Journal of Hazardous Materials, 36 (1994) 133–141
Elsevier Science B.V., Amsterdam

Impact of low O_2 on fires*

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Abstract

It is the thesis of this paper to show that through control of oxygen, fires can be markedly minimized or eliminated while still maintaining an atmosphere that will sustain human life. The driving force in this study is to decrease the fire hazard in manned capsules, such as in space, under the ocean, submarines, etc. which operate in an environment exceedingly hostile to life and from which escape is next to impossible. In most studies on fire, the earth's atmosphere with its 21% (v/v) oxygen is almost a given and is not usually varied. But it takes both a fuel and an oxidizer to have a fire, and though we study extensively the impact of structure, composition, concentration, flammability limits, energies of ignition, propagation rates, etc., for the fuel component of the combustion process there is a significant paucity of information on the impact of variations of the oxidizer. In this paper, the oxidizer of choice is oxygen because we also want to sustain life, and one of the beauties of a totally closed environment is that the oxygen can be varied at will, and we can take advantage of that fact to minimize or quench fires while not jeopardizing life.

1. Dependence of fires on oxygen concentration

The behavior of fires is surprisingly sensitive to even small changes in the concentration of oxygen (%) and surprisingly insensitive to changes in its partial pressure (pO_2). This is most easily shown in measurements of burning rate (which controls propagation, heat release, vitiated gas production, etc.) as a function of both concentration and partial pressure of oxygen in closed chambers. Figure 1 shows the burning rate of filter paper (held horizontally) in different O_2/N_2 mixtures at 1 atm total pressure [1]. The data show the marked dependence of burning rate on O_2 concentration, other things being essentially equal, i.e., N_2 and O_2 have such close molecular weights, heat capacities, thermal conductivities, etc. that substitution of one for the other has little physical effect on the fire and what is seen is the importance of the chemical

* Presented at the ACS-CHAS Symposium on Fire and Explosions, Washington, DC, August 27, 1992.

0304-3894/94/$07.00
SSDI 0304-3894(93)E0065-A

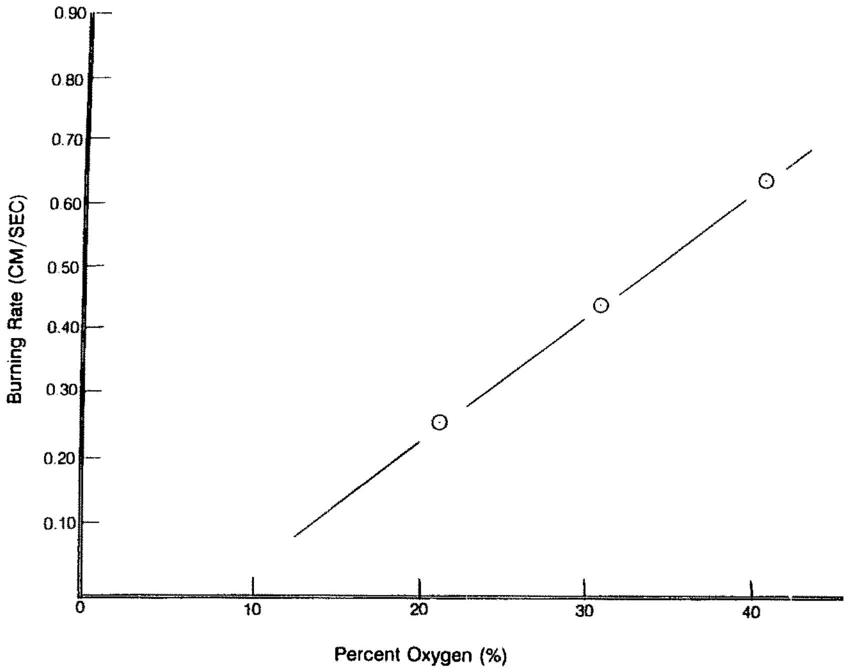


Fig. 1.

contribution of oxygen concentration. On the other hand, Fig. 2 shows that increasing the total pressure of the gas mixture (and thereby also the partial pressure of O_2) over a five-fold range, has a relatively small effect on burning rate [1]. This is partially explained by the fact that we are also increasing the partial pressure of N_2 which continues to act as a heat sink to control heat and mass transfer and thereby flame spread. Note also in Fig. 2 the marked differences in burning rates between the 21% and the 31 and 41% experiments, again showing the importance of concentration of O_2 vice the partial pressure of O_2.

Burning rate of liquid fuels also show a high dependence on O_2 concentration as shown by Figs. 3 and 4, Fig. 3 being data for kerosene [2] and Fig. 4 for methyl alcohol [3]. The apparent differences in these two sets of data are largely because of experimental conditions used, the geometry of the experiment influencing rate of fuel evaporation which also impacts burning rate.

It is interesting to note that these data imply a lower limit for oxygen concentration below which the fuel will not burn. As mentioned earlier, lower flammability limits for fuels have been extensively studied, and for a number of gases the corresponding lower limits for oxygen for the given fuel have also been studied [4]. Figures 1–4 show the same applies to solids and liquids. The

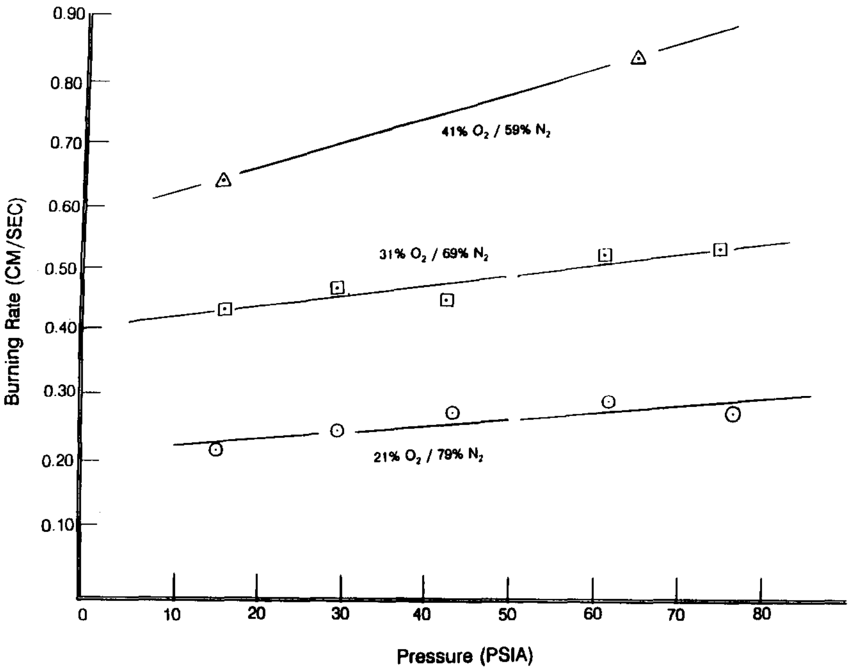
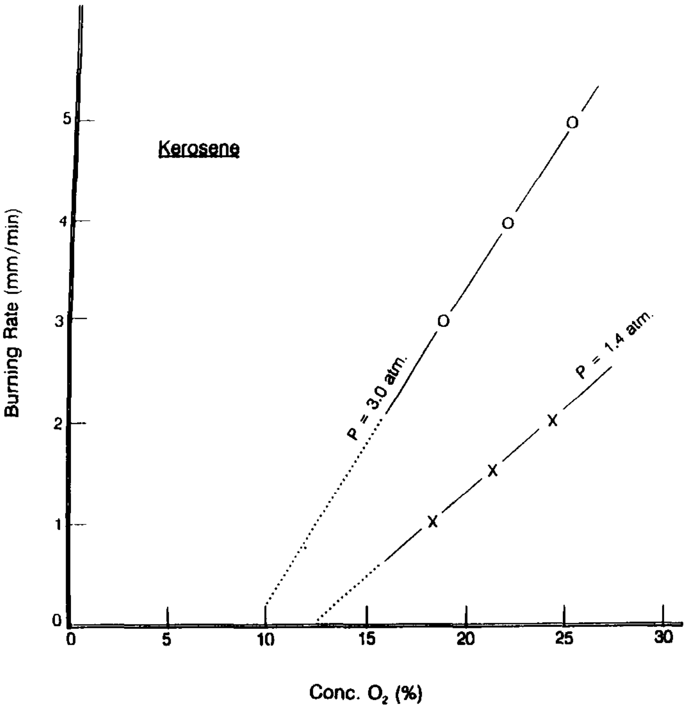


Fig. 2.

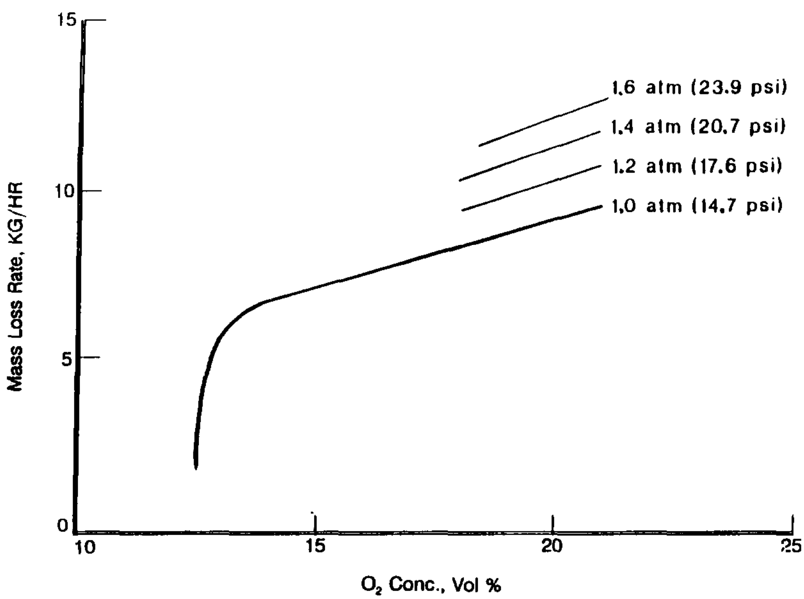
concept of Oxygen Index (the lowest concentration of O_2 that will support fire propagation) is well known, and there is an ASTM apparatus and procedure to measure it [5]. One objection to Oxygen Indices as measured by the ASTM procedure, however, is that the numerical values obtained are not the lowest oxygen concentration at which that material will indeed burn in the real world. This is because the sample is ignited at the top, and, because of gravitational effects (fires resist burning downwards because the hot gases produced are buoyant and contribute little to preheating the still unburned material) they self-extinguish at higher oxygen levels than if the sample had been ignited at the bottom. There is also some lack of consistency with the data obtained with observations made in real life. Table 1 shows some ASTM Oxygen Indices for some common materials, and it is seen that materials that we know will burn readily in air have Indices above the 21% of oxygen of air. Also, note that 3/4 in. plywood has a lower Index (i.e., it burns more easily) than 3/8 in. plywood — yet, experience tells us that the more surface area we have of a given substance the easier and faster it will burn (e.g., excelsior made from a given log burns much faster than the log itself).

Measurements of other fire behaviour properties, such as heat release, ignition, etc. also show a dependence on oxygen concentration, but not quite as dramatically as propagation [6].



Kerosene
Burning Rate (mm/min)
P = 3.0 atm.
P = 1.4 atm.
Conc. O_2 (%)

Fig. 3.



1.6 atm (23.9 psi)
1.4 atm (20.7 psi)
1.2 atm (17.6 psi)
1.0 atm (14.7 psi)
Mass Loss Rate, KG/HR
O_2 Conc., Vol %

Fig. 4.

TABLE 1

Oxygen Indices

Material	ASTM Oxygen Index
Filter paper	18.2
Cotton	18.6
Rayon	18.9
Sugar	22.0
Red oak	22.7
Wool	23.8
3/4" Plywood	24.3
3/8" Plywood	29.2

2. Dependence of life on oxygen partial pressure

In contrast to fires, life is primarily dependent on the *partial pressure* of oxygen (regardless of concentration) and also in contrast to fires life is surprisingly tolerant of wide ranges of partial pressures (i.e., life seems much more flexible and adaptable in this regard than fires are). This is illustrated in Table 2 which shows human habitation under a wide range of oxygen partial pressures. It is well known that a person does not jump from one extreme to the other suddenly without penalty (e.g., mountain sickness) and that in time too much oxygen can be toxic, but the fact remains that the human animal has a wide range of adjustability, and we can take advantage of this.

3. Closed environments

Table 3 shows three markedly different environments in which people lived and operated successfully, and yet in which fire behavior is radically different. In the Apollo rocket type environment, at 100% oxygen, fires are almost explosive. Indeed, in the Apollo fire of 1967, from recognition of ignition to rupture of the capsule was only about 15 seconds, and the fire was essentially over in only another 5 seconds or so [7]. Fires in submarines, at 21% O_2, are much closer to those we normally experience in everyday life (actually, some are more intense, for reasons not fully understood yet). In the case of Sea Lab, the aquanauts took tobacco with them into the capsule, but could not even get a match or lighter to ignite, and attempts to "light" cigarettes even from the hot space heaters in the capsule met with total and exasperating failure.

Table 3 illustrates quite clearly that fires are controlled by column 3 (conc. of O_2) and life is controlled by column 4 (pO_2) and that they are not the same.

TABLE 2

Oxygen partial pressure in inhabited atmospheres

Place/situation	pO_2 (atm)	Elevation (ft)
Apollo, take-off mode	1.09	
Apollo, flight mode	0.3–0.37	
Sea-level	0.21	0
Denver, Colorado	0.175	5,000
Airline cabin pressure[a]	0.16	8,000
Quito, Ecuador	0.15	9,300
LaPaz, Bolivia	0.134	12,000
Pikes Peak, Colorado	0.123	14,100

[a] Commercial airplane cabins are pressurized at ca. 8,000 ft equivalent.

TABLE 3

Encapsulated environments

Capsule	Total press. (atm)	% O_2	O_2 partial press. (atm)
Apollo	0.3	100	0.3
Submarine	1.0	21	0.2
Sea Lab II	7.0	4	0.3

4. Applications

In totally enclosed manned environments where the atmosphere can be controlled, such as in a submarine, advantage can be taken of the differences on oxygen dependence by fires and by life. From a fire standpoint, these can be passive and active.

4.1. Passive

The easiest passive approach for manned capsules is to have an atmosphere with an oxygen concentration well below the 21% of air. This can be accomplished by starting with such an atmosphere, or, in the case of a submarine, to breathe the oxygen down to the desired concentration before adding fresh oxygen. Indeed, in the U.S. Navy, submarines are now permitted to operate with oxygen concentrations down to about 17%. From a fire standpoint, what does 17% O_2 mean? The lowest concentration of O_2 at which highly flammable materials will burn, such as volatile liquid hydrocarbons, is around 12% (the diluent gas being N_2 [8]). This is a difference of 9% from the 21% in air. Thus, 17% O_2 is 4/9, or roughly half the drop needed to not have a fire at all. Does this mean 50% protection? Obviously, this is a much too simplistic approach, but it does suggest that a great deal of fire protection can be "bought" very simply, and without jeopardizing human performance. This can be said of any inhabited capsule, be it in space, under the ocean (either military or commercial), or at very high altitude, in which the environment just outside the skin of the capsule would be immediately lethal if that skin were breached. Recognize also that some materials that burn in air simply will not burn at 17% (the Oxygen Index concept), thus giving 100% protection against such fires.

Some people have expressed concern about operating a submarine at 17% O_2 (and ca. 1 atm total pressure) in that it might affect mental and/or visual acuity. However, an intensive study by the U.S. Navy [9] has shown no untoward effects with humans encapsulated in a chamber under these conditions for several days. Also, as indicated earlier, if life is dependent mostly on partial pressure rather than concentration of O_2, then the above conditions in a submarine would be equivalent to people living in Denver, Colorado, since both have a partial pressure of O_2 of 0.17 atm, yet people live and operate normally at even much higher altitudes than Denver and thus at lower O_2 partial pressures than 0.17 atm. Recognize also that most commercial aircraft are pressurized in flight to ca. 8000 ft altitude at which the pO_2 is 0.16 atm (cf. Table 2).

In order to corroborate the impact the O_2 concentrations on fires, in the U.S. Navy study [9], the occupants of the chamber found that candles and paper were easy to ignite at 21% O_2, candles were ignited with difficulty at 17% O_2 (it depended on whether they were upright, at 45°, or horizontal, again showing the importance of gravity on fire propagation), and none could be ignited at 13% O_2 (indeed, even matches could not be struck), all at ca. 1 atm total pressure. Yet people were living in these environments. Thus, lowering the oxygen concentration in closed inhabited environments does indeed "buy" a lot of fire protection.

4.2. *Active*

In case a fire does start in an enclosed capsule, such as a submarine, it can be easily quenched while still maintaining a habitable atmosphere merely by flooding the space with nitrogen. Table 4 illustrates the concept. It has been shown in a 325 m^3 chamber (FIRE I at NRL) that even raging fires are extinguished in seconds by adding N_2 gas so that the concentration of oxygen reaches about 12% (achieved by "burning" the oxygen, diluting it, or both). This corroborates the original findings of Coward and Jones [8], or our own work [1, 3, 10]. It has also been shown that rats (as surrogates for humans) were totally unharmed by such a fire extinguishing procedure [11]. Use of N_2 flooding opens up an additional avenue for fire protection in inhabited, closed and semi-closed spaces. The challenge on how best to use it is there.

Another form of active protection by reducing O_2 in manned but not totally enclosed environments is by control of ventilation. This is well known, e.g, starving a fire by closing the space. In view of the proliferation of air-conditioning in our living spaces, much could be done by reducing O_2 availability to the

TABLE 4

N_2 pressurization

Capsule	Total press. (atm)	% O_2	O_2 partial press. (atm)
Submarine	1.0	21	0.2
Add N_2	0.7		
	1.7[a]	12	0.2

[a] In diving, equivalent to 20 ft water.

fire by ventilation control. One exceedingly simple version of this is the use of "smoke curtains". Though ostensibly to reduce the spread of smoke *away* from the fire, their real impact is to reduce oxygen flow *towards* the fire, and thus slow it down. Use of "smoke curtains" alone have been successful in minimizing and extinguishing fires in NRL's test ship [12] and played a significant role in containing the accidental fire in the USS Conyngham [13]. Control of fires by ventilation control is a very fruitful area for additional study, and in view of its potential simplicity, should be addressed by the research community more vigorously than it is.

5. Epilogue

In view of the extreme sensitivity of fires to oxygen concentration, one has to wonder why the Earth's atmosphere has 21% oxygen and was it ever thus? How fortuitous this value is, and what does it mean for the development of humankind and civilization? What if it were something slightly different, such as 23%? Or 19%? Would mankind have evolved to this present state of civilization and culture? Probably not, because man's technological development has been too closely related to and dependent on fire, and fire behavior under these other concentrations of oxygen is sufficiently different to impact markedly on its use and control.

Also, there is ample evidence that the Earth's early atmosphere was a reducing one, not an oxidizing one as it is now. How and why did it change? Why did it stop at 21%? From man's standpoint, how lucky, because, in terms of the Earth's history, Homo Sapiens is such a Johnny-come-ever-so-lately that by the time he/she showed up the oxygen had long flattened out at 21%, and mankind could evolve in comfort at that value. But, as shown above, Homo Sapiens is now sufficiently sapient to take advantage of greater control of at least unwanted fires. And, in view of our still massive fire losses (5000 deaths/year in the U.S. alone), should be doing more than he/she is.

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