

**Chapter 10**

**EFFECT OF ENVIRONMENTAL  
VARIABLES**

by

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We are primarily discussing fires that occur in buildings and under 'normal' conditions. But, clearly, some fires of great concern may not be in buildings; these include fires in submarines, spacecraft, and the like. The prevailing conditions will then, most likely, also be different for such fires. The variables which may be altered include:

- oxygen concentration in the combustion air
- the temperature of the incoming combustion air
- the presence of additional gases not occurring in normal air
- total pressure
- wind blowing across the burning object
- relative humidity
- the acceleration of gravity

Some of these are also common in 'normal' conditions — wind blowing across a fire is common, as are extremes of relative humidity. Oxygen concentration may drop in portions of a building once a fire develops and, in addition, CO<sub>2</sub> will show up as a diluent. Other conditions, such as changes in total pressure or in the acceleration of gravity will normally only be required in such specialized applications as the design of spacecraft.

Unfortunately, there is very little information on the effects of most of these environmental variables. What information there is has often been gathered under conditions which do not lead to actual predictive relationships (for example, test results on burning rates of small specimen coupons ignited with a Bunsen burner do not yield much data of generality). In this Chapter, we will try to collect as much general-purpose data as can be found which would be of aid to the fire protection engineer. Topics which are highly specialized to the design of spacecraft will not be covered; for these we refer the reader to NASA's excellent *Spacecraft Fire Safety* [1].

## OXYGEN CONCENTRATION

This effect may be of concern in most fires, since once a fire gets larger, the inflow of air to the combustion zone may contain mixed-in combustion products and, therefore, a diminished oxygen concentration. Changes in oxygen concentration will have an effect on various aspects of combustion. Since in the previous Chapters we delved in some ways into combustion variables other than heat release rate, in this Chapter we will also consider the data for each of these, in turn.

In general, we will only consider the effect for oxygen concentrations < 21%. In building fires, oxygen concentrations can fall due to vitiation, but cannot rise above their original value. We further note that tests which subject building products or materials to concentrations > 21% lack realism and may give misleading results. Into this category fall the limiting oxygen index test (LOI) and the new Factory Mutual test procedures for cables. Such testing is especially inappropriate for materials containing fire retardants. Raising the oxygen concentration in the combustion air to > 21% directly raises the flame temperature. Many flame retardants are sensitive to flame temperatures for their proper action. When exposed to unrealistic and incorrect flame temperatures, their action cannot be correctly assessed.

The *Limiting Oxygen Index* (LOI) Test [2] involves the candle-like burning of a rod of plastic material. The apparatus is supplied with an adjustable oxygen/nitrogen flow mixture; the test requires that the minimum concentration of oxygen be found for which the specimen will continue burning downward without flame extinction. Since the results are quoted as an oxygen concentration, the results have widely been interpreted to suggest that a material will not burn in a given atmosphere if its LOI is greater than the oxygen concentration in that atmosphere, which can be even > 90% O<sub>2</sub>. Such, of course, is not the case at all. A number of theoretical analyses of the method have been made [3],[4],[5]. These show that the LOI value, far from reflecting a general property of the material, simply determines the oxygen concentration for which laminar, downward, against-the-wind flame spread ceases in the absence of external heating. The test, in fact, has nothing to do with burning rates at all, but is a flame spread test of a very specific geometry, with data scarcely to be applicable to differing geometries. It has become understood within the fire protection engineering community that the test should not be used to predict actual fire hazard conditions, although it may have a limited role for quality control monitoring, where low cost, sensitivity, and good repeatability are important, but accurate prediction of fire hazard is not.

Another test where unrealistic oxygen levels are used is the test the Factory Mutual System is starting to use for rating of electric cables. In this test [6] the FMRC Flammability Apparatus is used, with an air stream being fed which

contains 40% oxygen. While such elevated oxygen levels would be appropriate were the testing intended for some spacecraft or industrial application which actually used 40% oxygen atmospheres, the test is, unfortunately, intended for normal building fires.

## Ignition

There are a number of different phenomena under the general topic of ignition, including piloted ignition, autoignition, spontaneous heating, and various other, less common events. In the simplest case of piloted ignition of solids from radiant heating, the ignition event can be visualized as occurring at a time when there is a critical rate of pyrolysis products leaving the surface [7]. This rate is typically seen to be about 1 to 4x10<sup>-3</sup> kg/m<sup>2</sup>-s in ignitions under normal oxygen conditions and is presumed to correspond to the lower flammable limit being attained for the mixture above the material's surface. Based on this reasoning, ignition should be little affected by O<sub>2</sub> concentration, since a fuel's lower flammable limit is independent of O<sub>2</sub> concentration over a wide O<sub>2</sub> range.

Experimental data for O<sub>2</sub> effects on radiative ignition have been scarce; somewhat more data have been available on convective ignition, specifically, for solid rocket propellants. A theory by McAlevy, *et al.* [8] suggests that the ignition time should depend on the oxygen mass fraction as

$$t_{ign} \propto m_{O_2}^{-2/3}$$

however his experimental results show

$$t_{ign} \propto m_{O_2}^{-n}$$

where n = 1.2 to 1.5. Kumar and Hermance [9] also conducted a theoretical study of propellant ignition. Evaluated for various material properties, their results typically show

$$t_{ign} \propto m_{O_2}^{-n}, \text{ where } 1 \leq n \leq 2, \text{ for } m_{O_2} \geq 0.2$$

$$\text{and } n \rightarrow 0 \text{ for } m_{O_2} \leq 0.2$$

The solid propellant studies, in addition to being restricted to a convective ignition mode, deal with heterogenous systems, where an oxidizer is already mixed in with the fuel. Thus, their application to common fire types may be limited.

For accidental fires, ignition is most likely to be from radiative heating, and with the condensed phase being pure fuel, with no oxidizer admixture. A theoretical analysis of this case was done by Kashiwagi [10], but for the case of autoignition only. Kashiwagi showed there to be a limiting value of  $m_{O_2}$  needed for successful ignition; this value depends on the exact problem being solved, but may be in the vicinity of 0.15. For  $m_{O_2}$  just slightly higher than this minimum value, there is a very narrow area, where ignition time goes from infinite to a modest value, as  $m_{O_2}$  is raised slightly. For further increases in  $m_{O_2}$ ,  $t_{ign}$  is little affected by  $m_{O_2}$ , dropping about 15% as  $m_{O_2}$  goes from 0.23 to 1.00. A very limited amount of data was obtained by Alvares [11], on cellulose samples only; these experiments confirm the trends calculated by Kashiwagi.

The most recent study available in this area was the work of Mulholland and co-workers [12], who studied combustion under lowered  $O_2$  conditions in the Cone Calorimeter; the main focus of that study was on heat release rate and product yields, thus, the main findings are discussed in the pertinent sections below. Mulholland *et al.* studied PMMA, ABS, polyethylene and Douglas Fir, over the  $O_2$  range from 21% to the lowest value at which sustained burning could be achieved, typically 14%. In this series of tests,  $t_{ign}$  was independent of  $m_{O_2}$ , over the entire range that burning could be sustained.

### Flame spread

The effects of oxygen concentration on flame spread have been of concern for quite some time. In an early review [13], Magee and McAlevy found that for several geometrical and flow arrangements, the flame spread velocity,  $V$ , was related to  $m_{O_2}$  in a power law relationship, with  $V \propto m_{O_2}^2$ . Later, Fernandez-Pello and Hirano [14] re-examined this power-law relationship and found that it to hold only for large  $m_{O_2}$  values. For lower oxygen concentrations, the dependence of the flame spread rate on oxygen mass fraction becomes progressively greater, approaching an infinite-slope asymptote at the  $m_{O_2}$  value at which extinction occurs. Most recently, Mekki and co-workers [15] examined against-the-wind spread over wood and over PMMA. In both cases they found actual data to be better predicted by the first power of  $m_{O_2}$  than by the square. However, Mekki was only able to examine the oxygen mass fraction range from 0.23 to 1.00, and did not obtain data in the more interesting regime of  $< 0.23$ .

In an experimental study of flame spread over thin paper specimens, Frey and T'ien [16] also found the dependence at high  $m_{O_2}$  values to be on the first power of  $m_{O_2}$ , and an increasing higher-power dependence at low oxygen values. It is, perhaps, not surprising that flame spread phenomena should show the same, very-sharp dependence on  $m_{O_2}$  at  $m_{O_2}$  values near extinction. For the remainder of the  $m_{O_2}$  range, all existing work, thus, generally points towards a first-power dependence. In a somewhat different approach, Altenkirch [17] has suggested that oxygen fraction is among the variables which may be successfully correlated by the use of the Damköhler number.

### Mass loss rate

The mass loss rate of a specimen can be visualized to be determined by two main factors: the heat flux to the specimen and the physicochemical reactions taking place within or on the surface of the specimen. The oxygen content affects the former only to a limited degree. This is easiest to see in the case of pyrolysing materials in pure nitrogen. The reduction in heat flux will depend, of course, on the amount of heat flux present, by contrast, from the specimen's own flame when burning in a 21% oxygen environment. For many cases of interest, however, including most small scale fire tests, the fluxes from the specimen's own flame are substantially smaller than the external fluxes imposed by a heating apparatus or an already existing fire.

The response of a material will depend on whether its decomposition is or is not affected by oxygen from the outside environment. The exact answer will depend on the chemical nature of the material burning. Kashiwagi and Ohlemiller examined the pre-ignition mass loss rates of PMMA and polyethylene under various heat flux and oxygen concentration conditions [18]. The effect of oxygen concentration was significant at a low heating flux (17 kW/m<sup>2</sup>), but much less so at a higher one (40 kW/m<sup>2</sup>). The same authors later studied wood under similar conditions and provided some illustrative data [19]; neither of these studies produced data correlations or numerical computation procedures. Mikkola [20] examined a number of additional studies on wood materials and makes the recommendation when oxygen concentration is reduced to the 8% to 10% range, that the mass loss rate should be estimated as being 80% of its rate at 21%  $O_2$  conditions.

The effects of oxygen level on the mass loss rate have also been studied by Tewarson [21],[22] and Santo [23]. For some materials, they found a direct, linear relationship between  $m_{O_2}$  and the mass loss rate. This relationship remains linear down to the lowest  $m_{O_2}$  value at which combustion is sustained, but the relationship has an offset, i.e.,

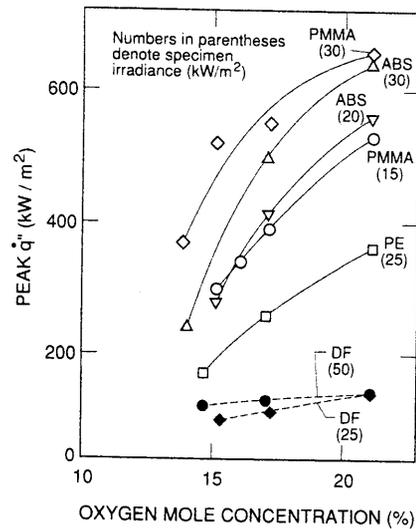
$$\dot{m}'' = aY_{O_2} - b$$

For other materials, especially charring materials, however, this linear relationship levelled off at higher  $m_{O_2}$  values.

Mass loss rate was also studied by Mulholland, *et al.* [12] in conjunction with their HRR study, described below. For PMMA, ABS, polyethylene, and Douglas fir, they found that the mass loss rate trends exactly mirrored the HRR trends, that is to say, the *effective heat of combustion* was independent of  $O_2$ .

### Heat release rate

Mulholland, *et al.* [12] have made a heat release rate study on a number of materials, going down from ambient 21% oxygen concentration to the lowest

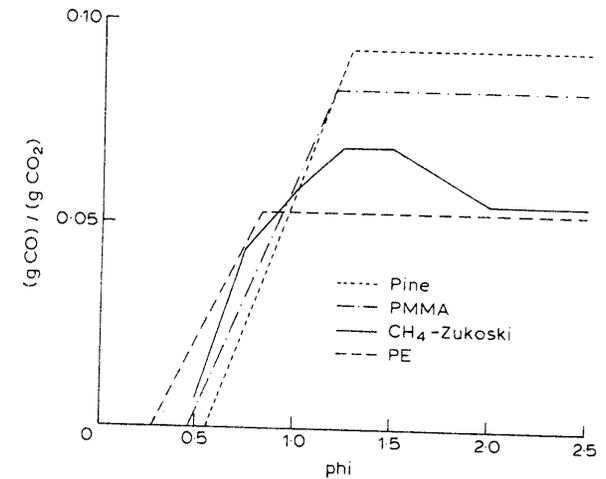


**Figure 1.** The dependence of the heat release rate on oxygen concentration (PMMA = polymethylmethacrylate; ABS = acrylo-nitrile-butadiene-styrene; PE = polyethylene; DF = Douglas fir)

concentration at which sustained combustion could be achieved in an enclosed Cone Calorimeter. The latter value was, of course, found to depend both on the test material and on the irradiance, but was typically around 14%. The results for a number of materials are shown in Fig. 1. It can be seen that for thermoplastics (PMMA, ABS, and PE) the effect was strong and was progressively greater at lower oxygen concentrations. For the one charring material tested, Douglas fir (DF), the dependence was very slight, with a linear proportionality.

#### Yields of products of combustion

The effect of oxygen levels on the yields of CO, of other toxic gases, and of smoke from fires has been considered to be an issue of acute fire engineering interest. Data, however, have been scarce. The data that are available fall into two categories. In the first type of geometry, which we shall call *simulated room fire*, an experimental geometry is used which resembles a model-scale room with a single door or window opening. Fuel is introduced as a gas burner or as a pool fire at the floor level. Oxygen is drawn in by natural convection from the ambient air, which in all experiments reported to date has been at 21%. The *amount* of oxygen available, however, is controlled by diminishing the window opening or other means. Thus, the total *ratio* of oxygen to fuel may be driven to quite small values. Typically, values which are fuel-rich by about a factor of 2.5 (compared to stoichiometric fuel/air ratios) are reached. Experiments of this type have been conducted by Prof. Edward Zukoski at the California Institute of Technology (see



**Figure 2.** The dependence of CO on the fuel/air ratio (the equivalence ratio  $\phi$  is defined as the actual fuel/air ratio, divided by its value under stoichiometric supply conditions; thus,  $\phi < 1$  denotes fuel-lean conditions, while  $\phi > 1$  is fuel-rich).

Ref. [24]) and by Dr. Craig Beyler at Harvard [25]. The yield of CO has generally been the most important variable to be determined in these tests. Only a very few materials have been examined to date, and the results are somewhat sketchy; a simplified correlation (Fig. 2) shows that some predictive guidance is already available, however. Fig. 2 shows that for  $\phi < 1$ , *i.e.*, for fuel-lean conditions, there appears to be a universal curve. Above  $\phi = 1$  (fuel-rich burning), two trend-lines may be seen, one for fuels which contain oxygen atoms their structure (pine, PMMA), and a second for those that do not (methane, polyethylene). The evolution of CO was expressed as g CO/g CO<sub>2</sub>, instead of as CO yields, since this form of data reduction was better able to collapse the data and to clearly indicate the difference between oxygenated and non-oxygenated fuels. It bears special emphasis that the CO is here seen to depend on  $\phi$  and on whether the fuel is oxygenated, but not on other *fuel properties*.

The second type of experiment we shall call the *coaxial flow geometry*. This can be represented, among other environments, by an enclosed Cone Calorimeter, where the air being supplied is at a lowered O<sub>2</sub> concentration. This simulates the vitiation of air by combustion products during a fire in an enclosure. Such data were reported in the same Cone Calorimeter study by Mulholland [12] above. In such a geometry, fuel-rich conditions cannot be achieved without lowering the flow rates so much that straight-through flow ceases and the whole apparatus is enveloped in ponded-up combustion gases. The latter, would, of course, correspond the creation of the simulated room geometry conditions in an

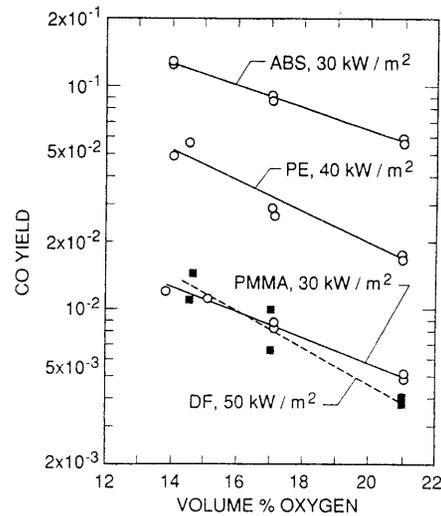


Figure 3. CO yields, as measured by Mulholland *et al.* in the coaxial flow geometry

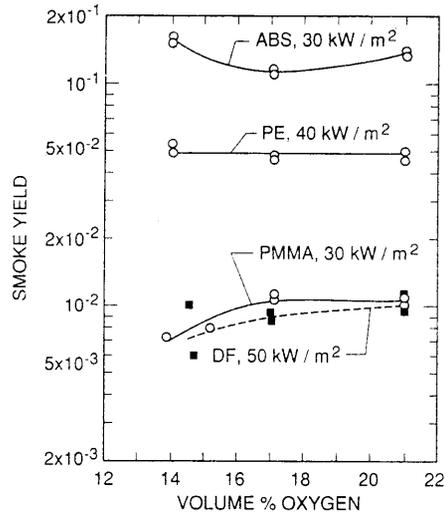


Figure 4. Soot yields, as measured by Mulholland *et al.* in the coaxial flow geometry

inappropriate apparatus. By maintaining steady flow conditions, Mulholland could only reach  $\phi$  values of no higher than 0.3. Fig. 3 shows the yields of CO measured in this apparatus. In this geometry and this burning regime (low  $\phi$ , low CO yields) the data are not uniquely correlated to  $\phi$ .

Smoke studies in the simulated room fire geometry are not available; they are available, however, in the coaxial flow geometry study of Mulholland. His findings for soot yields are given in Fig. 4. The dependence on oxygen concentration is seen to be slight to nil.

### THE TEMPERATURE OF THE INCOMING COMBUSTION AIR

The temperature of the incoming combustion air can change from its ambient value during the later stages of a fire, possibly in conjunction with its vitiation. This topic would fall largely in the category of post-flashover fires, which have generally been studied in much less of a fine-scale detail than have developing fires. Preheating the incoming air will change a number of aspects of combustion, including raising the flame temperature and extending the range of the flammability limits.

During the early 1980's, FMRC installed an air heater on their Flammability Apparatus to enable HRR tests to be run with heated combustion air. No publications on this subject, however, have emerged from FMRC, nor has this topic been studied by other workers in any geometries that would be applicable to building fires.

### PRESENCE OF ADDITIONAL GASES NOT OCCURRING IN NORMAL AIR

There are probably thousands of publications which have dealt with the general issue of combustion processes in atmospheres where some additional gas component is present in the combustion air. The motivation for these types of studies is usually to understand flame extinction or to characterize the effectiveness of gaseous extinguishing agents. Unfortunately, such studies have normally been done on specialized burners and in other experimental geometries which do not lend themselves to characterizing heat release rates or other variables of interest in the present book. Thus, such studies are outside the scope of this work; readers interested in following the progress of such studies should consult recent volumes of symposia of The Combustion Institute and the journals *Combustion and Flame* and *Combustion Science and Technology*.

One example where data of this nature were obtained in a heat release rate apparatus is the recent study by Mulholland *et al.* [12]. Fig. 5 shows their results

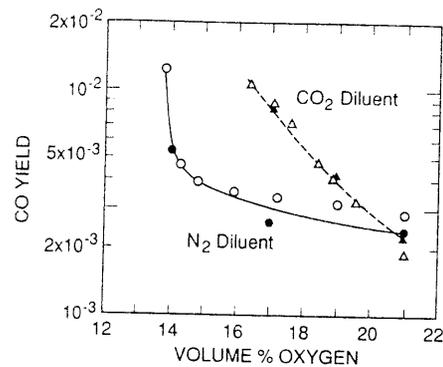


Figure 5. CO yields for propane, as a function of two different diluent gases, measured by Mulholland *et al.* in the coaxial flow geometry

for CO yield, obtained in the enclosed Cone Calorimeter for propane under comparative conditions of N<sub>2</sub> and CO<sub>2</sub> diluents. For a given O<sub>2</sub> concentration, the CO<sub>2</sub> diluent gave significantly greater CO yields than did the N<sub>2</sub> diluent. Note, however, that with the CO<sub>2</sub> diluent there was less potential for dilution before steady burning ceased (leftmost points on graphs). Thus, interestingly enough, at extinction conditions the CO yields were the same for both diluents, although O<sub>2</sub> concentrations were dissimilar.

### TOTAL PRESSURE

The effects of pressure on the burning of combustibles has become of great interest to the U.S. Navy as a means of extinguishing fires. The principles of this are elementary. In a landmark paper entitled *Habitable Atmospheres Which Do Not Support Combustion* [26], Huggett explained that for survival humans depend on there being a minimum *partial pressure* of oxygen, and a minimum concentration. By contrast, the combustion process requires a minimum flame temperature to avoid extinction. This minimum flame temperature can be related to a minimum heat capacity per mole of O<sub>2</sub>, this being about 170 to 210 J/°C per mole O<sub>2</sub>. Thus, if the *total pressure* of the atmosphere is increased by the forced injection of an inert gas into a sealed atmosphere, it may be possible to extinguish a fire without injuring persons. Initial tests conducted by the Navy in small scale [27] showed this concept to be viable. In small scale pool fire tests extinction was typically achieved when the nitrogen diluent raised the total pressure to about 1.6 atmospheres. Subsequently, engineering details have been pursued in an ambitious program of large-scale tests [28]. The actual Navy studies were empirical in nature and focus solely on extinguishment. Since extinguishment is not within the scope of this book, we will not discuss the Navy findings in detail.

### Ignition

Similarly as for oxygen concentration effects, the total pressure is expected to affect the ignitability of a material indirectly by its effect on the lower flammable limit. For many materials, over a fairly wide range of pressures, the lower flammable limit is not significantly affected by total pressure [29]. The early propellant studies of McAlevy, *et al.* [8] showed a theoretical dependence of

$$t_{ign} \propto P_{tot}^{-1.44}$$

while corresponding experimental measurements gave

$$t_{ign} \propto P_{tot}^{-1.77}$$

Very similar results are also reported by Kumar and Hermance [9]. The work of Beyer and Fishman [30] suggests that the pressure dependence becomes small at low heat fluxes (such as might be expected from an accidental fire), provided the value of P<sub>tot</sub> is not also low.

In a more comprehensive study, Shannon [31] obtained detailed ignition times plots for a number of propellants, covering a wide range of pressures and heat fluxes. The effects of pressure were not well-represented as a power law. Instead, for P<sub>tot</sub> greater than about 2 atm, there was negligible effect on t<sub>ign</sub>. For P<sub>tot</sub> < 2 atm, however, the negative exponent was increasingly greater for lower values of P<sub>tot</sub>. The experiments of Kashiwagi, *et al.* on both pure fuels and on propellants [32] indicate a behaviour at very large values of P<sub>tot</sub> (> 20 atm) where instead of becoming independent of P<sub>tot</sub>, the ignition times vary according to

$$t_{ign} \propto P_{tot}^{-1}$$

Ohlemiller and Summerfield [33] in a similar study, also show a continued dependence of t<sub>ign</sub> on P<sub>tot</sub>, even at high P<sub>tot</sub> values.

The work of both Kashiwagi [32] and Ohlemiller [33] suggests that a combined correlation of the effects of oxygen fraction and the total pressure should not be sought in the use of partial O<sub>2</sub> pressure as a correlating variable, unless only the regime of large m<sub>ox</sub> and P<sub>tot</sub> values is considered, and only approximate results are sought.

### Flame spread

Magee and McAlevy [13] found that for thick fuels the flame spread velocity was proportional to slightly higher than the 1/2 power of the total pressure. For thin fuels, however, the pressure effect was very tiny, being about to the 0.1 power.

Frey and T'ien, again, studied the variables over a wider range [16] and found an 0.1 power dependence only for thin fuels at high (in comparison to the limiting pressure at extinction) pressures and spreading vertically down. For horizontal spread the exponent was higher, but was not unique, there being a strong coupling between oxygen fraction and total pressure effects. In both cases, similarly as for the oxygen fraction effect, the dependence on the total pressure became much greater as the pressure was lowered towards the extinction value. Fernandez-Pello and Hirano [14] found that over a limited range extinction could be represented by a constant value of  $P_{tot} \times X_{O_2}$ , i.e., a constant partial pressure of oxygen. Outside of this limited range, however, such a simplification did not hold.

### Mass loss rate and heat release rate

Test instruments for measuring mass loss rates or heat release rates have rarely been built to allow pressure to be varied. We know of only two such examples. A hyperbaric burning chamber was constructed at Factory Mutual Research by Alpert [34] in the mid-1970's. The limited data taken showed that over a certain range of test variables, a dependence of the mass loss rate was according to:

$$\dot{m}'' \propto P_{tot}^{2/3}$$

This has not been applied in practical materials testing. More recently, Prof. Corlett at the University of Washington constructed a hyperbaric chamber for conducting various studies [35] on the burning rate of materials; data reports are not yet available, however.

## WIND

Wind velocity is a major factor in determining flame spread and is accounted by most flame spread theories, which are outside the scope of this book. Wind can equally be an important factor for ignition. We do not know of any systematic studies in this area; a limited amount of guidance is offered by Janssens [36].

### Mass loss rate and heat release rate

These effects have been of interest to researchers studying liquid pool fires. Larger pools are typically burned outdoors, where windfree conditions may be difficult to obtain; thus, quantification of the effect has always been seen to be important. Wind across a burning specimen affects both convective and radiative heat transfer. For a horizontal pool fire, wind will cause the flames to lie down, thereby changing the entrained air amount and also both the convective and the radiative heat fluxes to the pool surface. Experimental data on this issue, unfortunately, are contradictory. Capener and Alger [37] measured 1 and 3

m diameter pool fires of jet fuel JP-5. In their data, the burning rate of a 1 m pool in a 6 m/s wind drops to about 1/2 of its still-air value. The exact opposite was found by Lois and Swithenbank [38], who measured a burning hexane pool: they observed a doubling of the burning rate in a 4 m/s wind, with no further increase at higher velocities. Blinov and Khudiakov [39] also studied the effect of wind on pool of hydrocarbon fuels. They express their measurements as a relationship:

$$\frac{\dot{m}''_{windy}}{\dot{m}''_{still}} = 1 + 0.15 \frac{v}{D}$$

where  $v$  = wind velocity (m/s), and  $D$  = pool diameter (m). Their relationship should not be used for wind velocities great enough to cause blowoff. Beyond about 5 m/s some fuels can be blown off, but blowoff depends on the exact details of flameholder action at the edge of the pool.

## RELATIVE HUMIDITY

Relative humidity has a relatively minor effect in the *gas phase*, for even at 100% R.H. and 25 C, the absolute amount of water is only about 2% by mass. The importance of R.H., instead, comes from the fact that many of the common combustibles are *hygroscopic*. Wood, cotton, and other cellulosic materials are the most commonly encountered hygroscopic combustibles. It is for this reason, of course, that many standard fire tests require that the specimen be equilibrated to a standard R.H. value, often 50% R.H. being chosen.

The science of sorption of water by wood is thoroughly addressed in a book by Skaar [40]; thus here we will only cite studies on the fire response of cellulose.

## Ignition

The effect of R.H. on piloted wood ignition can be correlated through the moisture content of the wood. Even though the ignition process involves a complicated relation between heat transfer, mass transfer, and chemical reaction, it turns out that the effects of moisture can be predicted satisfactorily from some simple relations. Simms and Law [41] first showed that it is sufficient to account for the effect of moisture content on the thermal properties (thermal conductivity  $k$ , density  $\rho$ , and heat capacity  $C$ ), and they provide appropriate expressions for such correlations. Current studies on this effect are presented in Chapter 8, in the section on ignition. With cellulose and some other materials there is also the more specialized problem of spontaneous ignition *due to* self-heating associated with absorption of moisture from the air by these materials. Since self-heating problems are outside the scope here, we mention this in passing and refer the reader to studies by Walker [42] and Back [43].

### Flame spread

Flame spread rates are governed by a number of properties of the material, of the flames, and of the environment. Of the material properties, the same thermal properties ( $k$ ,  $\rho$ ,  $C$ ) which govern ignition, also are equally important for flame spread. Moisture effects on flame spread, as measured in the ASTM E 162 test, were reported by Lee and co-workers [44] for cellulosic building boards. They found, for example, that changing specimen condition for fibreboard specimens from 0 to 100% R.H. raised the moisture content from 1% to 25% and cut the flame spread rate by about half. This was attributed to an increase in the thermal inertia by about a factor of 2.5. Pickard and Wraight studied flame spread over moist paper [45]; some data correlations are offered for their results. Moisture effects on mattresses were documented by Land [46] and on upholstered chairs by Hägglund and co-workers [47]. None of these studies gave design guidance or theoretical predictions. A theoretical model for flame spread over moist materials was presented by Ying [48]. His work may represent a starting point, but contain neither closed-form design expressions nor experimental verification.

### Mass loss rate

Mikkola [20] correlated a number of studies where mass loss rates for wood materials were determined and provided the following correlation:

$$\dot{m}'' \propto \frac{1}{1 + 2.5w}$$

where  $w$  = the moisture content, expressed as the ratio (mass of water)/(mass of dry wood).

### Heat release rate

The heat release rate can be considered as the product of the mass loss rate and the effective heat of combustion. Thus, for wood materials, Mikkola recommends [20] using the above expression for the mass loss rate and gives the following relationship for the effective heat of combustion, applicable only during the time of flaming (not glowing) combustion:

Moisture content, $w$	Effective heat of combustion (MJ/kg)
0	15
0.8-0.10	12.5
0.20	10.5

Chamberlain [49] conducted an extensive study of the heat release rate of wood materials, including the effect of moisture. He concluded that each 10% rise in the R.H. decreases the heat release rate by about 4%.

## ACCELERATION OF GRAVITY

### Ignition

Limited experiments have suggested that the ignitability of a material is not significantly affected by a lowered gravity or by micro-gravity conditions [50]. This is in agreement with the findings of Strehlow and Reuss [51], who concluded that gravity had but a minor effect on the lower limit of flammability.

### Flame spread

The role of 'g' in flame spread has most comprehensively been examined by Olson and co-workers [52]. For normal earth gravity to 4 times that, they found, in the spread-against-wind configuration, that flame spread rates varied roughly proportional to  $g^{-1}$ . For  $g \rightarrow 0$ , flame spread rates were only about 45% of the value occurring at normal earth gravity. The region between  $g = 0$  and normal earth gravity was not explored, however. This is consistent with earlier experiments by Kimzey [50]. Only one particular flame spread geometry was explored, however, in Olson's studies. For other, earlier studies, the reader might also wish to consult Schreihans [53], Altenkirch [17],[54], and Hall [55]. Most of these earlier studies showed little effect of gravity when greater than normal earth gravity conditions were considered.

### Mass loss rate and heat release rate

Some very early experiments by Hall [56] indicated that, once ignited, a material is likely to burn even through periods of weightlessness. His study suggested that burning was in some sense accelerated during weightlessness. In general, extensive studies have not been made of the effects of gravity on the rates of mass loss or heat release. For small items, where convective effects dominate, it would be expected that the burning rate would follow Spalding's B-number theory, as outlined in Chapter 7. This theory, for example, predicts that the burning rate of a small sphere will be proportional to the 1/4 power of  $g$ . The burning of larger items tends to be dominated by radiative transfer. Here the effects of gravity are much smaller and indirect. The only gravity effect will be if the sootiness of the flames or the shapes of the radiating bodies are affected; this, of course, is possible.

## REFERENCES

1. Spacecraft Fire Safety (NASA Conference Publication 2476). National Aeronautics and Space Administration, NASA Lewis Research Center, Cleveland (1987).
2. Standard Method of Test for Flammability of Plastics using the Oxygen Index Method (ASTM D 2863), American Society for Testing and Materials, Philadelphia.
3. Sibulkin, M., and Little, M.W., Propagation and Extinction of Downward Burning Fires, *Combustion and Flame*. **31**, 197-208 (1978).
4. Bulewicz, E. M., Some Notes on the Oxygen Index and Inflammability Limits, *Archiwum Termodynamiki i Spalania*. **7**, 175-190 (1976).
5. Kanury, A.M., Theoretical Analysis of Fire and Flammability Tests: III. The Limiting Oxygen Index Test, pp. 187-198 in *International Symposium: Fire Safety of Combustible Materials*, Edinburgh (1975).
6. Specification Test Standard for Cable Fire Propagation (Class No. 3972). Factory Mutual Research, Norwood (1989).
7. Kanury, A.M., Ignition of Cellulosic Solids: Minimum Pyrolysate Mass Flux Criterion, *Combustion Science and Technology*, **16**, 89 (1977).
8. McAlevy, III, R.F., Cowan, P.L., and Summerfield, M., The Mechanism of Ignition of Composite Solid Propellants by Hot Gases, p. 623 in *Solid Propellant Rocket Research*, M. Summerfield, ed., (Vol. 1, Progress in Astronautics and Rocketry). Academic Press, New York (1960).
9. Kumar, R.K., and Hermance, C.E., Gas Phase Ignition Theory of a Heterogeneous Solid Propellant Exposed to a Hot Oxidizing Gas, *Combustion Science and Technology*. **4**, 191-6 (1972).
10. Kashiwagi, T., A Radiative Ignition Model of a Solid Fuel, *Combustion Science and Technology*. **8**, 225-236 (1974); also **14**, 119-122 (1976).
11. Alvares, N.J., Oxygen Concentration and Pressure Effects on the Ignition of Cellulosic Fuels by Thermal Radiation, U.S. Radiological Defense Laboratory, San Francisco (1967). NTIS No. AD 650 622.
12. Mulholland, G., Janssens, M., Yusa, S., and Babrauskas, V., The Effect of Oxygen Concentration on CO and Smoke Produced by Flames, submitted to *Fire Safety Science — Proc. of the Third International Symposium* (1991).
13. Magee, R.S., and McAlevy, R.F., III, The Mechanism of Flame Spread, *J. Fire & Flammability*. **2**, 271-297 (1971).
14. Fernandez-Pello, A.C., and Hirano, T., Controlling Mechanisms of Flame Spread, *Fire Science and Technology*. **1**, 17-54 (1982).
15. Mekki, K., Atreya, A., Agrawal, S., and Wichman, I., Wind-Aided Flame Spread over Charring and Vaporizing Solids: An Experimental Investigation, to be published in *23rd Symp. (Intl.) on Combustion*, The Combustion Institute, Pittsburgh.
16. Frey, A.E., jr., and T'ien, J.S., Near-Limit Flame Spread over Paper Samples, *Combustion and Flame*. **26**, 257-267 (1976).
17. Altenkirch, R.A., Eichhorn, R., Shang, P.C., Buoyancy Effects on Flames Spreading down Thermally Thin Fuels, *Combustion and Flame*. **37**, 71-83 (1980).
18. Kashiwagi, T., and Ohlemiller, T.J., A Study of Oxygen Effects on Nonflaming Transient Gasification of PMMA and PE During Thermal Irradiation, pp. 815-823 in *Nineteenth Symp. (Intl.) on Combustion*. The Combustion Institute, Pittsburgh (1982).
19. Kashiwagi, T., Ohlemiller, T.J., and Werner, K., Effects of External Radiant Flux and Ambient Oxygen Concentration on Nonflaming Gasification Rates and Evolved Products of White Pine, *Comb. and Flame*. **69**, 331-345 (1987).
20. Mikkola, E., Charring of Wood (Research Report 689). Valtion Teknillinen Tutkimuskeskus, Espoo, Finland (1990).
21. Tewarson, A., Flammability of Polymers and Organic Liquids, Part I, Burning Intensity (FMRC Serial 22429), Factory Mutual Research Corp., Norwood (1975).
22. Tewarson, A., and Steciak, J., Fire Ventilation (NBS GCR-83-423), [U.S.] Natl. Bur. Stand. (1983).
23. Santo, G., Influence of Oxygen Depletion on the Radiative Properties of PMMA Flames (FMRC J.I. OAOE6.BU-3), Factory Mutual Research Corp., Norwood (1979).
24. Pitts, W.M., Executive Summary for the Workshop on Developing a Predictive Capability for CO Formation in Fires (NISTIR 89-4093). [U.S.] Natl. Institute of Standards and Technology (1989).
25. Beyler, C.L., Major Species Production by Solid Fuels in a Two Layer Compartment Fire Environment, pp. 431-440 in *Fire Safety Science—Proceedings of the First International Symposium*, C.E. Grant and P.J. Pagni, eds., Hemisphere Publ., Washington (1986).
26. Huggett, C., Habitable Atmospheres Which Do Not Support Combustion, *Combustion and Flame*. **20**, 140-143 (1973).
27. Gann, R.G., Stone, J.P., Tatem, P.A., Williams, F.W., and Carhart, H.W., Suppression of Fires in Confined Spaces by Nitrogen Pressurization: III. Extinction Limits for Liquid Pool Fires, *Combustion Science and Technology*. **18**, 155-163 (1978).
28. Submarine Hull Insulation Fires—Suppression with Nitrogen Pressurization and Corrosion Rates of Metals (NRL Report 8943), Naval Research Laboratory, Washington (1986).
29. Zabetakis, M.G., Flammability Characteristics of Combustible Gases and Vapors (Bulletin 627), U.S. Bureau of Mines (1965).
30. Beyer, R.B., and Fishman, N., Solid Propellant Ignition Studies with High Heat Flux Radiant Energy as a Thermal Source, p. 673 in *Solid Propellant Rocket Research*, M. Summerfield, ed., (Vol. 1, Progress in Astronautics and Rocketry). Academic Press, New York (1960).
31. Shannon, L.J., Composite Solid-Propellant Ignition by Radiant Energy, *AIAA J.* **8**, 346-353 (1970).

32. Kashiwagi, T., Waldman, C.H., Rothman, R.B., and Summerfield, M., Ignition of Polymers in a Hot Oxidizing Gas, *Combustion Science and Technology*. **8**, 121-131 (1973).
33. Ohlemiller, T.J., and Summerfield, M., Radiative Ignition of Polymeric Materials in Oxygen/Nitrogen Mixtures, pp. 1087-1094 in *Thirteenth Symp. (Intl.) on Combustion*. The Combustion Institute, Pittsburgh (1970).
34. Alpert, R.L., Pressure Modeling of Fires Controlled by Radiation (FMRC Serial 22360-5), Factory Mutual Research Corp., Norwood (1976).
35. Lockwood, R.W., and Corlett, R.C., Radiative and Convective Feedback Flux in Small Turbulent Pool Fires with Variable Pressure and Ambient Oxygen, pp. 421-426 in *Proc. of the 1987 ASME-JSME Thermal Engineering Joint Conference*, American Society of Mechanical Engineers, New York (1987).
36. Janssens, M., Ph.D. Dissertation, U. of Gent, Gent, Belgium (1991).
37. Capener, E.L., and Alger, R.S., Characterization and Suppression of Aircraft and Fuel Fires (WSCI 72076). Paper presented at the Western States Section meeting of the Combustion Institute, Monterey, CA (1972).
38. Lois, E., and Swithenbank, J., Fire Hazards in Oil Tank Arrays in a Wind, pp. 1087-1098 in *Seventeenth Symp. (Intl.) on Combustion*, The Combustion Institute, Pittsburgh (1978).
39. Blinov, V.I., and Khudiakov, G.N., Diffusion Burning of Liquids. U.S. Army Translation. NTIS No. AD296762 (1961).
40. Skaar, C., *Water in Wood*. Syracuse University Press, Syracuse, NY (1972).
41. Simms, D.L., and Law, M., The Ignition of Wet and Dry Wood by Radiation, *Combustion and Flame*. **11**, 377-388 (1967).
42. Walker, J.K., The Role of Water in Spontaneous Combustion of Solids, *Fire Research Abstracts and Reviews*. **9**, 5-22 (1967).
43. Back, E.L., Auto-Ignition in Hygroscopic, Organic Materials—Especially Forest Products—as Initiated by Moisture Absorption from the Ambient Atmosphere, *Fire Safety J.* **4**, 185-196 (1981/82).
44. Lee, T.G., Loftus, J.J., and Gross, D., Effect of Moisture on Surface Flammability of Coated and Uncoated Cellulosic Materials, pp. 112-123 in *Moisture in Materials in Relation to Fire Tests* (ASTM STP 385). American Society of Testing and Materials, Philadelphia (1965).
45. Pickard, R.W., and Wraight, H., The Effect of Moisture on the Ignition and Flame Propagation of Thin Cellulosic Materials (Fire Research Note 450). Fire Research Station, Borehamwood (1961).
46. Land, R.I., Test Burns of Mattresses and Bedclothes (Home Fire Project Report 24). Harvard University, Dept. of Applied Science, Cambridge (1981).
47. Hägglund, B., Janssons, R., and Onnermark, B., Fire Development in Residential Rooms After Ignition from Nuclear Explosions (FOA Rapport C20016-D6-A3). Försvarets Forskningsanstalt, Stockholm (1974).
48. Ying, S.-J., Flame Propagation of Burning Solid Material with Moisture, *Fire Technology*. **7**, 243-250 (1971).
49. Chamberlain, D.L., Heat Release Rate Properties of Wood-Based Materials (NBSIR 82-2597). [U.S.] Natl. Bur. Standards (1982).
50. Kimzey, J.H., Flaming during Weightlessness (NASA TM-X-58001), NASA (1966).
51. Strehlow, R.A., and Reuss, D., Flammability Limits in a Standard Tube, Chapter 3 in *Combustion Experiments in a Zero-gravity Laboratory*, T.H. Cochran, ed., (Vol. 73 in Progress in Astronautics and Aeronautics). AIAA, New York (1981).
52. Olson, S.L., Ferkul, P.V., and T'ien, J.S., Near-Limit Flame Spread over a Thin Solid Fuel in Microgravity, pp. 1213-1222 in *22nd Symp. (Intl.) on Combustion*, The Combustion Institute, Pittsburgh (1988).
53. Schreihans, F.A., and Drysol, D.E., Flammability Characteristics of Some Organic Spacecraft Materials in Zero Gravity (NASA NAS9-150), NASA (1965).
54. Altenkirch, R.A., Eichhorn, R., and Rizvi, A.R., Correlating Downward Flame Spread Rates for Thick Fuel Beds, *Combustion Science and Technology*. **32**, 49-66 (1983).
55. Kimzey, J.H., Gravity Effects on Combustion (MSC Internal Note MSC-ER-R-67-10), NASA Manned Spacecraft Center, Houston (1967).
56. Hall, A.L., Observations on the Burning of a Candle at Zero Gravity, Naval School of Aviation Medicine, Pensacola, FL (1964). NTIS No. AD-436897.