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# Naval Fire Fighting Trainers - Effect of Ventilation on Fire Environment (Model Calculations for 19F3 FFT)

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U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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Abstract

Using state of the art computer simulation techniques, design estimates of ventilation requirements were obtained for the U.S. Navy Fire Fighting Training Facilities. Specifically, two fire-building interaction scenarios were run for the 19F3 trainer: a 2.8 MW fire in an enclosure 4.6 x 4.6 x 3 m high, typical of the largest fire to be encountered in any of the several smaller fire areas (for example, a simulated bilge fire); and secondly, for the "19F3 pit fire" which simulates a deck spill of 6.4 MW in a 9.5 x 7.6 x 9.2 m high room.

Results are presented in terms of the ratio of the amount of air ventilated to the stoichiometric air requirements of the fire. Upper layer gas temperature, oxygen concentration, and the height of the hot upper layer interface are given as a function of this ventilation to stoichiometric ratio. As a guide, it is suggested that a minimum ventilation to stoichiometric ratio of 10 be considered as a starting point in arriving at a final design configuration. A ventilation ratio of 20, or even higher, should not be considered excessive. Probably more valuable than the ventilation design criterion developed would be the use of this study as a tool for the trainer staff. With it the operator is able to predict how a proposed change in any variable might affect trainer performance.

Finally, this study illustrates the need for additional experimental verification of the several mathematical plume entrainment models now existing, especially for their use in large fire applications. Recent analysis due to Rockett [1] stimulated by this work reinforces this point.

## 1. INTRODUCTION

The need for all weather, large scale fire training capability is relatively recent; consequently, the design of buildings to house large fires is not a well developed technology. Here "large" refers to a flame height or flame base area being a significant fraction of the dimensions of the enclosure. By contrast, a small bunsen burner flame in a laboratory generally does not affect, nor is it effected by, the enclosure environment. The heat release rate or combustion process does not significantly raise the temperature nor lower the oxygen concentration in the laboratory. Thus it is not necessary to bring fresh, make-up air into the building. On the other hand, as one increases the size of the fire, the building enclosure becomes dramatically coupled to the dynamics of the fire. Unlike the bunsen flame, the enclosure now has a pronounced effect on the behavior of the fire and the fire markedly influences conditions in the building. Unless exhausted properly, the hot combustion products will begin to "fill up" the upper part of the building. This layer will grow in volume - the interface between it and the cool air below will move down toward the floor. Its temperature will continuously increase and its oxygen content continuously decrease. A variety of dynamic coupling effects will then take over.

For further clarity, the difference between a naturally occurring fire and flames in a furnace combustion chamber must be contrasted. To casual observation, flames filling an enclosed volume containing inlets and outlets, such as occurs in a furnace, might seem to be similar to a fire occupying the interior space of a building enclosure. This view is quite incorrect.

In the case of the furnace, fuel and air, whether premixed outside the combustion chamber or aspiratedly diffused or mixed inside, are mechanically brought together for combustion by the burner. This is the big difference between furnaces and fires and the implications are far reaching. In fires, air is brought to the fuel via buoyancy forces, developed only by the fire itself. These forces are orders of magnitude smaller than those developed by the mechanical systems of burners installed in combustion chambers. The mixing process is much more efficient for the furnace, which means the furnace requires much less air than a naturally occurring fire of comparable heat release rate. The amount of air required for the furnace is close to the stoichiometric value (the theoretical amount of air required to convert all the fuel into the most stable product molecules). The flames in furnaces are generally hot, short and blue unless specifically designed to have a significant radiative heat transfer component. On the other hand, due to poor mixing in naturally occurring fires, lower temperatures are found. The flames are generally quite luminous due to carbon particles which are either oxidized in the upper regions of the flame zone or released as soot particles above it. This luminous zone or flame volume is much larger than that of a premixed flame of equal fuel flow rate. Because of poor mixing characteristics, longer times and distances are needed to get the required contact between the fuel and air.

If we define the flame tip as the end of the visible reaction zone then, for buoyant diffusion flames (fires), estimates of the amount of air entrained or sucked into the combustion zone at the flame tip range up to 20 times the stoichiometric air flow required [2]. This excess or dilution air explains why the bulk temperatures are so low in a buoyant diffusion flame compared to a furnace. Recall that, for the furnace situation, the reaction is essentially complete for air requirements at or around the stoichiometric value. Assuming, for simplicity, similar combustion efficiencies, we are required to remove the same total amount of energy from the building in the two cases. In the furnace case it is a small amount of very high temperature gas. For the fire it is a large amount of air at low temperature. What is important is how all the air for the fire gets moved in and out of the building. We are here concerned with purely buoyant diffusion flames - characteristic of the unwanted fire such as a pool spill or bilge fire or fire on a piece of upholstered furniture - where the fuel is generally spread over an area and has little efflux velocity. A jet diffusion flame on the other hand, which might result for example, from the ignition of a flammable gas escaping from a high pressure line, exhibits a different mixing mechanism. These flames resemble those of a torch with high gas velocity. The jet momentum develops large turbulent shear stresses at the jet boundary and very effectively entrains or mixes-in the requisite air for combustion, similar to mechanical mixing. These flames tend to be short and resemble more the furnace configuration. However, if a large amount of gas is escaping, such that the flame and/or gases contacts a structure before reaction completion and the momentum of the jet is dissipated, then the flame from that point on in space may resemble a buoyant diffusion flame.

If we are primarily concerned with buoyant diffusion flames or pool configurations, what are the implications of this different mixing process? In order to uncouple the fire from the building, very large quantities of air must be brought into and removed from the enclosure without disturbing the fire. Ideally, like a candle or the bunsen flame in the laboratory, the fire would behave as if the walls and ceiling were very far away, the fire would see (radiatively) and feel (fluid mechanically) an undisturbed or undisturbing ambient. For example, the new FAA fire test building near Atlantic City is 55 x 23 x 14 m high. The building was designed to withstand a fire involving a 20 x 20 ft (6.1 x 6.1 m) pool of JP-4 adjacent to a C-133 aircraft [3]. Using Hagglund and Persson [4] data for JP-4 pool fires the flame height would average somewhere around 8.7 m which represents about 60% of the ceiling height of the building and at the same time take up only 3% of the floor area! Since the building is equipped with large open doors and soot vents this fire will be essentially unaffected by being enclosed in the building.

As time proceeds in the usual situation of a fire in a building hot gases will begin to collect in the upper part of the building; the upper walls and ceiling will be heated and will influence the burning rate of the fuel due to the increased radiative heat flux back to the burning surface from the hot upper regions. This radiative feedback (or coupling) need not concern us here since the proposed fire training facility will use gas burners and therefore the instructor will have complete control of the burning rate. (Actually in terms of a realistic simulation one would prefer that the programmed burning rate to be constantly adjusted in time to account for this radiative augmentation of burning rate if suppression action were not being correctly taken.)

The other factor concerning building fire interactions, that of the air movement, cannot be ignored and constituted practically the entire effort of this study. It is the easily disturbed nature of buoyant diffusion flames that causes problems. A fire burning in the open -- or in a very large building with perhaps large hanger-like doors (a common way most large fire tests have been performed in the past) -- and in the absence of any wind, will exhibit buoyant forces that will bring in or entrain air from all sides in a symmetric fashion. For discussion call this an undisturbed or "base-line" fire. We should aim for this capability in the design of a fire building where simulation of out-of-door fires is intended. Air should be brought in in such a way that the fire behaves as if it were proceeding in an infinitely large, quiescent space. However, some simulations may involve a fire in a corner of the room or a fire in a given wind, etc. These will, in general, not be minor perturbations to the behavior of the base-line fire - the enclosure walls and ceiling, for example, may dominate the undisturbed buoyant forces and disturb the behavior in a very significant manner. For proper facilty design it must be known what the behavior of the fire is like in the absence of enclosure induced disturbances and, where the enclosure should interact with the fire, the effect of the enclosure. If the air inlet system (and obviously the exhaust system) is not carefully designed a significant built-in bias in the facility could result, rendering inaccurate simulation.

## 2. ANALYSIS

In the interest of avoiding possible undesirable aerodynamic effects associated with buoyant diffusion flames in an enclosure, this study was initiated to look at the fire development in the proposed trainer configurations using computer simulation techniques. The work also demonstrated the advantage that having this kind of predictive capability brings, not only to the designer of the facility, but also to the operator. The model in hand places the ability to check, a priori, how a proposed change in the simulation might affect the training as regards safety, realism, scheduling, etc.

The predictive model chosen is the Harvard Computer Fire Code V developed over the last decade for room fire simulation [5]. The Harvard computer fire simulation calculates the physio-chemical phenomena associated with fire growth and spread in an enclosure (room). It is a "zone" model, that is, uniform conditions (T, [], etc.) are assumed throughout a given region or zone within the room. A zone represents a portion of the real physical space, e.g., the fire plume, the gas in the upper (or lower) region of a particular enclosure. Conservation equations - coupled ordinary differential equations in the zone model - are solved for each zone with fluxes of mass, energy, species concentration, etc. crossing the zone boundaries. (In the limit of a very large number of zones the equations would become partial differential equations.) With certain inputs describing the ignition source, for example, in the case of a growing fire, the Harvard model will trace the time history of the fire. Through solution of the equations governing the known physical and chemical laws together with certain empirical information the program will yield temperatures, velocities and mass flows, heat fluxes, gas concentrations, etc. as a function of time.

An advantage of the Harvard simulation is that it is constantly being updated and contains the latest scientific and technological information available from the fire research community. Its development and improvement is being continued by the Center for Fire Research at NBS. The Harvard fire simulation model used for this study was designated as H05.2. The ".2" refers to the second major modification to the fifth version. The fire source is a programmed gas burner and the ventilation was controlled by inlet vents at the floor and exhaust vents near the ceiling of the enclosure. Since H05.2 has no provision for forced ventilation, the effect of varying the exhaust fan power was simulated by varying the area of the ceiling level vents. Inputs included geometric factors of the enclosure - length, width and height; geometric factors of the openings or vents; thickness and thermophysical properties of the walls, and the locations, geometry, thermophysical and thermochemical properties of the burning objects as well as some empirical information required for specifying or describing other physical and chemical phenomena associated with fire. It is in this latter category that the state of the art is constantly being upgraded.

Table 1 contains the two sets of input information for the present series of simulations:

Table 1.

Input Parameters

| | 19F3 Bilge Fire | 19F3 Pit Fire |
|---|---|---|
| **Enclosure Geometry:** | | |
| Length (m) | 4.60 | 9.45 |
| Width (m) | 4.60 | 7.62 |
| Height (m) | 3.00 | 9.15 |
| **Walls:** | | |
| Thickness (m) | 0.01 | 0.0254 |
| Thermal Conductivity (W/m°C) | 4.00 | 0.1340 |
| Specific heat (J/kg°C) | 52.00 | 1062 |
| Density ($kg/m^3$) | 7830 | 800 |
| **Vents:** | | |
| Inlet - (m x m) fixed | 2 - 4.6 x 1 @ floor | 6.10 wide x 3.66 high @ floor fixed |
| Outlet - variable (m x m) | 2 - 0 to9.2 x 1 @ ceiling | 0 to 36.8 m x 1.0 m @ ceiling |
| **Burning Object:** | | |
| Radius (m) | 0.564 | 2.58 |
| Flow (kg/s) (full "on" @ 4 sec.) | 0.0597* | 0.138* |
| Heat of Combustion (MJ/kg) | 46.0 | |
| Stoichiometric mass ratio | 15.20 | |
| $FCO_2$ | 2.94 | |
| FCO | 0.019 | |
| $FH_2O$ | 1.680 | |
| FS | 0.008 | |

*Nominal flow - later runs were increased by a factor of three (see fig. 5).

Figure 1 contains a sketch of the two configurations which were simulated during the present task. They are idealizations of two of the rooms within the proposed 19F3 building. The size of the outlet vents which simulate fan exhausted flow were varied from zero, or no fan flow, meaning the inlets were the only contact the enclosure had with the outside, to the very large vent areas indicated in the table. The thermal properties of the enclosure walls and ceilings are quite different in the two cases and represent 0.4" mild steel for the smaller room and 1" concrete for the larger room. To examine the effect of the wall in the smaller room the thermal conductivity and specific heat of the wall materials were decreased by a factor of 10. This kept the walls' thermal diffusivity constant while decreasing its thermal inertia by a factor of 100. This was done to slow the wall thermal response which, by minimizing some latent computational instability, greatly reduced computing times (and costs). This change was not essential and had little effect except to slow the temperature rise.

## 3. RESULTS

### 3.1 19F3 Bilge Fire

Figure 2 shows the first 50 seconds of the bilge fire simulation for a fixed burner gas flow rate (59.7 g/s). Actually for ease in the numerical scheme the burner comes on in stages reaching steady state at four seconds, thereafter the flow is constant. Any transients due to this effect will not be of much interest here since we are concerned with longer times. The ventilation condition for this fire resulted in an air flow to stoichiometric ratio of about 1.6 which will be seen to be extremely low, i.e., results are upper level temperatures above 900K and $O_2$ concentrations below 10%.

Figure 2 is typical of the transient response of an enclosure to a relatively large and steady fire source. The thickness of the layer of hot gas trapped under the ceiling grows quite rapidly and at about 10 s has reached a steady thickness of about 2-1/4 m. Recall that the bilge configuration room is only 3 m high and hence there is only about a 3/4 m high zone of relatively clear air at the floor. In fact, for this case the layer interface is so low that gases are actually exiting through the inlets! Ordinarily we would not be interested in operating the trainer in such a mode but the case described on Fig. 2 does represent a slowly responding situation because of the small value of exhaust flow and hence the conclusions about the transient behavior of this fire will be conservative in regards the behavior at larger exhaust flows.

The upper layer gas temperature and oxygen level reach a good portion of their longer-time values within a half minute or so. Unlike the layer thickness which appears very steady in time, the gas temperature is still growing slightly and the $O_2$ concentration is slightly falling at 50 seconds. In the comparison of different ventilation conditions to follow, 50 seconds will be arbitrarily chosen for the bilge fire simulation as the time which approximately represents steady conditions in the fire room. That is, the fire conditions at 50 s will be used to represent the steady state values of the parameters for that particular ventilation condition.

Also shown on Fig. 2 is the rising value of the upper wall temperature. This is an example of truly non-steady behavior. The massive thermal capacity of the wall material has a dominant effect here. The gas temperature rises immediately as energy from the fire plume goes directly into heating the relatively low thermal mass gases. The gases then must transfer heat by convection and radiation into cool walls which must absorb lots of energy before their surface temperature rises significantly. The transient behavior of $T_{wall}$ seen on Fig. 2 has been slowed (as noted above) but will be similar for similar geometric configurations. The use of a single specified time, i.e., 50 s, is representative of near steady behavior for contrasting different ventilation rates.

Figure 3 shows the bilge fire conditions as a function of the ratio of exhaust ventilation flow rate to the stoichiometric air flow required. The data was obtained by varying the amount of air removed from the ceiling outlets. The comparison is for the nominally steady state time of 50 s. The general behavior seen on Fig. 3 will be observed over and over again for different building configurations, fire sizes, etc. - only the details will differ. As the airflow through the building is increased and precautions about the easily disturbed nature of buoyant diffusion flames described in the Introduction are observed, upper level temperatures will decrease and oxygen concentrations will increase. The airflow rate has been normalized and quantified by its ratio to the stoichiometric air flow requirements of the fire, i.e., the size of the fire is taken into account. Figure 3 and other information yet to be presented suggest that, to maintain a satisfactory atmosphere for training, something in the order of 10 or more times stoichiometric air flow will be required of the ventilation system depending on the particular specifications. These would be, for example, that the upper level temperature not exceed a certain value or the upper level oxygen concentration stay above some limiting value. For the particular bilge fire seen on Fig. 3 a ratio of 6 to 7 would keep the oxygen mass concentration above 18% but to keep the temperature below 500F (530K) a ratio of 10-11 would be required.

The extreme conditions seen on Fig. 2 for the transient analysis correspond to the left hand side of the Fig. 3 at low ventilation ratios (1.6). To avoid hot combustion products exiting through the inlet the layer interface would have to be raised above the top edge of the inlet, 1 m interface height, by increasing the ventilation ratio to about 2-1/4. The ratio would have to be further increased to about 5-6 times stoichiometric to insure the hot gases just stay above the head of a tall trainee. More about layer height and door height will be said in reference to the pit fire.

### 3.2 19F3 Pit Fire

Figure 4 presents conditions at a longer time (300 s) for the less severe pit fire. Although absolutely larger (in terms of fire size) than the bilge example this fire-building combination is considerably less severe in terms of upper temperatures and oxygen depletions. The bilge fire represents about 50% more energy release per unit floor area than the pit configuration. Additionally the very high ceiling for the pit fire room permits significantly more heat transfer to the proportionately greater upper wall surface area. (Fail-safe burner controls for gas shutdown would be required for the bilge fire in the event of ventilation failure whereas the pit fire conditions, as we shall see, may not be as sensitive from a safety point of view.)

There is also one other significant difference in the two cases. For the pit there is a single large door for the inflow, the top of which is rather high (3.66 m) and out of which can flow the hot combustion products after the upper regions have filled. A fan is not even required if the conditions corresponding to zero abscissa on Fig. 4 can be tolerated. For the abscissa the title "ventilation flow" is used here to emphasize that this is only the flow going through fans or openings at the ceiling, not the flow spilling out the door. We would hardly bother to calculate these conditions for the bilge fire on Fig. 3 since, at a ratio equal to two, conditions are already untenable. Recall for the bilge fire that the top of the inlet is at 1 m.

At the zero-fan flow condition the interface height is 1.71 m, too low to permit all but a few short trainees to stand in relatively clean air. Running the fans doesn't accomplish very much at the low ventilation ratios. Only after reaching a ratio of 5 or so does the temperature begin to fall and the layer height rise. The figure shows the position of the top of the door on the layer height vs flow curve. In order to keep the height of the interface above the top of the door, i.e., keep hot combustion products from spilling out, a ratio of fan flow to stoichiometric flow equal to between 17 and 18 will be required. That is a substantial amount of fan capacity for marginal gains in layer temperature and oxygen depletion reductions.

This is a good illustration of the usefulness of having a predictive code before designs are finalized. If spillover from the door into the adjoining space can be tolerated then, according to Fig. 4, fan requirements for the pit fire would be minimal. There would still remain the problem of what to do with the combustion products flowing out into the adjoining space. Dumping into the atmosphere would be a possibility. The adjoining space could not be the outside of the building since the behavior of the fire itself would then be almost totally controlled by the wind conditions prevailing at the door and any systematic training schedule would be impacted.

### 3.3 Generalizations

To illustrate further the effect of door flow vs ceiling exhaust fan flow and some other general observations, the data from Fig. 4 has been redrawn onto Fig. 5 with the difference being the abscissa. Here it is total air flow, that is, the sum of the flows going out the door and through the fan. Alternatively it is the total flow into the room through the door or vents. These two, outflow and inflow, under steady state conditions must be almost the same, the difference is the mass of fuel generated by the fire itself (not what is entrained) which is usually negligible.

The solid lines designated "P" (for pit fire) for both temperature and oxygen concentration in the upper layer are shown extending down to an air flow ratio of 7.25. This corresponds to zero fan ventilation flow on Fig. 4 and represents the natural, buoyancy driven flow through the pit building door for that size fire. To get less flow, the door would have to be made smaller. We see the initial horizontal portion of the $T_g$ curve on Fig. 4 being greatly compressed on Fig. 5.

The dashed line designated P is for the same pit building with a fire three times the heat release rate of the standard case, corresponding to a 19 MW fire. Because flow rate and fire size do not scale exactly these calculations extend further down in flow ratios. What does appear to scale, however, is the upper gas temperature and oxygen concentration with the abcissa on Fig. 5, namely, total air flow to stoichiometric air required. We are not getting something for nothing because the denominator is now three times larger and hence the fan flow for a fixed ratio is now three times larger.)

The $O_2$ plot for the dashed curve is virtually identical to the solid line, the temperature is only slightly shifted upward from the solid line. (By the very nature of the calculation it turns out that the $O_2$ result must be independent of heat release, configuration, etc. In the steady state a mass and $[O_2]$ balance yields a simple expression for upper layer $O_2$ concentrations, $[O_2] = 0.23 [\phi - 1]/[\phi + 1/r]$ where $\phi$ is the air to stoichiometric ratio and r is the fuel stoichiometric mass ratio. This is not true when plotted in the fan flow coordinate of Fig. 4.)

The behavior of the oxygen concentration and temperature level with the ratio of total air flow to the stoichiometric required value, as illustrated by the P's on figure 5, suggests that this ratio might be a natural scaling parameter for enclosure fires. Some recent empirical correlations [7] based on a simple energy balance suggests a similar result. The generality of Fig. 5 which is a calculation based on a more careful theoretical treatment must be demonstrated.

Consider the curves designated "B" (for bilge fire). The solid curves are the same data as appears on Fig. 2. As expected, the oxygen concentration rises and merges with the P result exactly. The temperature behavior appears to agree with the trend of both the solid and dashed P result to within reasonable approximations. Like the dashed curve for P the dashed curve marked B is for a fire size three times that of the solid line. (Based on previous remarks about the severity of the bilge fire allowing the fire to be even larger would not be recommended!) This time the larger fire results in temperatures on the order of 150K higher than the smaller fire. In conclusion it would appear that the total air flow/stoichiometric air required ratio can be used as a guide to the general behavior of enclosure fire phenomenon but care must be exercised in any detailed interpretation. For example, the simple correlation of reference 7 quoted above contains, besides heat release rate and vent size, some account of the thermal properties of the wall absent in the abscissa of Fig. 5.

Finally the cross-hatched line on Fig. 5 represents a "fair" rendering of some asymptotic (in time) oxygen concentration measurements "near floor" for heptane and cardboard fires in a scale model of a rather large fire test building [6] (Factory Mutual Research Corporation, West Glocester, Rhode Island). The model was built to determine air pollution control system requirements for the full scale building. (There is anecdotal evidence in that reference which implies that the original architectural estimate for fan flow requirements was too small by a factor of between 5 and 10 times.)

The trend of the experimental data is similar to the present calculations - staying relatively high and flat for large ratios until around a value of 10 or so it begins to fall. It is not clear why the data falls consistently above the present prediction although perhaps the measurements were made close to the "clearer" air near the floor as opposed to being in the upper portion of our two layer idealization of a sharp interface. Nevertheless, the important consideration here is that the trend of the data is similar and the fall off at or around 10 is consistent with the prediction.

## 3.4 Extrapolation and Accuracy

The previous sections represent the best information presently available. There is not a great deal of experimental data available for fires of the magnitude contemplated for the pit building. In general the predictive models, or rather the components of the models, have been tuned by experiments closer in size to the developing, domestic-size room fire. In particular, there is one element, namely fire plume entrainment, which above all others (for this kind of specified input burning rate modeling) is critical. The upper layer conditions as well as the size of the layer reflected in layer height will depend very strongly on which mathematical model for fire plume entrainment is chosen. The difficulty comes about because of the very strong dependence of entrained flow upon height which the models exhibit. There is no experimental data for such large (high) fires from large burning areas.

Rockett [1] reviewed and compared all reasonable entrainment models or correlations presently available in the literature and included on-going research results from several laboratories. These were all tested against very carefully obtained doorway mass inflow and outflow data from a 2.8 x 2.8 x 2.1 m high room with a controlled gas burner fire source. The Harvard computer fire simulation was run to steady state conditions for all the entrainment models and the mass flow results predicted were compared with the measurements. In general, the entrainment models agreed to within only about 50% of the mean. However, the predictions of three of the entrainment models including that used for the present study fell quite close together and represented the experimental data quite well for the range of fire sizes included in the experimental study. (Some of the variability can be associated with interpretation of the experimental data. What is actually entrained in the normal plume, undisturbed by the room in which it exists, will be altered by additional entrainment due to distortion of the plume by the jet of air flowing in the room door, and by upper and lower layer communication through wall boundary layers.)

The study is an important step in model validation and offers significant insight for the user in terms of expected results and accuracy at this size enclosure. Unfortunately for the present purposes of larger fires and ceiling heights no data base exists to compare the model predictions, which have to be extrapolated well beyond the range or scale from where they were derived. The results did indicate, however, that except for one model the entrainment analysis used in the present work (Emmons-Mitler) was the most conservative regarding the necessary exhaust fan flow required to maintain a given layer height. Alternately, for a fixed exhaust stoichiometric flow ratio this model would predict the layer height to be the lowest of all the models except one. For example, on Fig. 4 at a ratio of 15 the layer height predicted by the present model is about 3.2 m. Other models predict heights of up to 5 m. Certainly from a safety or capacity point of view the present model would represent a conservative design. The one model which yielded a layer height which was lower than the others appears to be so far removed from the bulk of the results as not to be credible.

One recommendation growing out of this work which would help to alleviate the above discrepancies in entrainment extrapolation would involve making some straightforward measurements on the training facility before putting it in service. A thermocouple tree or some other, perhaps visual, means to locate the layer interface and a reading of the fan flow would be all that would be required. Finding layer height as a function of fan flow for a given geometric and thermal configuration, perhaps parameterized in heat release rate, would yield data which would be extremely valuable and could put the large fire problem onto firmer ground.

## 4. CONCLUSIONS

Computer modeling techniques have been applied to the ventilation design of Navy fire fighting trainers.

Quantitative information regarding conditions in two proposed fire-enclosure configurations for the bilge and pit fire of 19F3 have been derived. The ratio of fan exhaust flow to stoichiometric air flow requirement is seen to be a reasonable scaling parameter for flow requirements. Values of this ratio above ten are recommended as a starting point for fan size design considerations.

The need for large scale plume entrainment measurements is noted and the possibility of using some of the Naval facilities to obtain such data is suggested.

## 5. ACKNOWLEDGMENTS

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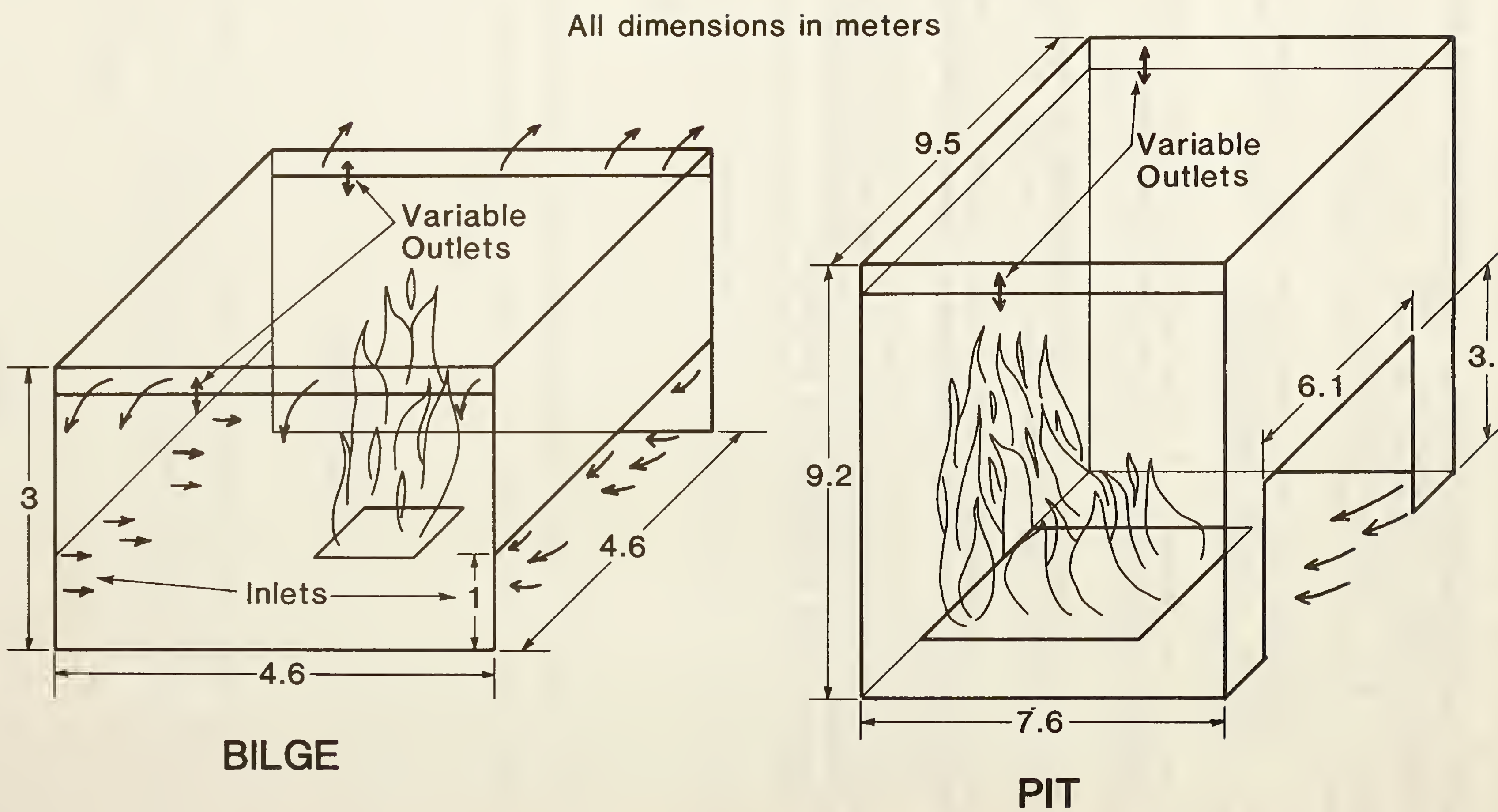


Figure 1 Enclosure Configurations Considered During this Study

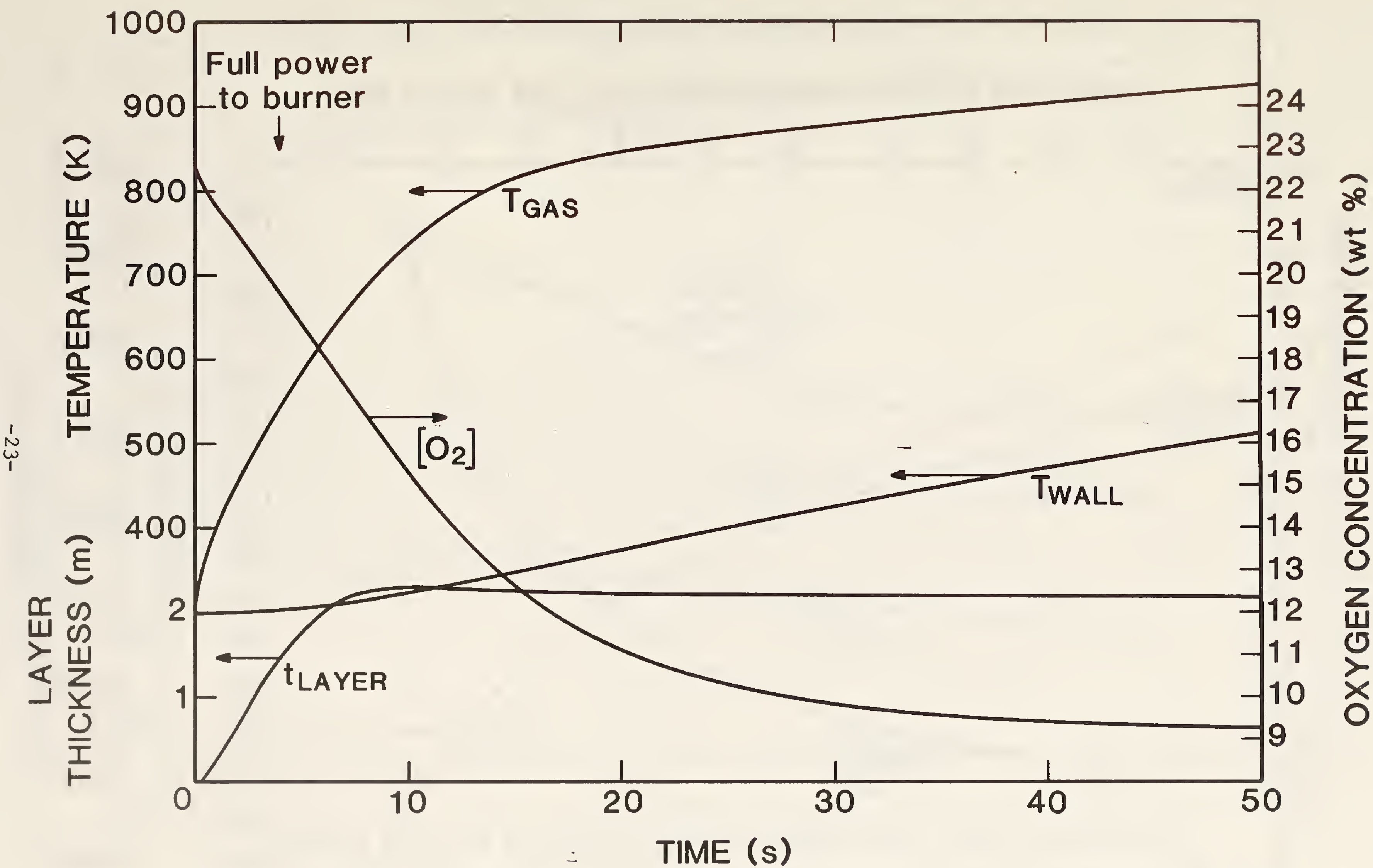


Figure 2 Typical Time-History of Upper Layer Conditions for Steady Fire

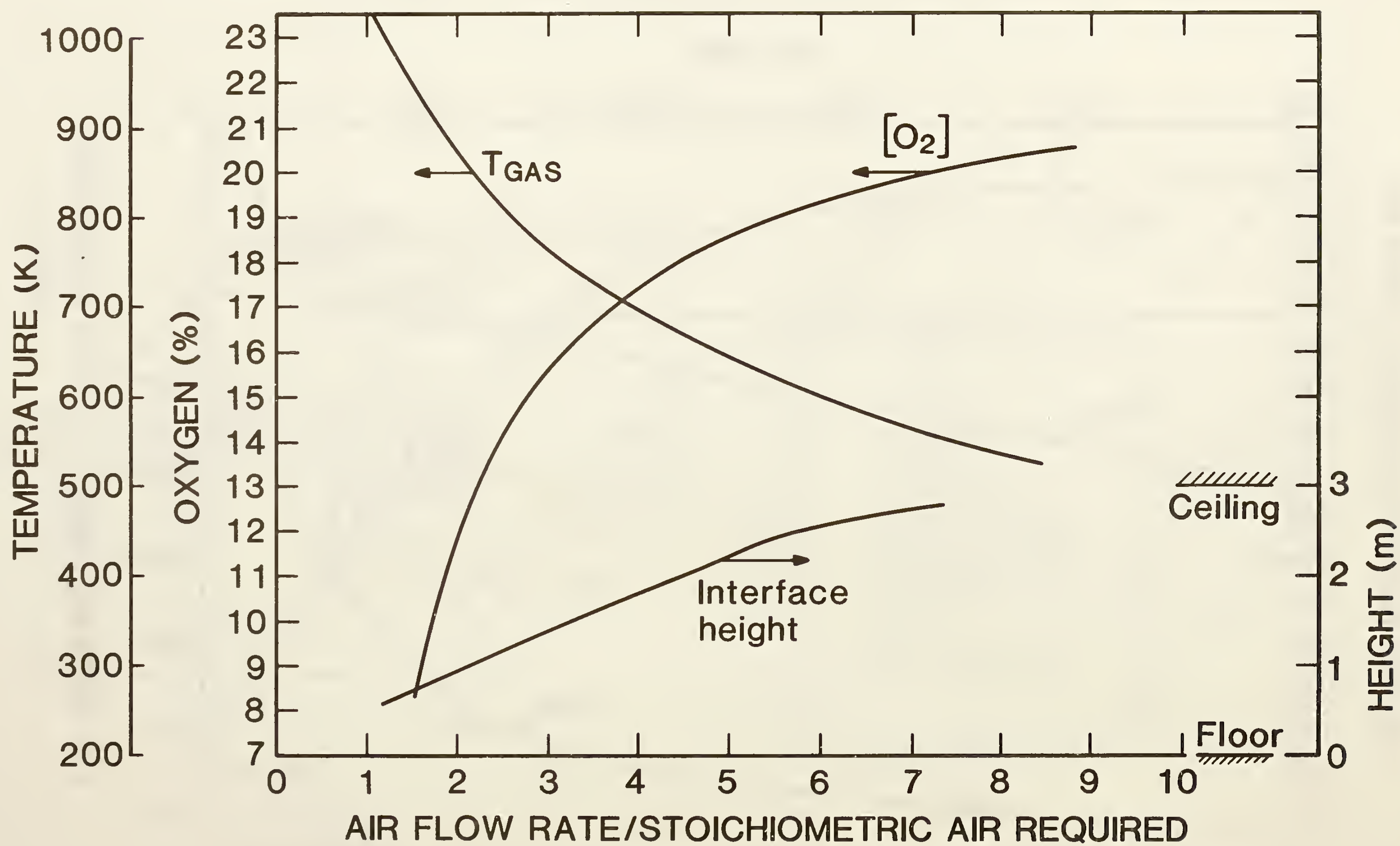


Figure 3 Resulting Upper Layer Conditions for a Given Fan Air Flow Rate (Bilge Fire)

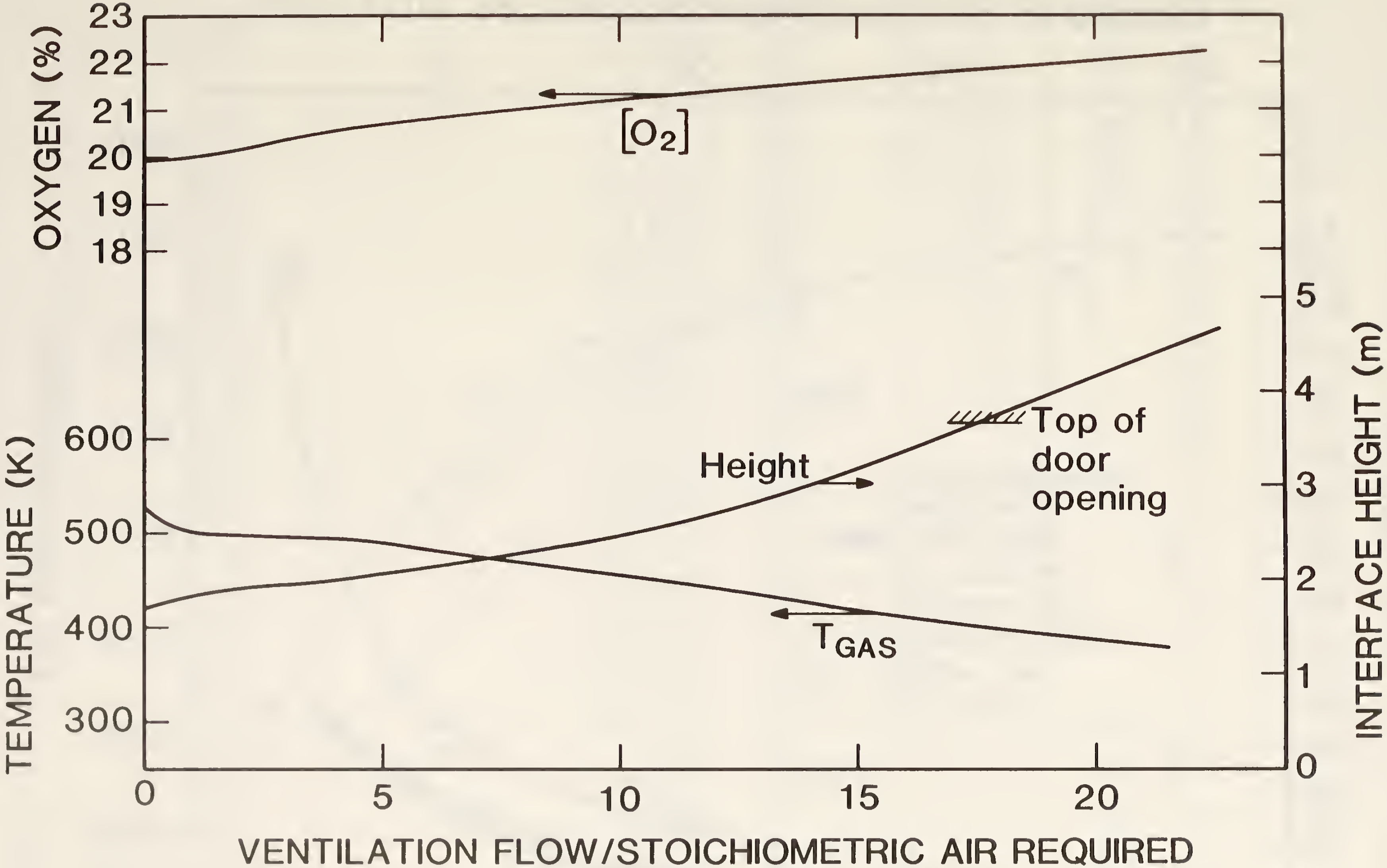


Figure 4 Resulting Upper Layer Conditions for a Given Fan Air Flow Rate (Pit Fire)

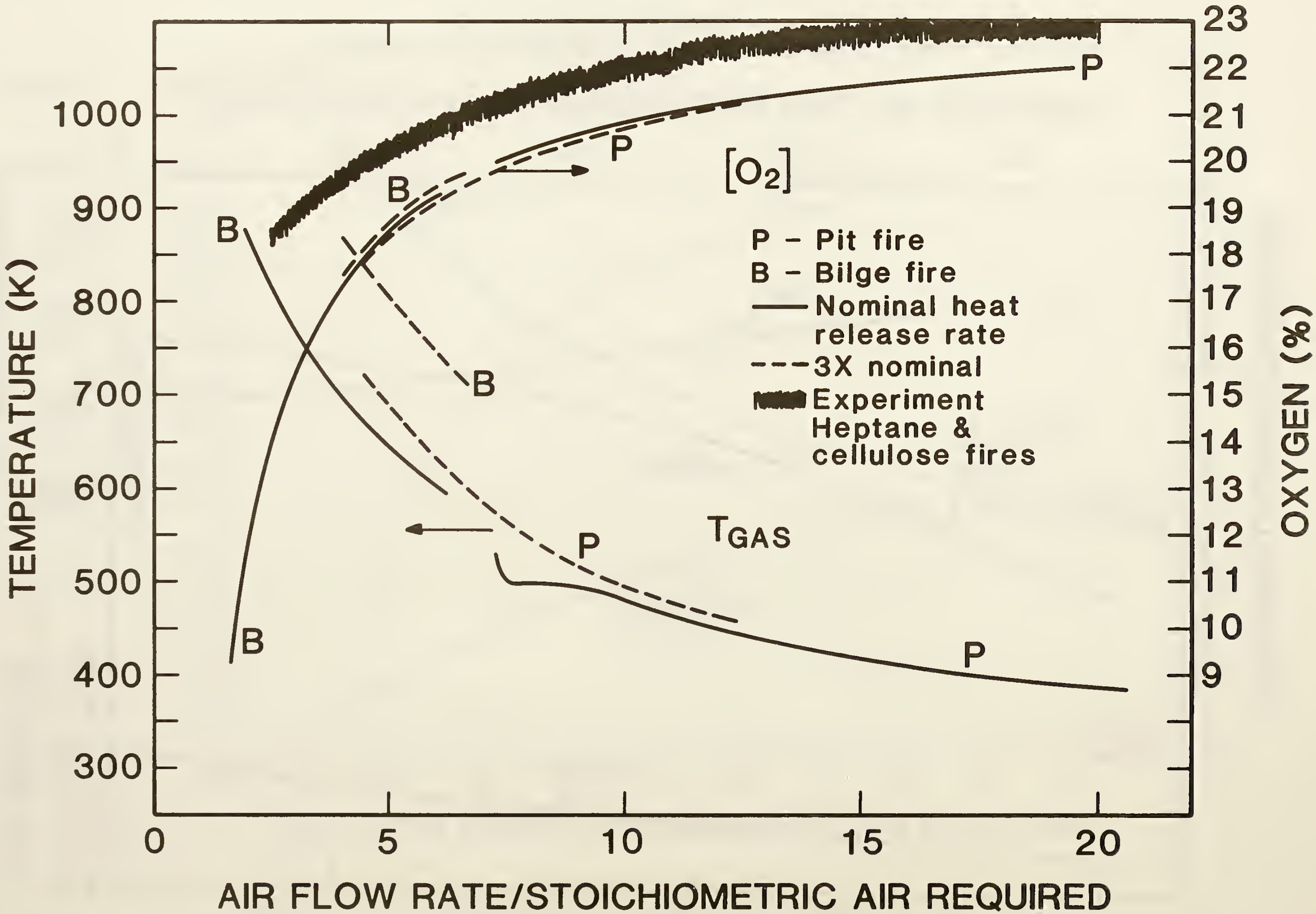


Figure 5 General Behavior: Upper Layer Conditions vs. Total Air Flow

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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)

The Harvard 5.2 Mathematical Fire Growth Model was used to calculate required ventilation rates for two simulated fire scenarios in the Navy 19F3 trainer. These calculations were performed for design purposes to insure that the hot gas layer temperature in the trainer would be acceptable and that the oxygen content of the gas would be above 18%. Wall temperatures were also calculated.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)
entrainment; fire models; fire plumes; fire safety; fire simulation; fire trainers; ventilation

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