FIRE TECHNOLOGY, VOL. 5, NO. 2, 112-121, MAY 1969

F71/00463

D75-10429

Pressure Rise Due to a Fire in an Enclosure

SAMI ATALLAH
Arthur D. Little, Inc.
JOHN N. deRIS
Factory Mutual Research Corporation

Can temperature and pressure rise resulting from a fast developing fire in an enclosure be predicted? Toward that end, the authors developed equations, the results of which were compared with the few available experimental data and with the Apollo accident pressure record.

AN UNCONTROLLED fast combustion process taking place in an unvented enclosure may result in temperatures and pressures that cannot be tolerated by the walls or contents. Regardless of whether this enclosure is a hermetically sealed electronic box, a laboratory combustion test glass jar, a space vehicle, or a hyperbaric chamber, an accidental fast developing fire may result in disastrous consequences.

The objective of this paper is to consider all possible models for the burning process within an enclosure containing an excess of oxidant, and to develop the equations describing the variation of temperature and pressure with time. The results predicted by these equations will then be examined in the light of the few available experimental data.

CONDITIONS LEADING TO A FIRE IN AN ENCLOSURE

The presence of an adequate supply of fuel, oxidant (usually oxygen), and thermal energy is a prerequisite for the initiation of a fire. The ease of ignition of a fuel depends upon several factors, among which are its ignition temperature, chemical composition, geometric shape, and spatial distribution.

The rate of burning of solid combustible materials has been shown to increase sharply with an increase in oxygen concentration.[1] Certain materials, which do not ignite in air, burn readily as the oxygen concentration

---

NOTE: The work reported here was performed at the Factory Mutual Research Corporation for NASA under Contract NAS 12-623.

is increased.[2] Experiments indicate that the horizontal burning rate of thin sheets is relatively independent of total pressure while the vertical rate, which is enhanced by a buoyant flame, increases with pressure.[3] It is doubtful, however, that the total pressure plays an important role during the combustion of well dispersed fuels in a high oxygen concentration.

Since the use of pure oxygen in space, medical, and underwater applications offers the greatest hazard, the analysis and equations that follow have been developed for a pure oxygen atmosphere. However, the equations can be easily modified to account for the presence of other diluents.

TEMPERATURE AND PRESSURE DEPENDENCE ON MASS BURNT

Combustion in an adiabatic enclosure produces the maximum possible temperatures and pressure. The following derivation assumes complete mixing and ideal gas behavior. In the reaction

$$C_cH_hO_x + \left(c + \frac{h}{4} - \frac{x}{2}\right) O_2 \rightarrow cCO_2 + \frac{h}{2} H_2O$$

M grams of a typical organic fuel, $C_cH_hO_x$, react with $\left(c + \frac{h}{4} - \frac{x}{2}\right)$ moles of O_2 to produce $\left(c + \frac{h}{2}\right)$ moles of product gases. At any time after ignition, the total number of moles present, N_{total}, will be

$$N_{total} = N_{O_2} + \frac{m}{M}\left(\frac{h}{4} + \frac{x}{2}\right)$$

An overall energy balance after time t from ignition when a mass m has been consumed can be written assuming no heat losses to the walls or to the contents of the enclosure. This would be approximately the case during a very fast combustion process.

$$m\,H_o = \bar{C}_v\left\{N_{O_2} + \left(\frac{h}{4} + \frac{x}{2}\right)\frac{m}{M}\right\}(T - T_o) \tag{1}$$

or

$$T = \frac{m\,H_o}{\bar{C}_v\left\{N_{O_2} + \frac{m}{M}\left(\frac{h}{4} + \frac{x}{2}\right)\right\}} + T_o \tag{2}$$

The corresponding equation relating pressure, P, to the total mass burnt, m, can be derived from Equation 2 and the gas laws. Assuming perfect behavior

$$P_o V = N_{O_2} R T_o \tag{3}$$

$$P V = \left\{ N_{O_2} + \left(\frac{h}{4} + \frac{x}{2} \right) \frac{m}{M} \right\} R T \tag{4}$$

Combining Equations 2, 3, and 4, one obtains

$$\frac{P}{P_o} = \left\{ 1 + \frac{m}{M N_{O_2}} \left(\frac{h}{4} + \frac{x}{2} \right) \right\} + \frac{m H_o}{\bar{C}_v N_{O_2} T_o} \tag{5}$$

For example, when 20 g of cellulose ($C_6H_{10}O_5$) is burnt adiabatically in a 125-liter chamber initially at 1 atm and 300° K and containing pure oxygen, a theoretical final temperature of 2,163° K and a pressure of 9.33 atm can be calculated. In practice, these temperatures and pressures are never achieved because of heat losses to the contents, walls and the surroundings.

In order to find the variation of enclosure temperature and pressure with time, the dependence of mass burning rate, $\dot{m}$, on time and pressure is needed. Since

$$m = \int_o^t \dot{m} \, dt \tag{6}$$

simple substitution into Equations 2 and 5 of the appropriate relationship between $\dot{m}$, time, and pressure will yield the desired equations. However, for fast combustion processes, such as would occur in enriched oxygen atmospheres, we have already indicated that total pressure should not play an important role in fire spread. Thus $\dot{m}$ will be considered a function of the area burnt which, in turn, is a function of time only.

VARIATION OF BURNING RATE WITH TIME

The burning rate of a solid depends on its geometric shape and spatial distribution. The linear burning rate of a homogeneous solid is constant at steady state. Simple models for burning are postulated below with the corresponding dependence of mass burning rate on time. The models are also illustrated in Figure 1.

a. Constant mass burning rate:

$$\dot{m} = k_1 \tag{7}$$

Two examples where a constant rate of burning is obtained are (*1*) a thin combustible rectangular sheet ignited along one edge (the sheet is totally consumed behind the flame and the length of the flame front is always constant), and (2) a fuel having a constant cross section burning downwards at steady state.

b. Linear dependence of mass burning rate on time:

$$\dot{m} = k_2 t \tag{8}$$

A linear dependence of burning rate on time is obtained in (*1*) a thin combustible sheet ignited at the center with the flame front expanding in all directions (the area between the flame and the ignition point is totally consumed), and (*2*) a rectangular combustible ignited along one edge and having a thickness large enough so that the area behind the flame continues to burn.

c. Burning rate dependent on the square of time:

$$\dot{m} = k_3 t^2 \tag{9}$$

This corresponds to combustion along the surface of a thick fuel where the flame front is expanding at a constant linear rate in all directions, but where the area between the flame front and the ignition point continues to

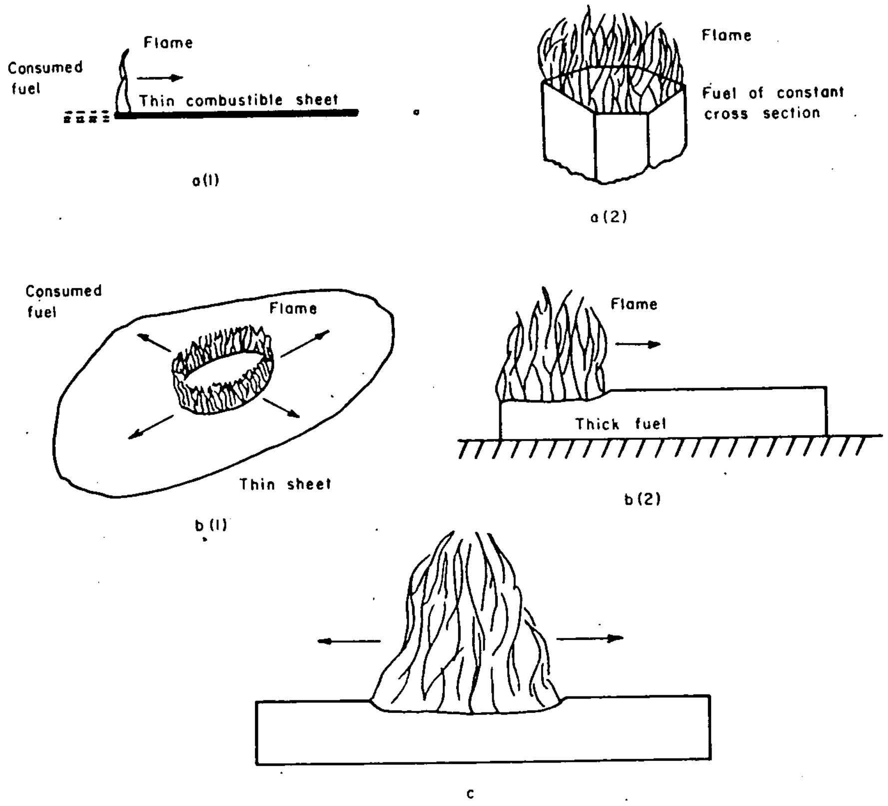

Figure 1. Simple models for burning.

burn. Equation 9 is true for turbulent flames only.

d. Exponential dependence on time:

$$\dot{m} = k_4 e^{k_5 t} \qquad (10)$$

The worst possible case for burning occurs when the fuel and oxygen are uniformly distributed and when the oxygen can gain access easily to all elements of the fuel.[4]

If the volume of the fire is proportional to the mass burnt, then the rate of growth of the fire is given by

$$\frac{dm}{dt} = k_5 m$$

or

$$m = m_o e^{k_5 t} \qquad (11)$$

which reduces to Equation 10 upon differentiation.

Another way of arriving at the same expression is to consider a system consisting of several fuel elements each being similar to that described under *c*. A fraction of the total heat generated, α, goes into evaporating or pyrolyzing more fuel, i.e.

$$\alpha \dot{Q} = \frac{dA}{dt} C_p \rho \tau (T_{vap} - T_o) \qquad (12)$$

where $C_p \rho \tau (T_{vap} - T_o)$ is the energy required per unit surface area to raise fuel temperature to vaporization.

Since $\dot{Q} \sim \dot{m}(t) \sim A(t)$ for the model described under *c* then $A(t) = k_6 \frac{dA(t)}{dt}$ or $\dot{m} = k_6 \frac{d\dot{m}}{dt}$, which again leads to Equation 10.

A third way of arriving at the same result is to say that the rate of evaporation and eventual burning of a fuel in an adiabatic enclosure is proportional to the total heat content of the enclosure, Q, which, in turn, is dependent on the total amount of fuel burnt up to that time, i.e.

$$\frac{dm}{dt} \sim Q \sim m$$

Regardless of the method of derivation, this model assumes that an initial small fire consumes a mass m_o by one of the other mechanisms described in *a*, *b*, or *c* before it grows exponentially (i.e., at $t = 0$, $m = m_o$). This behavior has been observed experimentally by Denison *et al.*[5] in experiments with denim overalls burnt in oxygen atmospheres. Within 0.6 sec after ignition, a flame had swept over the whole surface in the manner described by model *b(1)*, after which edges of sleeves and trouser legs began to burn. After 7.5 sec, 30 per cent of the garment was burning, and at 11.3 sec, the whole surface was engulfed by intense flames.

It should be pointed out that the burning rate of a mixture of combustibles having different configurations would be extremely difficult to predict from the burning rates of the individual components. The fast burning, high-heat-generating combustible will be a controlling factor contributing towards a general increase in the burning rates of adjacent combustibles. On the other hand, the presence of a flame-retarding agent in one combustible may inhibit the rate of burning of another highly combustible element.

COMPARISON OF EXPERIMENTAL DATA WITH THEORETICAL PREDICTIONS

With all the experimental studies that have been performed on the flammability of materials in oxygen enriched atmospheres, very little data are available in the literature on the variation of enclosure temperature and pressure during the combustion process. A number of studies have been performed by Botteri, but the pertinent data has not been extracted from recorder charts yet. Only one of his plots of pressure versus time is available[6] for the combustion of a stoichiometric amount of cotton in an oxygen filled chamber, 45.25 liters in volume at half an atmosphere. This plot is reproduced in Figure 2.

Another source of data was the record of the Apollo 204 space cabin fire.[7] A plot of cabin pressure versus time is reproduced in Figure 3.

The actual time taken to reach a given pressure was read from the experimental plots (Figures 2 and 3) while the mass burnt to reach that pressure was found from Equation 5. The dependence of mass burnt on time was found by plotting *m* versus *t*. It was found that the exponential model gave an excellent fit (See Figure 4).

The equations describing this dependence were

$$\left.\begin{aligned} m &= 0.3\,e^{0.35\,t} \\ \dot{m} &= 0.105\,e^{0.35\,t} \end{aligned}\right\}\ \text{Botteri} \qquad (13)$$

$$\left.\begin{aligned} m &= 3.1\,e^{0.39\,t} \\ \dot{m} &= 1.21\,e^{0.39\,t} \end{aligned}\right\}\ \text{Apollo accident} \qquad (14)$$

It was interesting to note that the slopes of these two lines were roughly the same. Even Denison's data,[5] although in different units, seems to follow the same slope. The slope is related to the fraction of chemical energy generated within the chamber that goes into heating the fuel to its vaporization temperature as shown by Equation 12. This fraction is apparently about the same in all cases. On the other hand, the value of m_o depends on the scale of the experiment and the size of the ignition source.

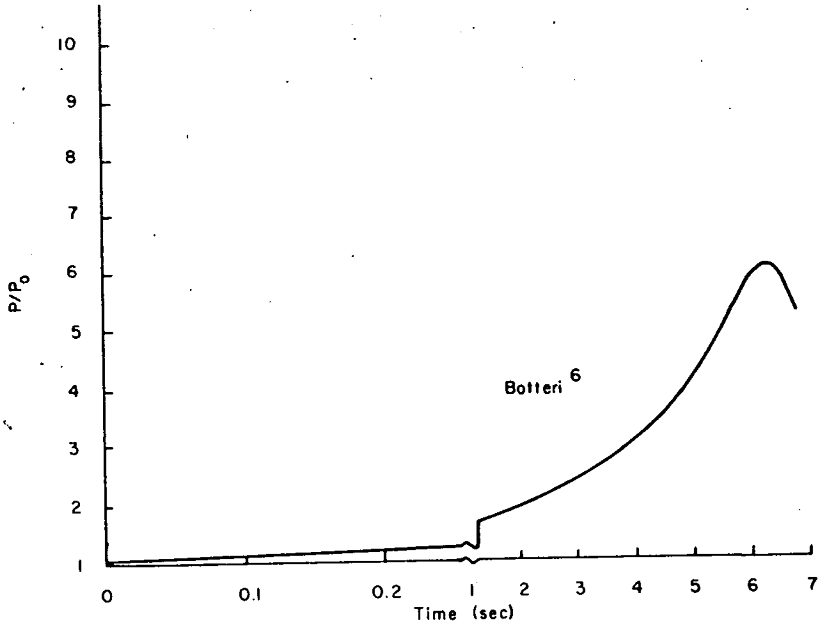

Figure 2. Pressure profile during the combustion of cellulose in oxygen.

It should also be noted that, under the assumptions made in this derivation (adiabatic, non-condensing products, etc.) only a small mass is theoretically needed to burn exponentially in order to achieve the pressures actually reached in both systems. About 110 and 2.2 grams need to have burnt in the Apollo cabin and in Botteri's chamber, respectively, before the pressure reached a maximum value.

Apparently, during the initial stages of the combustion process in an oxygen enriched atmosphere, the reaction is so fast that the system follows the assumption of adiabatic behavior made in the derivations. However, at a certain point, heat losses to the wall and contents, water vapor condensation on the cold walls, and the dilution of oxygen with combustion products become significantly large, so that even though the combustible contents continue to burn, the pressure begins to drop.

The escape of gases from the Apollo vehicle due to wall failure was another major factor in reducing the pressure. Obviously, heat losses to the walls and contents and dilution of oxygen were more important factors in Botteri's small chamber than in the much larger Apollo vehicle.

NOMENCLATURE

A = Surface area burnt, cm^2
C_p = Specific heat of fuel, cal/g ° C
$\bar{C}_v$ = Average molar specific heat if all enclosure gases at constant volume, cal/g-mole ° C

Absolute pressure (psia)

c =
H_o =
h =
M =
m =
$\dot{m}$ =
N =
P =
P_o =
Q =
$\dot{Q}$ =
R =
T =
T_o =
t =
V =

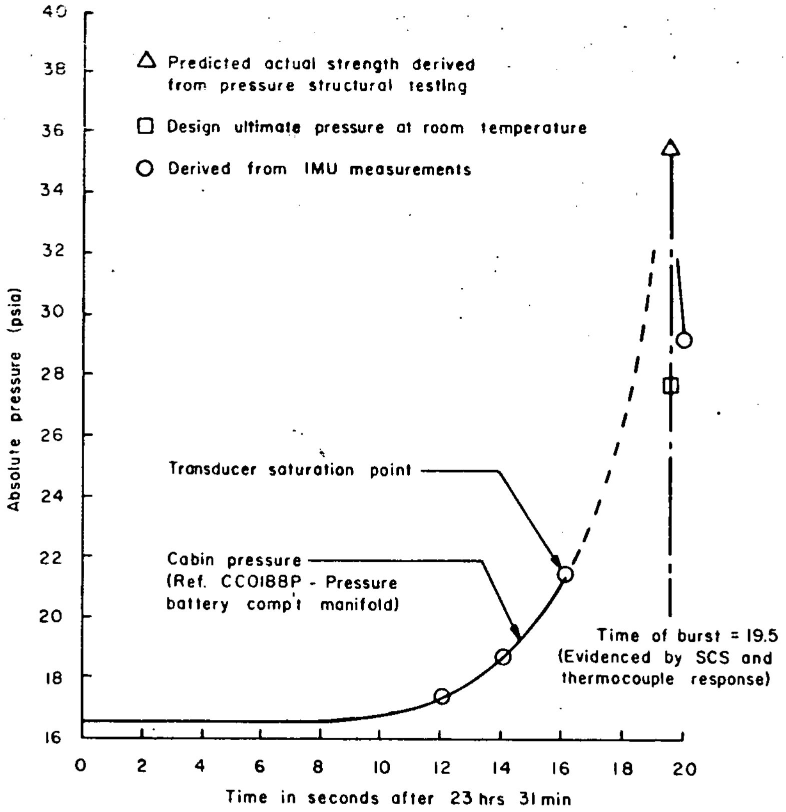

Figure 3. Apollo 204 cabin pressure during the fire.[7]

c = Number of carbon atoms in $C_c H_h O_x$
H_o = Heat of combustion of $C_c H_h O_x$ at T_o, cal/g
h = Number of hydrogen atoms in $C_c H_h O_x$
M = Molecular weight, g/mole
m = Mass of fuel, g
$\dot{m}$ = Mass burning rate $= \frac{dm}{dt}$, g/sec
N = Number of moles
P = Pressure at any time t, atm
P_o = Initial pressure of the enclosure, atm
Q = Heat content of enclosure, cal
$\dot{Q}$ = Rate of heat generation, cal/sec
R = Gas constant, atm cm^3/g-mole ° K
T = Temperature of the gas at any time t, ° K
T_o = Initial temperature, ° K
t = Time, sec
V = Volume of enclosure, cm^3

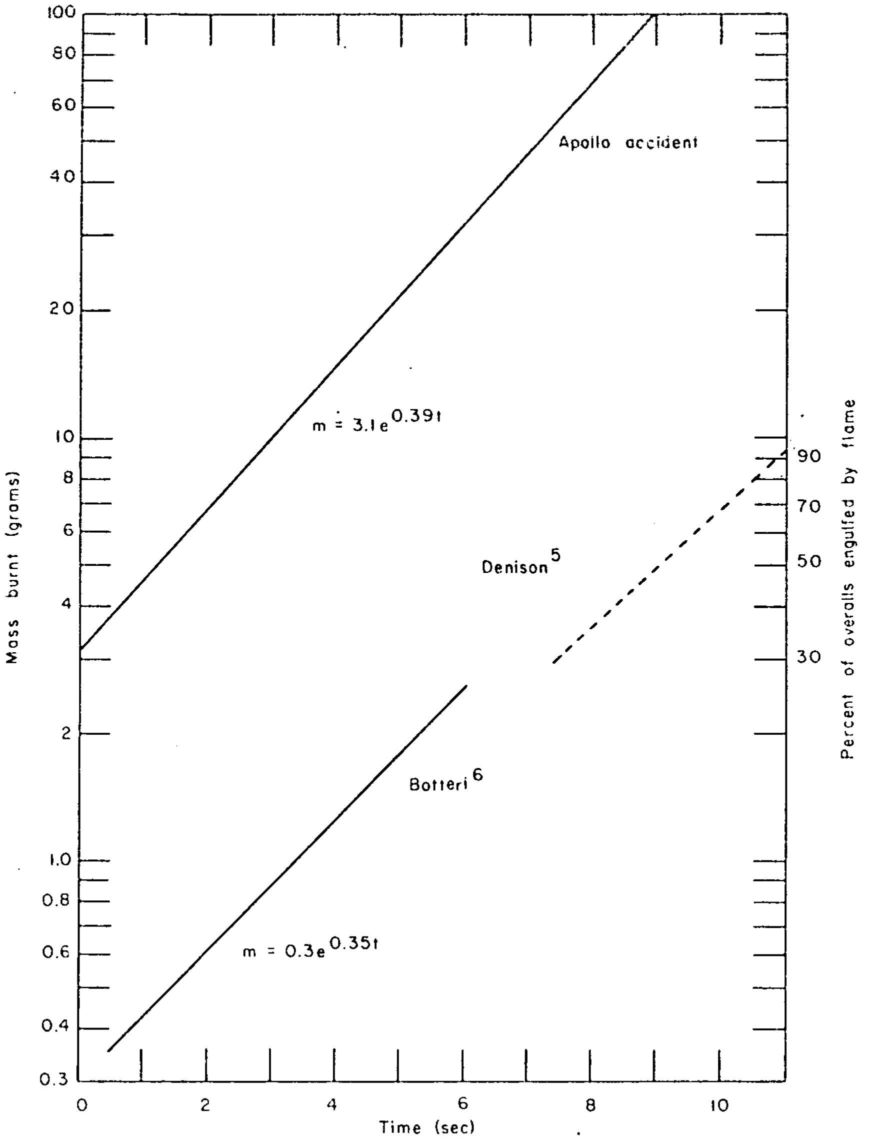

Figure 4. Semilogarithmic plot of mass burnt versus time.

x = Number of oxygen atoms in $C_nH_hO_x$
α = Fraction of heat generated that is fed back to the fuel
ρ = Density of fuel, g/cm^3
τ = Characteristic thickness of the pyrolysis zone of the fuel, cm

REFERENCES

[1] Huggett, C., et al, "The Effects of 100% Oxygen at Reduced Pressure on the Ignitability and Combustibility of Materials," SAM-TR-65-78, December 1965, Brooks Air Force Base.

[2] Johnson, J. E., and Woods, F. J., "Flammability in Unusual Atmospheres, Part I -- Preliminary Studies of Materials in Hyperbaric Atmospheres Containing Oxygen, Nitrogen and/or Helium," NLR Report 6470, October 31, 1966, Naval Research Laboratory.

[3] Huggett, C., "Fire Hazards in Spacecraft Atmospheres," NASA Report No. TMX-60870, Accession No. N68-17367, March 1967, *Proceedings of the Fifth Annual Meeting*, Working Group on Extraterrestrial Resources, Marshall Space Flight Center, Huntsville, Alabama.

[4] Friedman, R., "A Survey of Knowledge about Idealized Fire Spread Surfaces," November 27-28, 1968, Paper presented at the Eastern Section of the Combustion Institute, Carnegie-Mellon University, Pittsburgh, Pennsylvania.

[5] Denison, D. M., and Tonkins, W. J., "Further Studies Upon the Human Aspects of Fires in Artificial Gas Environments," FPRC/1270, September 1967, Flying Personnel Research Committee, Ministry of Defense, RAF Institute of Aviation Medicine, Farnborough, Hants.

[6] Botteri, B. P., "Fire Protection for Oxygen-Enriched Atmosphere Application," *Fire Journal*, Volume 62, No. 1, January 1968, pp. 48-55.

[7] Report of Apollo 204 Review Board — Report of Panel 5, "Origin and Propagation of Fire," Appendix D-5 Enclosure 5-8, 1967, U. S. Government Printing Office. ✓

O.P.