross dimensions of the fuel pile.

The burning rate, R, appears on both sides of eq. (1). However, it is readily shown that a more suitable form can be written:

$$R/R_r = f\ (G,\ \dot{m}_a\ /R_r) \qquad (2)$$

Similarly, the functional forms for gas temperature and composition are derived:

$$\left.\begin{array}{l}\text{Temperature}\\ \text{\% Concentration of gas specie}\end{array}\right\} = f(C,\ \dot{m}_a/R_r,\ \underline{x}/H) \qquad (3)$$

where $\underline{x}/H$ is the nondimensional vectorial location of the observation point, H being a suitable reference length such as the enclosure height.

The functional forms, eqs. (2) and (3), may seem quite reasonable, but being based on phenomenological reasoning, an examination for consistency with prior knowledge in related areas is in order. In fact, it will become evident that the forms may be incomplete.

Burning Characteristics of Wood Piles

Consider the unconfined combustion of wood cribs. For sufficiently large stick spacing, the burning rate per unit surface area, $\dot{m}''$, is independent of stick spacing and the crib is said to be well ventilated. For sufficiently small stick spacing, $\dot{m}''$ becomes dependent on the stick spacing and the crib is said to be underventilated.

Experimentally it has been found that for well-ventilated cribs:

$$\dot{m}'' \propto b^{-n} \tag{4}$$

where b is the stick thickness and n is an exponent variously quoted as 0.6(10) and 0.5(11).

Gross(10) measured the burning rates, R_r, of a large number of wood cribs and concluded, in effect, that for underventilated cribs:

$$\frac{R_r}{A_s b^{-n}} = f\left(\frac{\dot{m}_{ac}}{A_s b^{-n}}\right) \tag{5}$$

where A_s is the exposed surface area of the crib and $\dot{m}_{ac}$ is the mass flow rate of air through the vertical shafts of the crib. Hence, the burning rate relative to that for a well-ventilated crib (obtained by increasing stick spacing) appeared to be a unique function of the mass flow of air relative to the well-ventilated burning rate. Gross demonstrated a fair correlation by assuming that n = 0.6 (based on theoretical arguments) and that the mean air velocity is proportional to the square root of the crib height, h_c, so that $\dot{m}_{ac} \propto h_c^{1/2} A_v$, where A_v is the area of the vertical shafts in the crib.

Block$^{(11)}$ has since carefully restudied the crib problem, both theoretically and experimentally. By considerations of the detailed mass, momentum, and energy transfers in the flow through the crib shafts, he was able to predict burning rates in terms of basic geometries and physical properties of the fuel. Correlation of his extensive burning rate data for cribs appears considerably better in variables that he derived than in Gross' variables$^{(10)}$. A major reason appears to be an experimental finding which directly implies in the context of equation (5) that the mass flow of air through the crib shafts is proportional to $A_v s^{1/2}$, where s is the stick spacing, rather than $A_v h_c^{\frac{1}{2}}$ as used by Gross. Block's correlation is quite general but awkward to interpret in the current context. An attempt has, therefore, been made to use Block's experimental finding implying $\dot{m}_{ac} \propto A_v s^{1/2}$ in the simple form of eq. 5. Using n = 0.5, suggested by Block to give a better fit with experimental data, equation (5) becomes:

$$\frac{R_T}{A_s b^{-1/2}} = f\left(\frac{A_v}{A_s} s^{1/2} b^{1/2}\right) \qquad (6)$$

Figure 2 is the best fit (by eye) through Block's data on burning rate when plotted in the variables of eq. (6). The curve represents all data points to within ±20 percent, as accurately as does Block's own correlation. Thus, Gross' original hypothesis in the form of eq. (5) seems to stand up as well as any other correlation suggested, provided the mass flow of air through the crib is taken in accordance with Block's findings. However, if actual theoretical predictions for burning rates are needed, Block's work$^{(11)}$ remains the only source.

Consequences for Modeling Hypothesis

Suppose the wood cribs of the preceding section were burned in an enclosure. Obviously, the functional form of eq. (6) would now have to include dependence on variables which characterize the change in the crib environment, i.e., the chemical composition and flow properties of the ambient gas. Therefore, one would expect the appropriate form to be:

$$\frac{R}{A_s b^{-1/2}} = f\left(\frac{A_v}{A_s} s^{1/2} b^{1/2}, G, \dot{m}_a/R \right) \qquad (7)$$

This form is identically equal to:

$$\left(\frac{R}{R_r}\right) \frac{R_r}{A_s b^{-1/2}} = f\left(\frac{A_v}{A_s} s^{1/2} b^{1/2}, G, \frac{\dot{m}_a}{R_r} \frac{R_r}{R}\right) \qquad (8)$$

The group $R_r / (A_s b^{-1/2})$ is itself relatable to a variable on the right-hand side according to eq. (6); so eq. (8) can in principle be solved for R/R_r :

$$R/R_r = f\left(\frac{A_v}{A_s} s^{1/2} b^{1/2}, G, \dot{m}_a/R_r\right) \qquad (9)$$

Equation (9) differs from the original form, eq. (2), by the appearance of the additional variable $(A_v/A_s)s^{1/2}b^{1/2}$, which essentially represents the porosity of the fuel pile. If the pile is loosely packed, the porosity factor probably has no effect, as suggested by Fig. 2.

For geometrically similar enclosures and similar temperature and gas concentration distributions, the mass flow of air through the vents is proportional to $H^{5/2}$ (or equally well in more familiar terms, to $Ah^{1/2}$). The final form for the burning rate can, therefore, be written:

$$R/R_r = f\ (P,\ G,\ H^{5/2}/R_r) \tag{10}$$

where

$$P = (A_v/A_s)\ s^{1/2}b^{1/2}, \text{ porosity factor}$$

Similarly, the associated forms for temperature and gas composition become:

$$\left.\begin{matrix}\text{Temperature}\\ \%\text{ Concentration of gas specie}\end{matrix}\right\} = f(P,G,H^{5/2}/R_r,\ \underline{x}/H) \tag{11}$$

Equations (10) and (11) constitute the final modeling relations. Equation (11) states that in order to reproduce temperatures and gas compositions in enclosures of different linear scales H, the enclosures must be geometrically similar (constant G), the unconfined burning rate of the fuel must vary with $H^{5/2}$, and the porosity factor of the fuel, P, must be conserved. Then, according to eq. (10), the ratio of burning rate to unconfined burning rate remains constant in the different scales.

Thermal Response of Enclosure Walls

It has been implicitly assumed so far that all heat lost from the gas phase is by convection at the vents. But heat is also exchanged by radiation and convection at the enclosure walls and lost by radiation through the vents. To conserve temperature from one scale to the next, and possibly in turn other variables (R/R_r, gas composition), these exchanges have to scale as the convective heat flux at the vents, i.e., as $H^{5/2}$.

Since the enclosures are geometrically similar, the vents will transmit a constant fraction of the net radiant flux in the enclosure. The net flux depends on the radiation from the fire and re-radiation from the walls. Since the direct radiation from the fire is expected to scale with the burning rate, which scales with $H^{5/2}$, the radiant loss through the vents will scale properly if the re-radiation scales as $H^{5/2}$.

The re-radiation and convective exchange at the walls have to be forced to scale. In a first approximation, the problem reduces to adjusting the wall properties so that the inside surface temperature reached by the walls during a time interval characteristic of the fire duration is reproduced from scale to scale. It has been estimated that, in insulated enclosures, practically all heat transferred to the walls is stored there. Radiant and convective heat-loss rates from the exterior surfaces of the enclosure are small in comparison with the heat storage rates in the walls. This circumstance simplifies the problem.

Treating the wall as a homogeneous material, the thermal response is approximated by the heat conduction equation:

$$\rho c \frac{\partial (T-T_o)}{\partial t} = k \frac{\partial^2 (T-T_o)}{\partial z^2} \tag{12}$$

with the boundary conditions:

$$q = k \left. \frac{\partial (T-T_o)}{\partial z} \right|_{z=0} ; o = k \left. \frac{\partial (T-T_o)}{\partial z} \right|_{z=\delta} \tag{13}$$

where ρ, c, k are density, specific heat, thermal conductivity of the wall, T is temperature, T_o is initial temperature, t is time, z is normal distance from inner surface, q is the heat transfer rate per unit area to the wall, and δ is the wall thickness. Time is normalized with a characteristic fire duration, t_r, and wall depths, z, are normalized with the wall thickness, δ. Then eqs. (12) and (13) can be represented:

$$\frac{\partial (T-T_o)}{\partial (t/t_r)} = \frac{k t_r}{\partial^2 \rho c} \frac{\partial^2 (T-T_o)}{\partial (z/\delta)^2} \tag{14}$$

$$q \propto \frac{k}{\delta} \left. \frac{\partial (T-T_o)}{\partial (z/\delta)} \right|_{z/\delta = 0} ; o = \left. \frac{\partial (T-T_o)}{\partial (z/\delta)} \right|_{z/\delta = 1} \tag{15}$$

It is concluded that the temperature rise, $(T-T_o)$, is a unique function of t/t_r and z/δ, provided:

$$1.\ \frac{kt_r}{\delta^2\rho c} = \text{constant} \ ; \quad 2.\ \frac{k}{\delta q} = \text{constant} \qquad (16)$$

Thus, if the two conditions in eqs. (16) are satisfied from one enclosure scale to the next, the temperature reached by the inner wall surface of the enclosure in the characteristic fire duration is reproduced.

For the various enclosure scales, $q \propto H^{5/2}/H^2 = H^{1/2}$. The characteristic fire duration can be taken proportional to the ratio of initial mass of the crib (W) and the mass burning rate (R):

$$t_r \propto W/R = (R_r/R)/(R_r/W) \propto (R_r/R)/(R_r/A_s b) = [(R_r/R)/(R_r/A_s b^{-1/2})]b^{3/2}$$

Since R/R_r and $R_r/A_s b^{-1/2}$ are conserved in the modeling procedure (the latter factor because the fuel porosity is conserved, together with eq. (6)), the characteristic fire duration is taken proportional to $b^{3/2}$. Then the requirements expressed in eq. (16) can be written:

$$1.\ \frac{kb^{3/2}}{\delta^2\rho c} = \text{constant} \ ; \quad 2.\ \frac{k}{\delta H^{1/2}} = \text{constant}$$

or, alternatively, by using the second condition in the first:

$$1.\ \frac{H^{1/2}b^{3/2}}{\delta\rho c} = \text{constant} \ ; \quad 2.\ \frac{k}{\delta H^{1/2}} = \text{constant} \qquad (17)$$

Since the stick thickness, b, is involved, any attempt to satisfy these conditions must be coordinated with a method of keeping the porosity factor of the fuel (defined under eq. (10)) constant from scale to scale.

PARTIAL TEST OF MODELING HYPOTHESIS

Adaptation to Current Experiments

It is recalled that the experiments were performed in enclosures of similar proportions. Conditions of geometric similarity (constant G) then prevailed for the same relative vent height, h/H, in the two enclosures.

The wood cribs were geometrically similar, which implies that the porosity factor $P = (A_v/A_s)\ s^{1/2}\ b^{1/2}$ was proportional to b, the stick width, or alternatively, proportional to $W^{1/3}$. The actual weight variations used placed the porosities within the interval "I" in Fig. 2.

No measurements were made of the unconfined burning rates, R_r. However, it was assumed that the correlation in Fig. 2 applied. It may be verified that the interval "I" of the correlation, which represents all the cribs used, is a section of a parabola, so that:

$$(R_r/A_s b^{-1/2})^2 \propto (A_v/A_s)\ s^{1/2}\ b^{1/2} \qquad (18)$$

which for the geometrically similar cribs can be written:

$$R_r/b^{3/2} \propto b^{1/2}$$

$$R_r \propto b^2 \propto W^{2/3} \qquad (19)$$

Thus, the unconfined burning rate is deduced to have been proportional to $W^{2/3}$.

Equations (10) and (11) may now be tailored to the current experiments. R_r is first replaced by $W^{2/3}$, keeping in mind that porosity factors only in the range "I" of Fig. 2 are allowed and that the wood identity is maintained. G is replaced by h/H, and x/H is deleted since all measurements of temperature and gas concentrations were made at the same relative location. To retain familiar quantities as far as possible, the quantity $H^{5/2}$ is replaced by the ventilation parameter $Ah^{1/2}$. Then eqs. (10) and (11) become:

$$\left.\begin{array}{l} R/W^{2/3} \\ \text{Temperature} \\ \text{\% Concentration of gas specie} \end{array}\right\} = f\,(P,\ h/H,\ Ah^{1/2}/W^{2/3}) \quad (20)$$

The requirements for modeling the thermal response of the enclosure walls, eqs. (17), involve both the stick thickness, b, and the enclosure scale, H. Results from the two enclosures are to be compared at common values of h/H and $Ah^{1/2}/W^{2/3} \propto H^{5/2}/b^2$. Hence, since $b \propto H^{5/4}$, eqs. (17) for the current choice of cribs become:

$$1.\quad \frac{H^{19/8}}{\delta\rho c} = \text{constant}; \qquad 2.\quad \frac{k}{\delta H^{1/2}} = \text{constant} \quad (21)$$

Denoting quantities in the smaller enclosure by subscript "S" and those in the large enclosure by subscript "L", these conditions imply:

$$1.\ \left(\frac{\rho_L c_L}{\rho_S c_S}\right)\left(\frac{\delta_L}{\delta_S}\right) = \left(\frac{H_L}{H_S}\right)^{19/8} = 2^{19/8}\ ; \qquad 2.\ \left(\frac{k_L}{k_S}\right)\left(\frac{\delta_S}{\delta_L}\right) = \left(\frac{H_L}{H_S}\right)^{1/2} = 2^{1/2} \quad (22)$$

For enclosures of identical materials, as in the current experiments, these requirements cannot be satisfied simultaneously; the first requires an increase in wall thickness with enclosure scale, while the second requires a decrease. As it turned out, the second requirement was approximately satisfied by the enclosures. However, a far better compromise would have been to design according to the first requirement which, it can be shown, is the only important one in the limit of very high thermal conductivity where the wall is a heat sink of uniform temperature. Since the wall thickness was decreased when the larger chamber was put to use, rather than increased in conformity with the better compromise, wall temperatures and gas temperatures may be expected to be higher in the larger enclosure than in the smaller one.

Results

Figure 3 is a plot of the burning rate factor, $R/W^{2/3}$, as function of the ventilation factor, $Ah^{1/2}/W^{2/3}$, at three different relative vent openings, h/H. Data from the smaller enclosure are represented by open symbols, while data from the larger enclosure are represented by solid symbols. Good agreement is obtained between measurements in the two enclosures. Unfortunately, the number of experiments conducted at similar combinations of $Ah^{1/2}/W^{2/3}$ and h/H in the two enclosures is small.

It is clear from Fig. 3 that the effect of the relative vent opening alone may be significant. At this stage, it is difficult to explain this behavior.

The dashed curve in the figure represents the <u>linear</u> relation between burning rate and ventilation parameter suggested by Gross and Robertson(5) as the best linear fit to data obtained for ventilation-controlled fires in enclosures being proportioned like the present enclosures

$$(R\ (\mathrm{g/sec}) = 0.0015\ Ah^{1/2}\ (\mathrm{cm}^{5/2}),\ \text{or}\ R/W^{2/3} = 0.0015\ Ah^{1/2}/W^{2/3}).$$

However, significant departures from this curve were obtained by the authors. It is remarked that their burning rates were averaged over the time interval from 80 to 30 percent of original crib weight, rather than the 80-55 percent interval used here.

Figure 4 presents concentrations of oxygen, carbon monoxide and carbon dioxide. The correlation between the two enclosures again seems satisfactory. While the data on burning rate in Fig. 3 did not seem sensitive to h/H in the range 0.04-0.06, a corresponding insensitivity was not so evident for the gas composition. Therefore, data from h/H = 0.06 only were elected to represent the smallest vent height.

Temperature measurements are shown in Fig. 5. While the ensemble of points seems to scatter about a wall-behaved imaginary curve, the scatter, in fact, represents effects of both the relative vent height and the enclosure size. The latter effect is on the order of 100°C for the two relative vent heights, $h/H = 0.10$ and 0.20, where experiments were conducted at comparable values of the ventilation factor in the two enclosures. Temperatures are higher in the larger enclosure, a trend anticipated in the preceding section because of improper scaling of wall thickness.

The final plot, Fig. 6, provides a comparison of fire behavioral modes in the two enclosures, as observed by eye. Data from all fires where visual observations were recorded have been used, including a few isolated fires at vent heights other than represented in previous figures. Each fire is represented by a symbol plotted on the coordinates of ventilation factor and relative vent height used for that fire. The appearance of a symbol is keyed to a fire behavior explained in the caption. The letter accompanying each symbol indicates the enclosure where the observation was made, "S" for the smaller enclosure and "L" for the larger enclosure.

For all fires with a ventilation factor exceeding about 10, flames emitted from the top of the crib and impinged on the ceiling (open symbols). For smaller ventilation factors, the flame would generally leave the crib proper to burn just above the floor of the enclosure in the space between the crib and one of the vents (half-solid symbols). Sometimes during these fires, the flame would burn for intermittent intervals at the vent itself (three-quarter solid symbols). Finally, for ventilation factors below approximately 3, flaming would usually give way to smoldering combustion soon after the initial fire-growth stage (solid symbols). In one isolated case, combustion ceased altogether (star); after the enclosure had cooled down, the crib was found to have a burned-out cavity surrounded by virgin wood.

The fire behavioral modes in the two enclosures are seen to be identical at the few, approximately common, combinations of ventilation factor and relative vent height covered in the experiments. Admittedly, no common combinations were tried for small ventilation factors, where the fire behavior is most sensitive to enclosure and fuel variables. However, if no distinction is made among behavioral modes involving flaming away from the crib and, additionally, effects of relative vent height are ignored, a successful gross correlation can at least be claimed.

It is recalled that the fuel porosities, P, were not conserved from the smaller to the larger enclosure. On the basis of Fig. 2, one would not expect an important effect for fuel piles of large porosity. But in the porosity interval "I", which contains the cribs used in these experiments, an effect of porosity could have been anticipated. The limited data presented here are not sufficiently conclusive to rule on the importance of fuel porosity; future work will include a study of this aspect.

NOMENCLATURE

A	total vent area
A_s	exposed surface area of crib
A_v	vent area of crib shafts
b	stick thickness in crib
c	specific heat of wall
G	relative geometry (length:height, etc)
H	enclosure height
h	vent height
h_c	crib height
k	conductivity of wall
$\dot{m}''$	mass burning rate per unit surface area of fuel
$\dot{m}_a$	mass flow rate of air through enclosure vents
$\dot{m}_{ac}$	mass flow rate of air through crib
n	exponent (0.5 to 0.6)
P	fuel porosity factor (defined under eq. 10)
q	heat transfer rate to enclosure wall per unit area
R	mass burning rate of fuel within enclosure
R_r	unconfined mass burning rate of fuel
s	stick spacing in crib
T	temperature
T_o	initial temperature
t	time
t_r	characteristic fire duration

W	initial mass of crib
$\underline{x}$	vectorial location of observation point
z	distance from inner surface of enclosure wall
δ	thickness of enclosure wall
ρ	density of wall

Subscripts

S	smaller enclosure
L	larger enclosure

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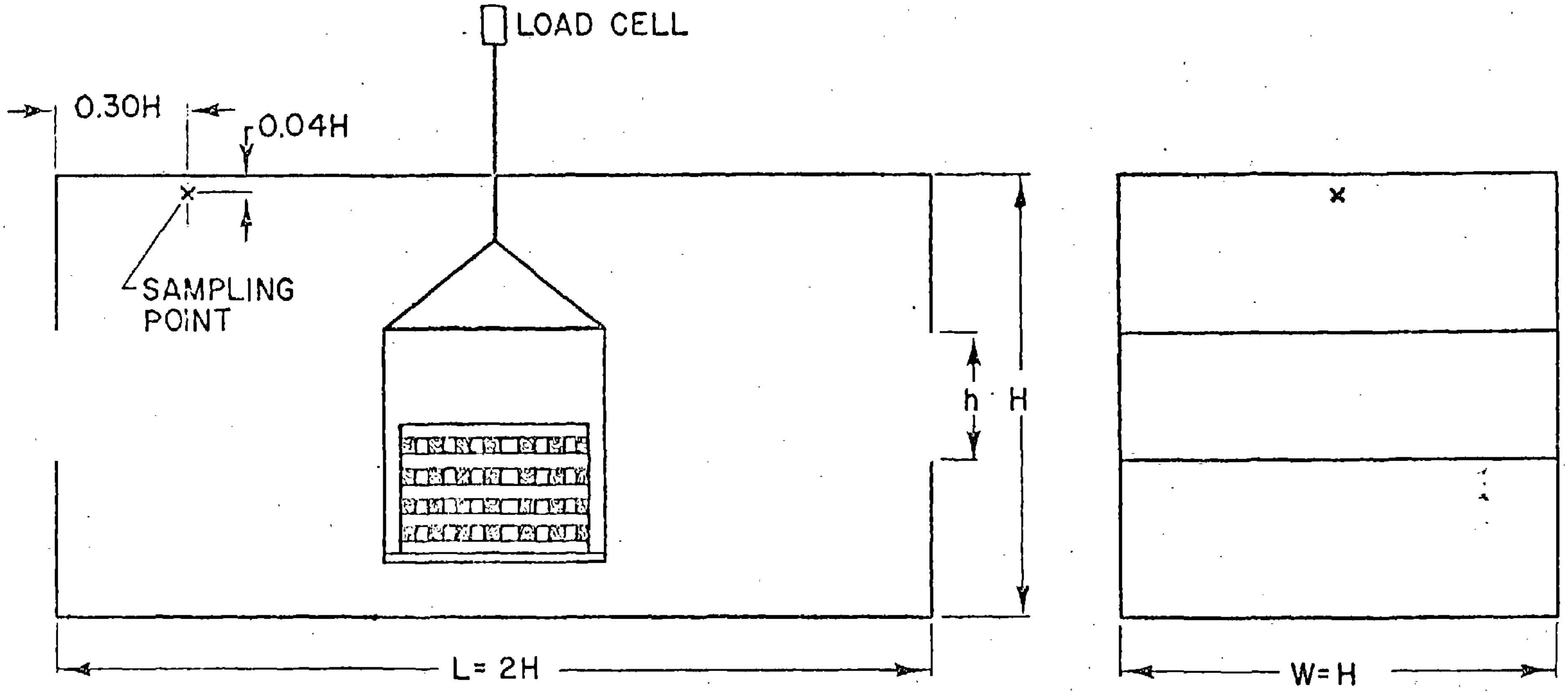
CAPTIONS FOR FIGURES

Fig. 1	Schematic of enclosures. Two enclosure heights were used, 48 and 98 cm.
Fig. 2	Simplified correlation for Block's data(11) on unconfined burning rates of wood cribs (Ponderosa Pine).
Fig. 3	Correlations of burning rates in the two enclosures at various relative vent openings. Linear relation between R and $Ah^{1/2}$ suggested by Gross and Robertson(5) included for reference.
Fig. 4	Major gas components at sampling point.
Fig. 5	Temperatures; average of readings at sampling point and image near opposite vent.
Fig. 6	Fire behavior for various combinations of relative vent opening and ventilation factor in smaller enclosure (S) or larger enclosure (L). Open circles: Flaming on crib. Half-solid circles: Flame floating above floor. Three-quarter solid circles: Flame floating abovefloor, sometimes burns at window. Solid circles: No sustained flaming. Star: No sustained flaming and only about 50 percent of wood consumed.


LOAD CELL
0.30H
0.04H
SAMPLING POINT
h
H
L= 2H
W= H

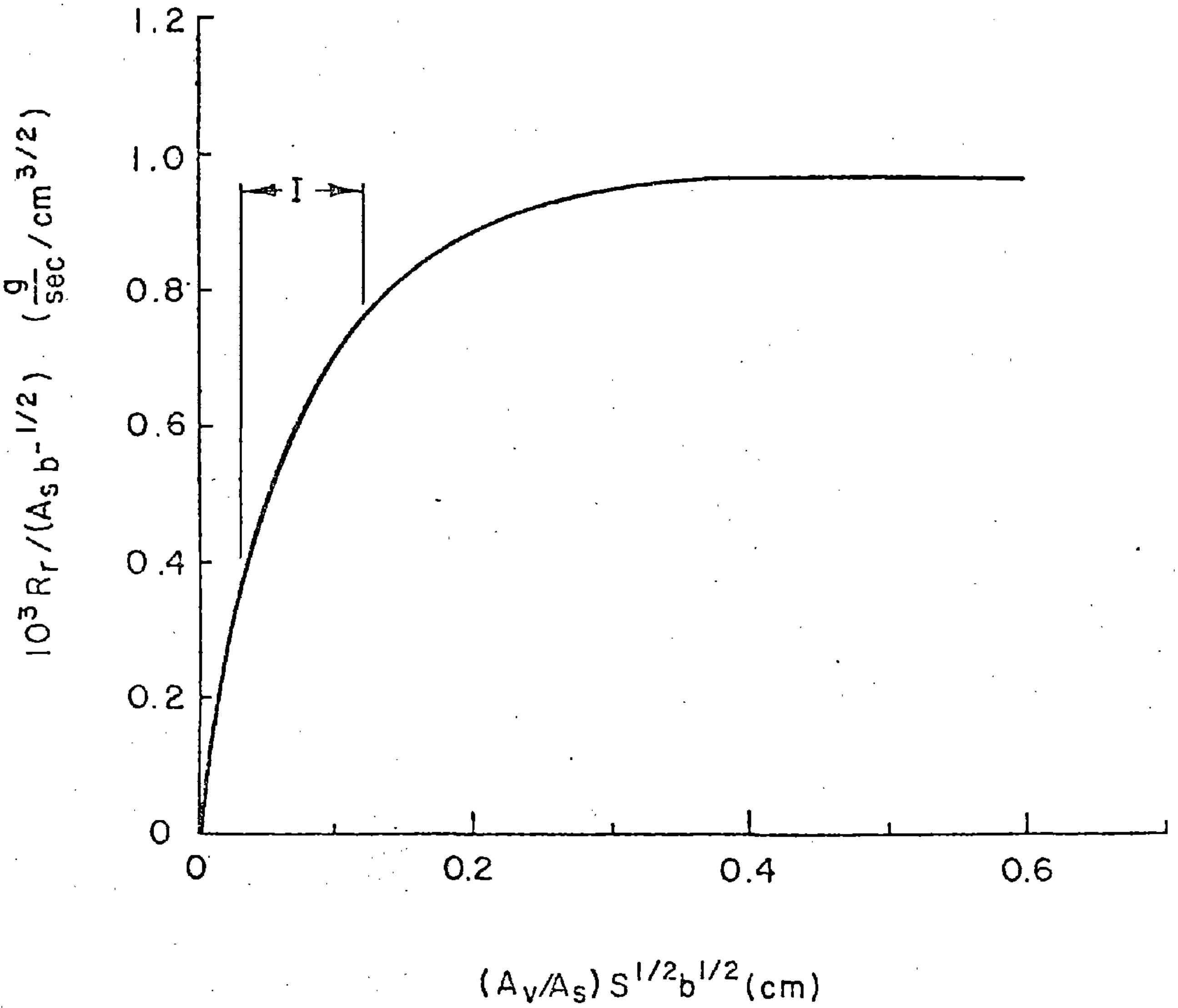
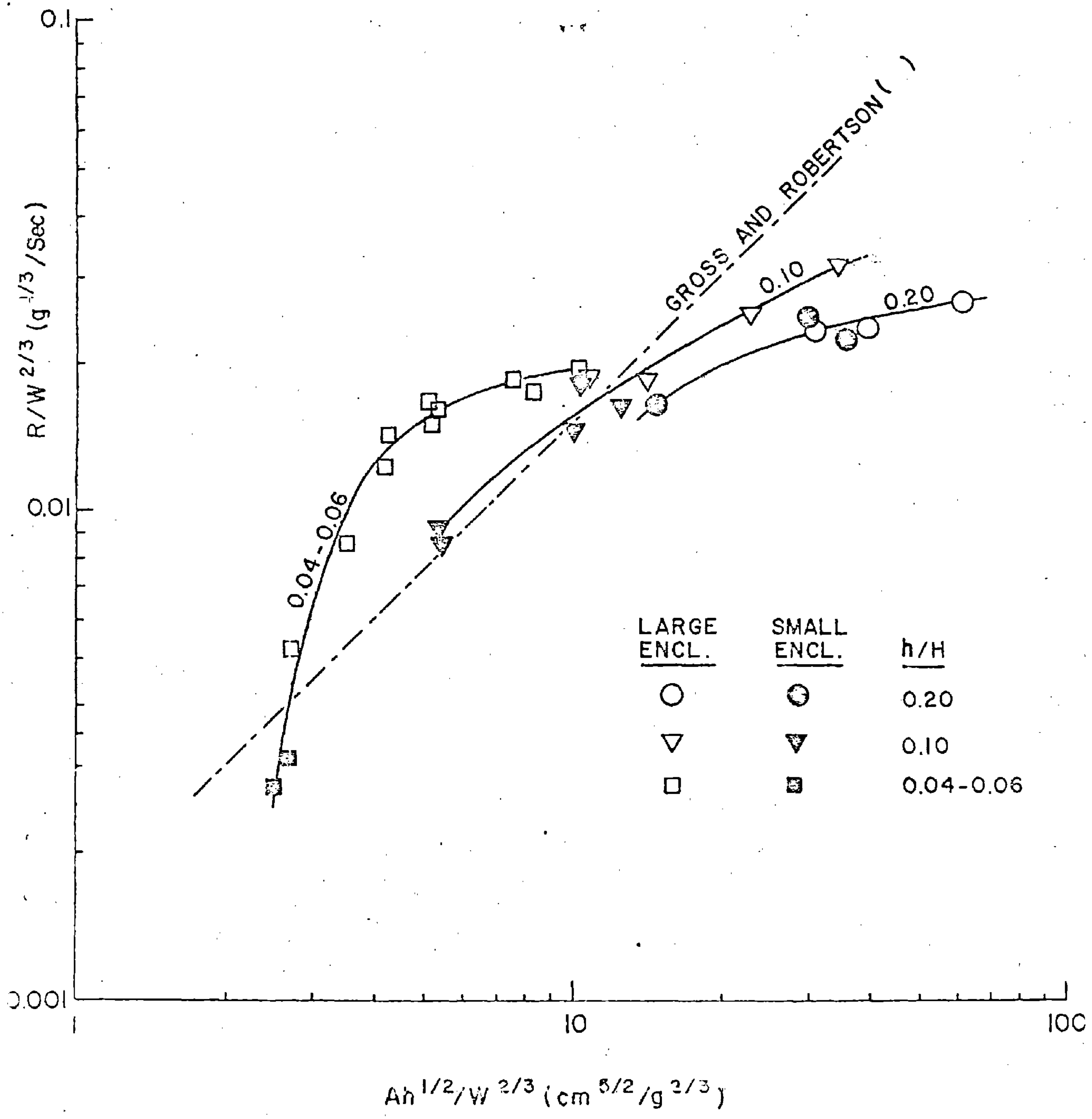
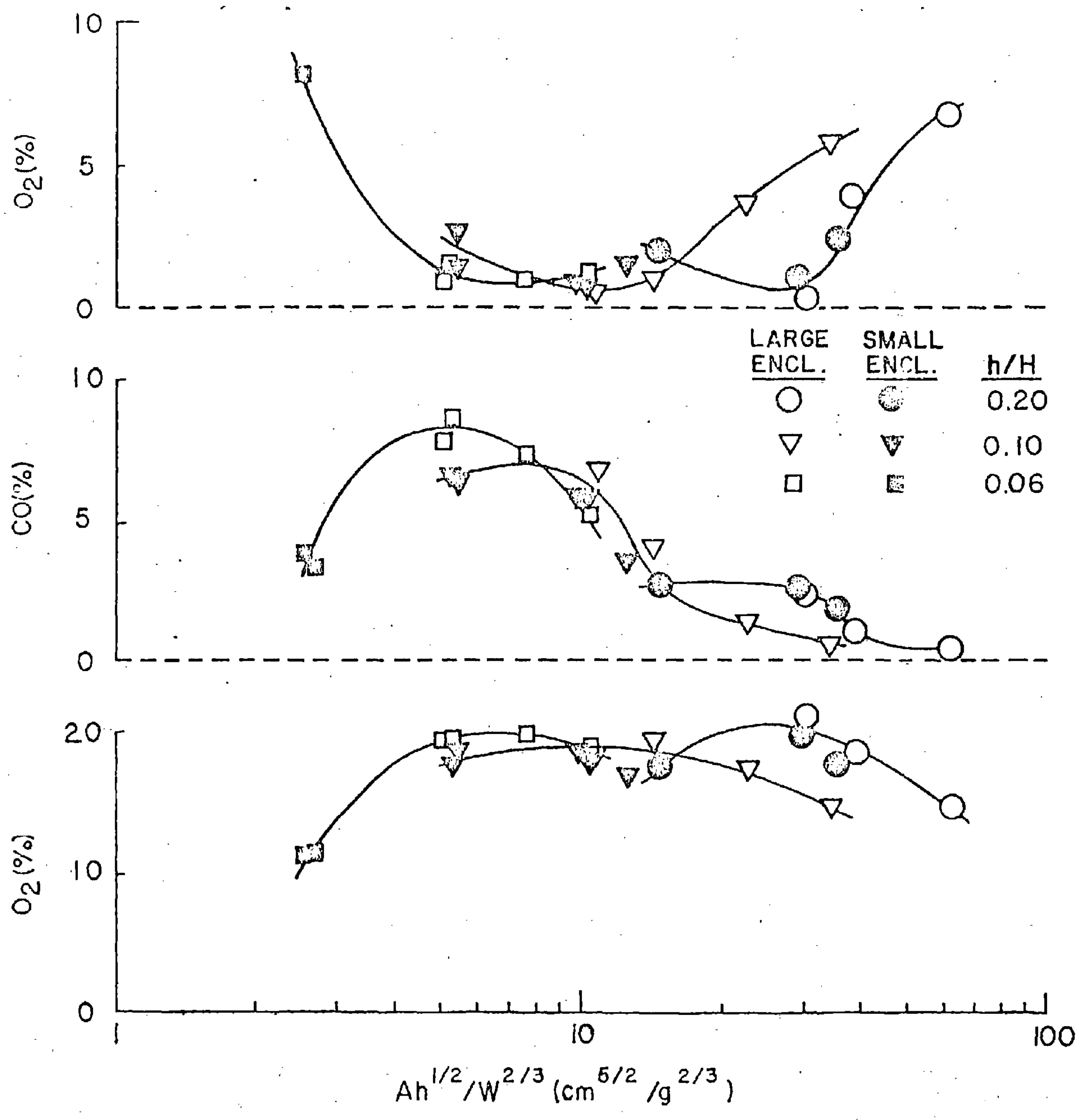
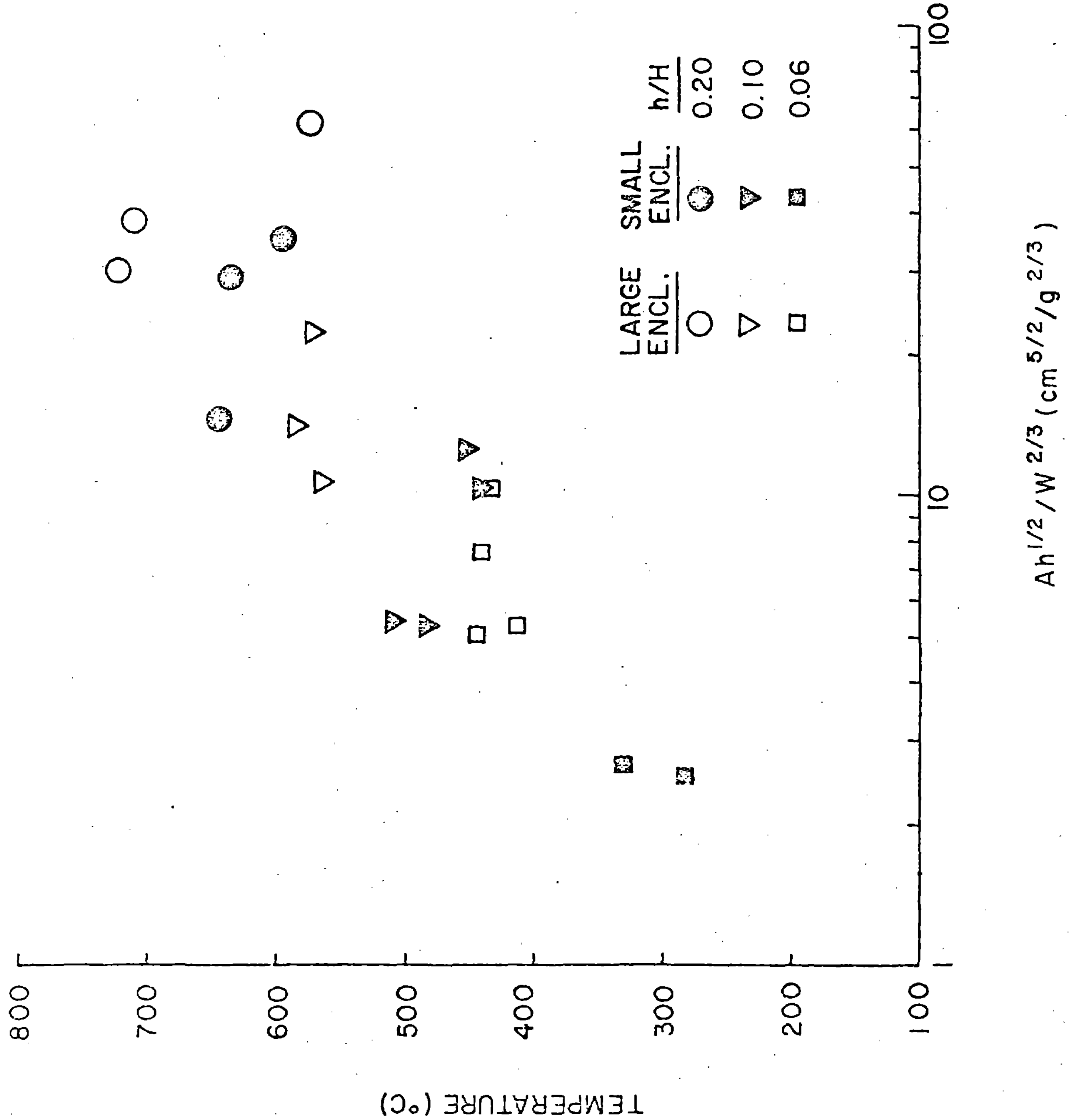

1.2
1.0
0.8
0.6
0.4
0.2
0
I
0
0.2
0.4
0.6
$10^3 R_r/(A_s b^{-1/2})$ $(\frac{g}{sec}/cm^{3/2})$
$(A_V/A_S) S^{1/2} b^{1/2}$ (cm)

FIG 2



0.1
0.01
0.001
R/W$^{2/3}$ (g$^{1/3}$/Sec)
1
10
100
Ah$^{1/2}$/W$^{2/3}$ (cm$^{5/2}$/g$^{2/3}$)
GROSS AND ROBERTSON ( )
0.10
0.20
0.04-0.06
LARGE ENCL.
SMALL ENCL.
h/H
○ ● 0.20
▽ ▼ 0.10
□ ■ 0.04-0.06


10
5
0
O_2(%)
LARGE ENCL.
SMALL ENCL.
h/H
0.20
0.10
0.06
10
5
0
CO(%)
20
10
0
O_2(%)
1
10
100
$Ah^{1/2}/W^{2/3}$ ($cm^{5/2}/g^{2/3}$)


TEMPERATURE (°C)
800
700
600
500
400
300
200
100
10
100
$Ah^{1/2}/W^{2/3}$ ($cm^{5/2}/g^{2/3}$)
LARGE ENCL.
SMALL ENCL.
h/H
○ ● 0.20
▽ ▼ 0.10
□ ■ 0.06

F135

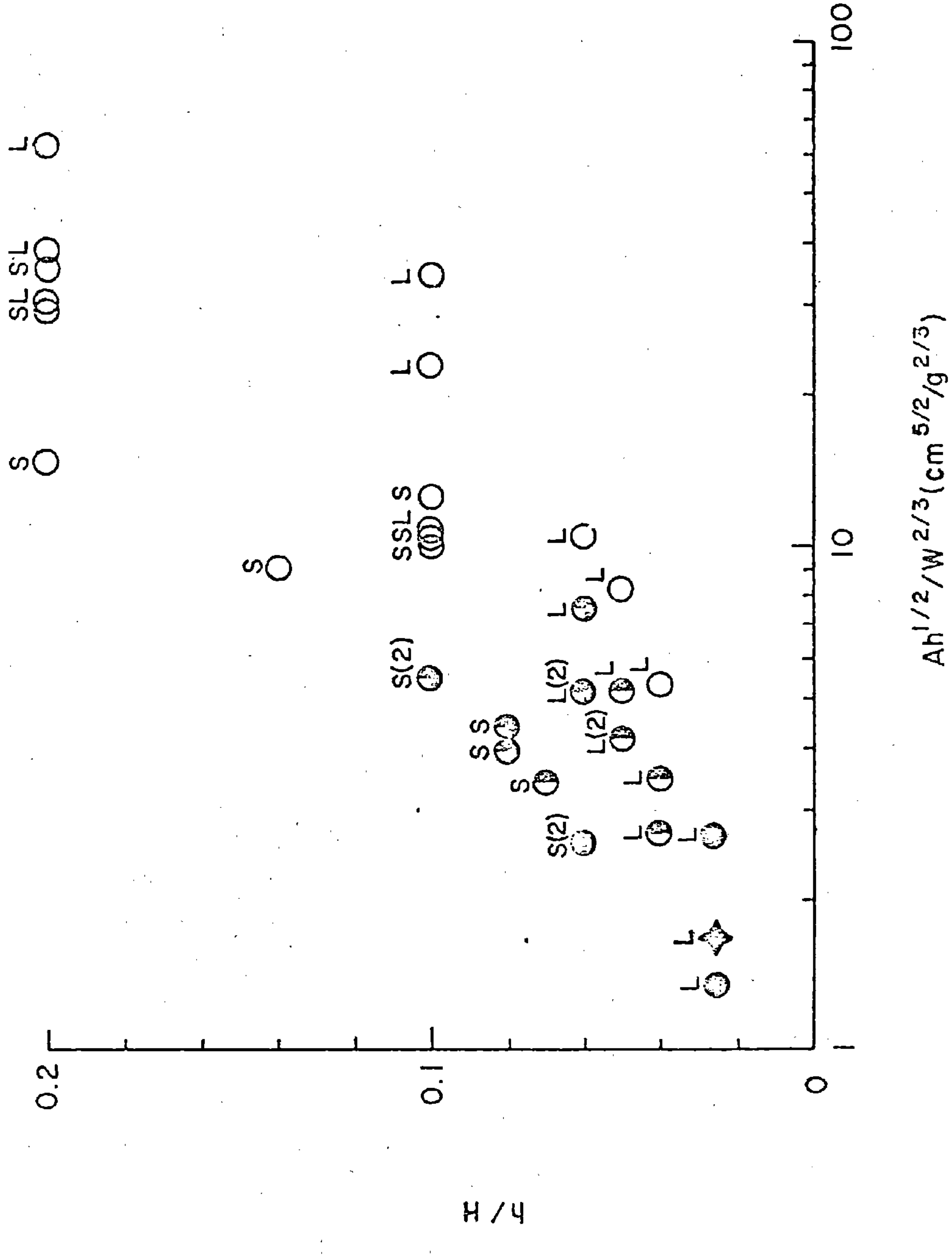

h / H
0.2
0.1
0
10
100
$Ah^{1/2}/W^{2/3} (cm^{5/2}/g^{2/3})$
S
SL SL
L
S
L
L
SSLS
S
L
L
L
S(2)
L(2)
L
L
SS
L(2)
S
L
S(2)
L
L
L
L

Fig. 1