

Combustion Processes in the Aerospace Environment

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The aerospace environment introduces new and enhanced fire hazards because the special atmosphere employed may increase the frequency and intensity of fires, because the confinement associated with aerospace systems adversely affects the dynamics of fire development and control, and because the hostile external environments limit fire control and rescue operations. Oxygen enriched atmospheres contribute to the fire hazard in aerospace systems by extending the list of combustible fuels, increasing the probability of ignition, and increasing the rates of fire spread and energy release. A system for classifying atmospheres according to the degree of fire hazard, based on the heat capacity of the atmosphere per mole of oxygen, is suggested. A brief exploration of the dynamics of chamber fires shows that such fires will exhibit an exponential growth rate and may grow to dangerous size in a very short time. Relatively small quantities of fuel and oxygen can produce a catastrophic fire in a closed chamber.

THE AEROSPACE FIRE ENVIRONMENT

Unusual and severe fire hazards are associated with the specialized environments of interest to the aerospace community. This paper defines the nature of these specialized environments and their effects on the combustion process.

Fire in the normal terrestrial environment is familiar to all. It is known how fires are started, how they develop, and how they can be prevented or controlled. What, then, is unique about the aerospace environment that the associated combustion hazards have attracted such wide attention?

First, note that the aerospace environment is a closed environment, separated from the normal terrestrial environment by physical barriers. In a closed system the pressure and composition of the gaseous environment can and usually will differ from that of the normal at-

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mosphere. The pressure can range from the vacuum of outer space through the hyperbaric region of medical interest to the high pressures encountered in undersea deep submergence systems. Since one is concerned primarily with habitable environments for unprotected personnel, a lower practical pressure limit may be set in the neighborhood of 3 psia, although combustion may persist to considerably lower pressures.

The oxygen concentration may vary from pure oxygen used in medical and space applications to the very dilute mixtures used in high pressure undersea systems. Environments which afford a greater combustion hazard than the normal atmosphere are of principal interest. These will be referred to as oxygen-enriched atmospheres and, by a generally accepted definition, including atmospheres in which the oxygen concentration exceeds that of air (20.9 percent by volume) and atmospheres in which the partial pressure of oxygen exceeds that of the normal atmosphere (3.1 psia). This definition includes a spacecraft atmosphere of pure oxygen at 5 psia, a hyperbaric chamber operating at 4 atmospheres of compressed air, and a diving atmosphere of 3 percent oxygen in helium at 140 psia. In addition to oxygen, the environment may contain nitrogen and the minor constituents of ordinary air, or it may be a completely artificial mixture containing helium or other physiologically unreactive gases. Even mixtures of hydrogen and oxygen have been used in deep diving experiments.

In a closed environment combustion will be limited to the fuel and oxygen supplies originally present in the system. The products of combustion will also be confined. Temperature and pressure will increase rapidly and toxic combustion products will accumulate. The increase in pressure may lead to catastrophic failure of the environmental enclosure. By way of contrast, in an open environment the fire is supported by an unlimited oxygen supply from the atmosphere, while pressure buildup is prevented and heat and combustion products are dissipated by relatively free access to the surroundings.

The external environment of an aerospace system will generally be a hostile one; space, high altitudes, underseas, or even the familiar environment of the earth's surface if the pressure differential is such that rapid transfer from the internal to the external environment

would be difficult or hazardous. Obviously, the resources needed to combat a fire in a closed system must be largely contained within the system. Reliance cannot be placed on external aid. Space and weight limitations may further restrict the choice of protective measures. Finally, immediate evacuation of personnel may not be possible in the case of a fire in a closed environment. Not only must the occupants be able to survive for a time after the fire is extinguished, but the system must retain a degree of operability that will permit a return to a more friendly external environment where evacuation will be possible.

This, then, is the environment in which fires can occur in aerospace systems. It is apparent that such fires will create new or increased hazards. Vigorous action is required to minimize the probability that a fire will occur and to provide effective means of combating those that may occur despite all reasonable precautions. The way in which the closed environment affects combustion processes, an understanding of which is essential to the planning of an effective fire safety program, is described in the following sections.

ATMOSPHERIC COMPOSITION AND FIRE HAZARDS

The enhanced fire hazard associated with the aerospace environment is frequently attributed to the presence of an oxygen-enriched atmosphere. It should be obvious that this is not the sole cause of increased hazard, but it is a major contributor. Oxygen enrichment contributes to the fire hazard in three ways: first, the list of combustible fuels is considerably extended at high oxygen concentrations; second, the probability of ignition is increased, and third, the rates of flame spread, fuel consumption and energy release are greatly enhanced.

The increased combustibility of materials may be illustrated by an incident which occurred in a space simulator chamber operating at 5 psia of pure oxygen. An occupant of the chamber was replacing an ordinary electric light bulb when a spark ignited the plastic housing around the socket. He attempted to smother the fire with a towel which was close at hand, but the towel burst into flames. Next he attempted to use an asbestos fire blanket which had been provided for such emergencies. However, the fire blanket caught fire and burned vigorously. While the asbestos did not burn, an organic sizing material with which the blanket had been treated supported combustion in the oxygen atmosphere. At this point the occupant found that the skin on the palm of his hand was on fire. He rubbed his hands together and, upon separating them, found that both hands were afire. Fortunately, attendants outside the chamber were able to bring the chamber to atmospheric pressure, extinguish the fire, and rescue the occupants who were badly burned but survived.

Further differences in the combustibility of materials in pure oxygen and in air are shown in Table I.⁴ While a number of these materials do not sustain combustion in air, only the highly fluorinated materials failed to

burn in pure oxygen. In fact, even these materials will burn in pure oxygen when in the form of thin films if they are ignited at the bottom and allowed to burn in an upward direction. Further examples of differences in combustibility in air and in pure oxygen are shown in Table II.³ These materials were used in a simulator chamber involved in a fire. While they appear to have been well selected from the standpoint of low combustibility in air, this was of little help under the conditions of use in 5 psia of oxygen. It should be noted at this point that common flame retardant treatments

TABLE I. EFFECT OF OXYGEN ON IGNITION AND FLAME SPREAD RATES OF VARIOUS MATERIALS³

Material	Flame spread rate (in./sec.)	
	In air	In 258 mm. oxygen
Butyl rubber	0.006	0.40 ± 0.04
Canvas duck	NP	0.25 ± 0.05
Cellulose acetate	0.012	0.28 ± 0.12
Kel-F	NI	NI
Natural rubber	0.010	0.61 ± 0.05
Neoprene rubber	NI	0.32 ± 0.04
Nylon 101	NI	0.19 ± 0.05
Plexiglas	0.005	0.35 ± 0.01
Polyethylene	0.014	0.25 ± 0.05
Polypropylene	0.010	0.35 ± 0.01
Polystyrene	0.032	0.80 ± 0.20
Polyvinyl chloride	NI	0.10 ± 0.01
Silicone rubber	NI	0.14 ± 0.01
Teflon	NI	NI
Viton A	NI	0.003 ± 0.002

All samples except canvas duck, 3 by 1/2 by 1/8 in.; canvas duck, 3 by 1/2 by 1/50 in.

NP — No sustained propagation of flame.

NI — No ignition of material.

TABLE II. EFFECT OF OXYGEN ON IGNITION AND FLAME SPREAD RATE OF VARIOUS SPACE CABIN SIMULATOR MATERIALS³

Material	Flame spread rate (in./sec.)	
	In air	In 258 mm. oxygen
Aluminized Mylar tape	—	1.95
Aluminized vinyl tape	NI	3.1 ± 0.4
Asbestos insulating tape	NI	0.08
Chapstick	NI	1.82
Cotton shirt fabric	NP	1.50 ± 0.05
Electrical insulating resin	NI	0.27
Electrical terminal board	NI	0.06 ± 0.01
Fiberglass insulating tape	NI	4.2 ± 0.6
Foam cushion material	0.19	12.4
Foamed insulation	0.002	2.2 ± 0.2
Food packet, aluminized paper	NI	0.28 ± 0.05
Food packet, brown aluminum	NI	0.7 ± 0.30
Food packet, plastic	0.33	0.55
Glass wool	NI	NI
Masking tape	0.17	1.82
Paint, 3-M velvet	NI	0.15 ± 0.01
Paint, Capon-ivory	NI	0.38 ± 0.04
Paint, Pratt & Lambert, grey	NI	0.60 ± 0.2
Pump oil	NI	0.89
Refrigeration oil	NI	0.82 ± 0.07
Rubber tubing	0.03	0.24
Silicone grease	NI	0.92
Solder, rosin core	NI	0.18
Sponge, washing	0.07	8.1 ± 0.1
Teflon pipe sealing tape	NI	NI
Teflon tubing	NI	NI
Tygon tubing	0.18	0.50 ± 0.05
Wire, Mil W76B, orange	NI	0.57 ± 0.05

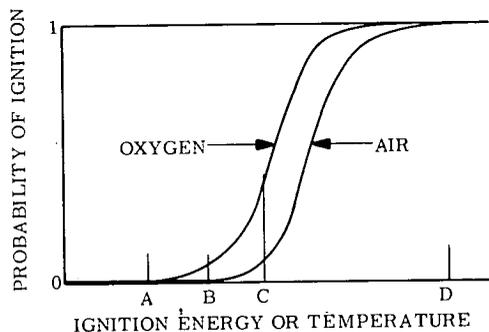
NP — No sustained propagation of flame.

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for textiles, which are effective in air, are almost completely ineffective in pure oxygen.¹

The effect of oxygen concentration on ignition contributes further to the increased fire hazard in aerospace systems. Measurements made in our laboratory³ as well as those of other investigators⁶ suggests only a modest decrease in ignition energy or ignition temperature in going from air to pure oxygen. On the other hand, it has been stated that a fire is a thousand times more likely to occur in an atmosphere of pure oxygen than in air. Reference to Figure 1 may help to resolve this apparent contradiction.

The probability that ignition will occur when a sample of solid combustible is subjected to an ignition stimulus depends on the energy content or temperature of the stimulus. Below a certain threshold value no ignition will occur. Above this threshold ignition becomes increasingly probable as the strength of the stimulus is increased until ignition becomes almost a certainty. As the oxygen content of the atmosphere is increased by increasing the percent of oxygen or the pressure, this curve is shifted slightly in the direction of lower ignition energy. Consider first an ignition stimulus corresponding to point A. Here the probability of ignition is extremely low in both air and oxygen. At point B the probability of ignition in oxygen is significant while the probability in air is still extremely low,



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Fig. 1. Probability of ignition in air and oxygen

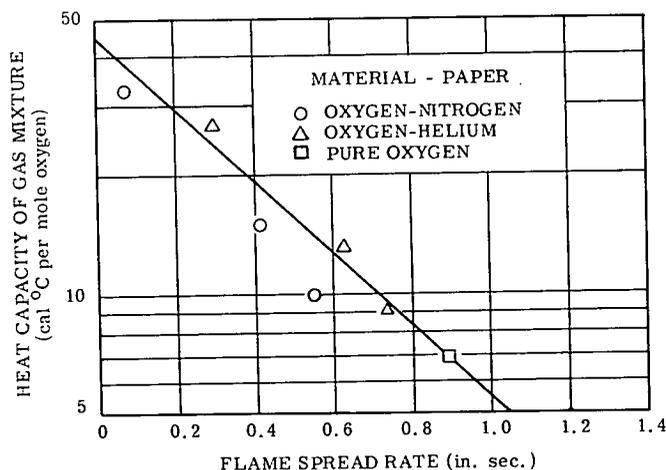


Fig. 2. Rate of flame spread in various atmospheres as a function of heat capacity.

consequently the oxygen atmosphere will appear to be many times more hazardous. At point C the probability of ignition in air begins to become significant and the difference between the two atmospheres is less apparent. Finally, in the region to the right of point D ignition is almost certain to occur in either atmosphere and no significant difference in ignition properties will be apparent. It appears, then, that under marginal ignition conditions the oxygen enriched atmosphere will lead to a somewhat higher incidence of fires. However, ignition must be considered as a possibility in any atmosphere capable of supporting combustion.

The third combustion hazard parameter which is affected by the environment is the burning rate. Strictly speaking, one should be concerned with the rate of energy release and the rate of generation of combustion products, i.e., the mass fuel consumption rate. In practice, ignition occurs at a point source, and the rate of growth of the fire is determined largely by the rate at which the flame spreads over the surface of combustibles to increase the amount of fuel involved in the fire. Consequently, most investigations in this area have been directed to the measurement of the rate of flame spread over surfaces.

Reported results of such measurements show considerable variability due to variation in experimental technique. Flame spread will be most rapid when the sample is ignited at the bottom and the flame propagates upward in the vertical direction due to engulfment by the hot combustion products. The rate will be slowest in the downward direction, while other orientations will show intermediate values.¹ Flame spread is most rapid along sharp edges and over materials in thin sections. Surface roughness and surface contamination will affect the results.³ Consequently, quantitative correlations between flame spread rates and environmental parameters are difficult to arrive at. Qualitatively, it is found that the rate of flame spread increases rapidly with increased oxygen concentration at a fixed total pressure⁴ and less rapidly with an increase in the oxygen partial pressure at a fixed composition.¹ In general, the flame spread rate is increased by from one to two orders of magnitude in going from air at 1 atmosphere to pure oxygen at 5 psia (Tables I and II).³

The addition of an inert gas at constant oxygen partial pressure reduces the rate of flame spread. Slightly higher rates are observed in oxygen-helium atmospheres than in equivalent oxygen-nitrogen atmospheres, but the difference is scarcely significant from the safety standpoint.^{1,4} At constant pressures a rough correlation is found between the flame spread rate and the heat capacity of the atmosphere per mole of oxygen (Figure 2).⁴ This suggests that above a critical value of the heat capacity the flame spread rate would be zero and the atmosphere would not support combustion. The magnitude of this critical value will depend on the flammability of the fuel. Since the energy released per mole of oxygen reacted is approximately constant, the heat capacity will be related to the flame temperature.

At constant atmospheric composition the flame spread rate increases with pressure. Burning rate data for filter paper burning upward at a 45° angle over the

pressure range from 3 psia to 150 psia and for gas compositions ranging from pure oxygen to oxygen diluted with up to 80% nitrogen or helium¹ are well correlated by an equation of the form

$$r = a \log (P^{1/2}/C'_p) + b.$$

Here r is the flame spread rate, P is the pressure, a and b are constants and C'_p is the heat capacity per mole of oxygen,

$$C'_p = (C_p)_{O_2} + \sum_X \frac{P_X}{P_{O_2}} (C_p)_X$$

where x refers to any inert diluent gas present. This suggests that the parameter $C'_p/P^{1/2}$ can be used as a rough index to the degree of fire hazard associated with any particular atmospheric composition and pressure as indicated in Table III.

Typical aerospace atmospheres, classified according to this scheme, are shown in Table IV. The first three are spacecraft atmospheres associated with the Apollo Program. Atmosphere No. 2 was involved in the fatal fire while No. 3 has been proposed to replace it. Although the latter must still be regarded as a highly hazardous atmosphere, it provides an additional margin of safety in conjunction with the drastic reduction in flammable materials in the redesigned spacecraft.

The increased fire hazard associated with the use of compressed air is indicated by systems 4, 5 and 6. Comparison of atmospheres 3 and 7 suggests that nitrogen is slightly more effective than helium as a diluent. Atmosphere eight suggests that reduction of the oxygen content of air to 15%, still within the habitable range, would produce a relatively safe atmosphere for many applications. Atmosphere 9 which was involved in a fatal fire in a Navy diving unit² falls in the high hazard category. Atmospheres 10 and 11 represent possible deep submergence atmospheres. Here a small change in oxygen content can produce a large change in the hazard rating.

A word of caution should be added at this point. This system of classification provides only an approximate guide and should not take the place of practical tests, particularly at high pressures where data are limited. The quantity, physical form, and spatial disposition of fuel elements can further modify the hazard situation. The index gives an indication of the probability of a fire starting, the rate of fire growth, and hence the time available for remedial action. Any fire in a closed chamber, if not quickly extinguished, will be catastrophic.

DYNAMICS OF CHAMBER FIRES

Even with a careful choice of materials, the minimization of ignition sources, and the selection of the least hazardous atmosphere that will meet other requirements of the mission, the possibility of a fire starting cannot be completely eliminated. What are the characteristics of a fire in close environment? How does it develop and what effects will it produce?

Consider a very simple model for a chamber fire with fuel elements uniformly distributed throughout the chamber volume V . At time $t = 0$ an ignition occurs at some point in the chamber, igniting a fuel element and generating a flame volume v_0 . This flame volume will grow and engulf other fuel elements. The rate of growth will be proportional to the quantity of fuel involved or the flame volume. Clearly, this will lead to an exponential rate of growth for the fire, at least during its initial phase.

$$\frac{dv}{dt} = k v$$

$$v = v_0 e^{kt}$$

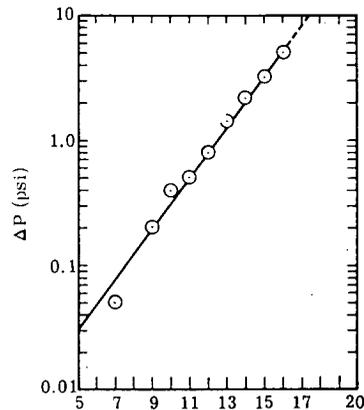
The growth constant k will depend on such factors as

TABLE III. HAZARD CLASSIFICATION OF ATMOSPHERES

$C'_p/P^{1/2}$	Degree of Hazard	Material Restrictions
>50	Fire will not propagate	None
40-50	Borderline — Test	Selective
30-40	Moderate — Similar to air	Fire Resistant or Retardant
20-30	Increased Hazard	Fire Resistant
10-20	High Hazard	Fire Resistant — Limited Quantities
<10	Extreme Hazard	Noncombustible

TABLE IV. HAZARD RATING OF AEROSPACE ATMOSPHERES

No.	Atmosphere		P_{PSIA}	P_{O_2} PSIA	$C'_p/P^{1/2}$
	Composition				
1	O ₂ 100%		5.0	5.0	8.3
2	O ₂ 100%		16.5	16.5	6.6
3	O ₂ 60%, N ₂ 40%		16.5	9.9	11.0
4	Air		14.7	3.1	33.3
5	Air		60.0	12.5	16.6
6	Air		300.0	62.7	7.4
7	O ₂ 60%, He 40%		16.5	9.9	9.8
8	O ₂ 15%, N ₂ 85%		16.5	2.5	43.6
9	O ₂ 28%, N ₂ 36%, He 36%		55.0	15.4	11.6
10	O ₂ 3%, He 97%		300	9.0	28.7
11	O ₂ 2%, He 98%		300	6.0	55.0



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PRESSURE-TIME DATA FOR CHAMBER FIRE

Fig. 3. Exponential growth of Apollo spacecraft fire.⁵

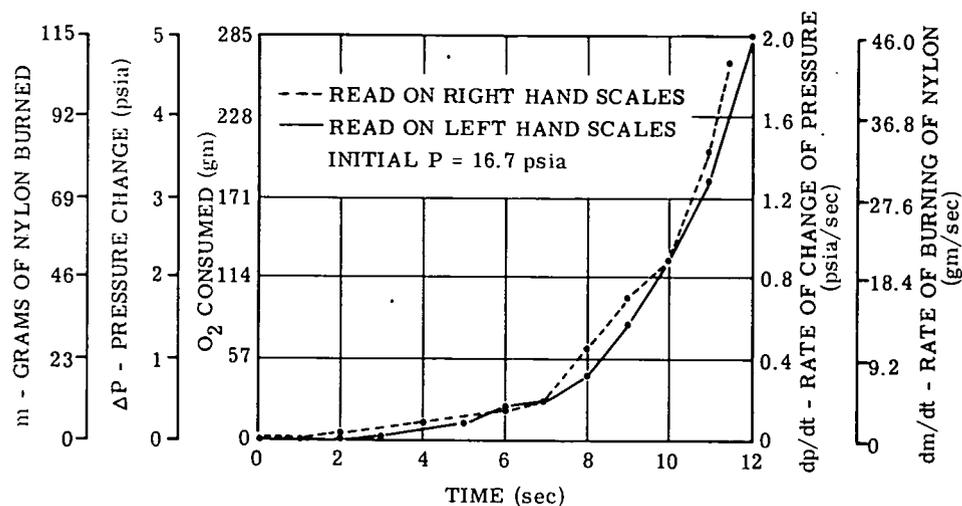


Fig. 4. Analysis of growth of Apollo spacecraft fire.⁵

ANALYSIS OF CHAMBER FIRE

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the fuel loading density, the combustion characteristics of the fuel, and the pressure and composition of the atmosphere. In a closed system the generation of a volume of hot combustion gas will result in a proportional pressure rise so we may write

$$\Delta P = P - P_0 = P_0 (e^{kt} - 1)$$

Then a plot of $\log \Delta P$ vs. t should give a straight line. Figure 3 shows such a plot of the pressure-time history for the Apollo spacecraft fire. It is seen that the prediction of an exponential rise in pressure is closely confirmed.⁵

A more detailed analysis of this particular fire is shown in Figure 4. The chamber volume was approximately 320 cu. ft. and it contained about 30.5 lb. of oxygen at an initial pressure of 16.7 psia. The fuel has been assumed to be nylon for simplicity; other organic fuels would lead to similar results. The change in pressure and the quantities of fuel and oxygen consumed (assuming an adiabatic system) are given at the left while the rates of pressure change and fuel consumption are shown at the right. The chamber ruptured at a ΔP of approximately 20 psi. This would correspond to the consumption of approximately one pound of fuel and 2.5 lb. of oxygen, or less than 10% of the total oxygen present. The elapsed time from fire start to chamber rupture was approximately 20 seconds. It is apparent that only a small quantity of combustible fuel is necessary to produce a dangerous fire in a closed chamber. It is also apparent that such fires can develop extremely rapidly, leaving only a very short time available for remedial action.

SUMMARY

The aerospace environment introduces new and enhanced fire hazards because the special atmospheres employed may increase the frequency and intensity of fires, because the confinement associated with aerospace systems adversely affects the dynamics of fire development and control, and because the hostile external environments limit fire control and rescue operations. New approaches to fire safety are required to reduce these hazards to acceptable levels.

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