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June 1966

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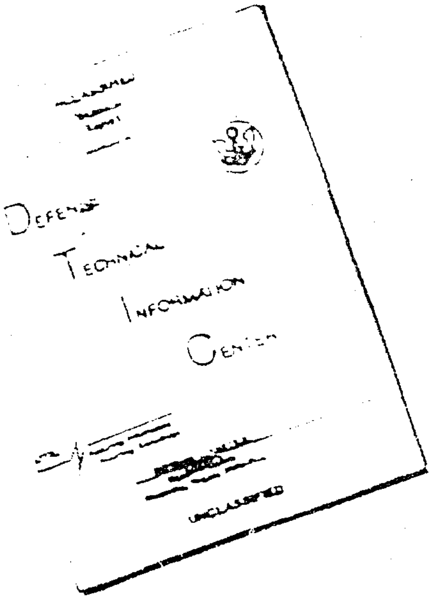

THE COMBUSTIBILITY OF MATERIALS IN OXYGEN-HELIUM AND OXYGEN-NITROGEN ATMOSPHERES

CLAYTON HUGGETT, Ph.D.
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FOREWORD

This report was prepared in the Advanced Technology Department of Atlantic Research Corporation, Alexandria, Va., under Contract No. AF 41(609)-2478 and Task No. 793002. Previous work under this contract was reported in SAM-TR-65-78. It was monitored by Dr. Hans G. Clamann and Captain John J. Hargreaves, Aerospace Medical Research Division, USAF School of Aerospace Medicine. The work was accomplished between August 1965 and November 1965.

This report has been reviewed and is approved.

ABSTRACT

The energy required for ignition of various materials and the rate at which flames spread over the surface after ignition were determined in oxygen-nitrogen and oxygen-helium mixtures in order to assess the fire hazards associated with proposed space cabin atmospheres.

It was found that flames spread more rapidly in oxygen-helium mixtures than in comparable oxygen-nitrogen mixtures. The experimental data correlated well with the specific heats of the gas mixtures per mole of oxygen, indicating that the flame temperature is the dominant factor in determining flame spread rates. A theoretical model of flame spread was developed.

Slightly more energy was required to ignite materials in oxygen-helium than in oxygen-nitrogen mixtures. However, the difference was small enough so as not to reduce significantly the fire hazards, especially since the flames spread more rapidly once the material was ignited.

It was concluded that fire hazards are greater in oxygen-helium atmospheres than in oxygen-nitrogen atmospheres.

TABLE OF CONTENTS

THE COMBUSTIBILITY OF MATERIALS IN OXYGEN-HELIUM AND OXYGEN-NITROGEN ATMOSPHERES

I. INTRODUCTION

The fire hazards associated with the use of space cabin atmospheres consisting of pure oxygen at reduced pressures are of such magnitude that consideration has been given to use of oxygen-helium or oxygen-nitrogen mixtures in their stead. Other factors have also entered into this consideration. However, the experimental evidence on the flammability of materials in atmospheres other than air was insufficient to provide a reliable comparison of the fire hazards associated with such atmospheres. The present investigation was undertaken to determine the flammability and ignitibility of materials in oxygen-helium and oxygen-nitrogen atmospheres. The safety of personnel involved in a long duration space cabin simulator experiment was of immediate concern and therefore was the primary motivating force for this investigation.

The energy required for ignition and the rate of flame spread over representative space cabin materials were determined in three oxygen-helium mixtures and in two oxygen-nitrogen mixtures. Similar data on the flammability and ignitibility of these materials in air and in pure oxygen were available from a previous investigation.

II. EXPERIMENTAL PROGRAM

The experimental procedures used in this investigation were the same as those used in the previous investigation of the effect of prolonged storage in oxygen atmospheres on the combustibility of space cabin materials. They are described in detail in the report of that investigation (1).

Briefly, one half inch wide, three inch long samples of the material to be tested were placed in a 3.2 cu.ft. chamber. The chamber was evacuated to 1 mm. Hg and filled to atmospheric pressure with the gas mixture being investigated. The chamber was then re-evacuated to the test pressure. Flame spread rates were determined over samples in a horizontal position by igniting the sample with a hot wire and photographing the spread of flames. The energy required for ignition was determined by focusing the energy from a 1,200-watt projection bulb on the sample by means of a pair of ellipsoidal mirrors and determining the time required for ignition. The radiant flux was maintained at 13.2 cal./cm.^{2} sec.

The materials selected for investigation were:

1. Wood
2. Paper
3. Paint
4. Cotton fabric
5. Plastic coated wire
6. Cellulose acetate
7. Foam cushion material

These materials were selected because good data were available on their combustion properties in air and in 258 mm. Hg of pure oxygen because they represented a suitable range of combustion properties, and because their physical form was convenient for the planned experimental measurements. Flame spread rates were determined for all seven materials.

Ignition energies were determined for the first five listed. The materials are described more fully in the appendix to this report. Flame spread rates were determined on duplicate samples of the materials in each of the five atmospheres investigated. Four determinations of ignition energy requirements were made for each of the five materials in the five atmospheres. A limited number of tests were conducted in air and in the 258 mm. Hg oxygen to insure that the equipment was functioning properly.

The five atmospheres investigated were:

20% oxygen - 80% helium at 760 mm. Hg
46% oxygen - 54% nitrogen at 380 mm. Hg
46% oxygen - 54% helium at 380 mm. Hg
70% oxygen - 30% nitrogen at 258 mm. Hg
70% oxygen - 30% helium at 258 mm. Hg

The mixed gases were supplied by the Southern Oxygen Company of Washington, D.C., and were certified to be within one-half percent of the nominal composition. The composition was checked by gas chromatographic analysis and found to be within the prescribed limits. The reported analyses are tabulated in the appendix to this report.

III. RESULTS

Flame spread rates

Flame spread rates for the various materials in air, oxygen-nitrogen, oxygen-helium and pure oxygen are presented in table I. The reported rates for the gas mixtures are the average of four determinations; rates were measured over two different portions of each of the two samples tested. The average deviations of the individual determinations are indicated in the table. The reported values for the samples burned in air and in pure oxygen represent results from only one specimen. The flame spread rates previously reported in the final report covering the effect of prolonged storage in oxygen are also included. As discussed in that report, there is an inherent variability in the combustion process and some scatter in the data is to be expected. However, with the exception of the cotton shirt fabric, the data are in excellent agreement. The previously reported value of flame spread rate over the cotton shirt fabric is considered to be more reliable as examination of the motion picture coverage of the sample burned in this investigation indicated that the edges of the sample were frayed. This caused an abnormally high flame spread rate.

The data indicate that flames spread faster in the helium-oxygen mixtures than in nitrogen-oxygen mixtures. The flames also spread faster as the percentage of oxygen in the mixtures was increased.

A limited number of tests were conducted in which the pressure of the helium-oxygen mixtures was varied. These results are shown in table II. These data indicate that the flame spread rate is not dependent upon the total pressure of the atmosphere in the range tested.

Correlation of the observed flame spread rates with the physical properties of the gas mixtures was sought. A reasonably consistent correlation was obtained by plotting the rate of flame spread for a given material against the logarithm of the heat capacity of the gas mixtures per mole of oxygen. These plots are shown in figures 1 to 7. The heat capacity data are given in table III, together with other properties of the gas mixtures. The scatter of data is sufficiently small to permit straightline extrapolation to zero flame spread rate. This intercept defines a critical inert gas dilution level for the material beyond

Table I

Flame Spread Rates for Materials in Various Atmospheres[a] (in./sec.)

Atmosphere	Air[b]	Air[c]	20% O_2 80% He	46% O_2 54% N_2	46% O_2 54% He	70% O_2 30% N_2	70% O_2 30% He	100% O_2 (c)	100% O_2 (b)
Pressure	760 mm	760 mm	760 mm	380 mm	380 mm	258 mm	258 mm	258 mm	258 mm
Wood	-	0.025	0.04	0.12	0.18	0.18	0.27	0.35	-
		±0.025	±0.005	±0.02	±0.03	±0.03	±0.03	±0.03	-
Paper	-	0.08	0.30	0.42	0.63	0.55	0.74	0.90	-
		±0.01	±0.06	±0.02	±0.05	±0.05	±0.06	±0.07	-
Cellulose Acetate	0.012	0.008		0.11	0.15	0.20	0.18	0.30	0.28
		±0.002		±0.01	±0.02	±0.03	±0.02	±0.01	±0.12
Cotton Fabric	0	0.10	0.17	0.9	1.1	1.8	1.2	3.2	1.5
		±0.01	±0.01	±0.3	±0.1	±0.2	±0.2	±0.2	±0.05
Foam Cushion	0.19	0.14	0	2.7	2.1	6.1	6.0	13	12.4
		±0.02	0	±0.8	±0.3	±0.5	±0.6	±1	±0.5
Plastic Wire	0	0	0	0.25	0.35	0.48	0.60	0.84	0.89
				±0.01	±0.02	±0.01	±0.02	±0.03	-
Painted Surface	0	0	0	0.21	0.27	0.32	0.42	0.45	0.38
				±0.01	±0.01	±0.02	±0.06	±0.05	±0.04

a. ± indicates average deviation
b. Previously reported SAM-TR-65-78
c. This investigation

Table II

The Effect of Pressure on Flame Spread Rate

Material	Atmosphere	Pressure mm Hg	Flame Spread Rate in/sec
Wood	46% O_2 - 54% He	380	0.18 ± 0.03
Wood	" "	760	0.18 ± 0.02
Paper	" "	380	0.63 ± 0.05
Paper	" "	760	0.64 ± 0.08
Wire	70% O_2 - 30% He	258	0.60 ± 0.02
Wire	" "	380	0.60 ± 0.02

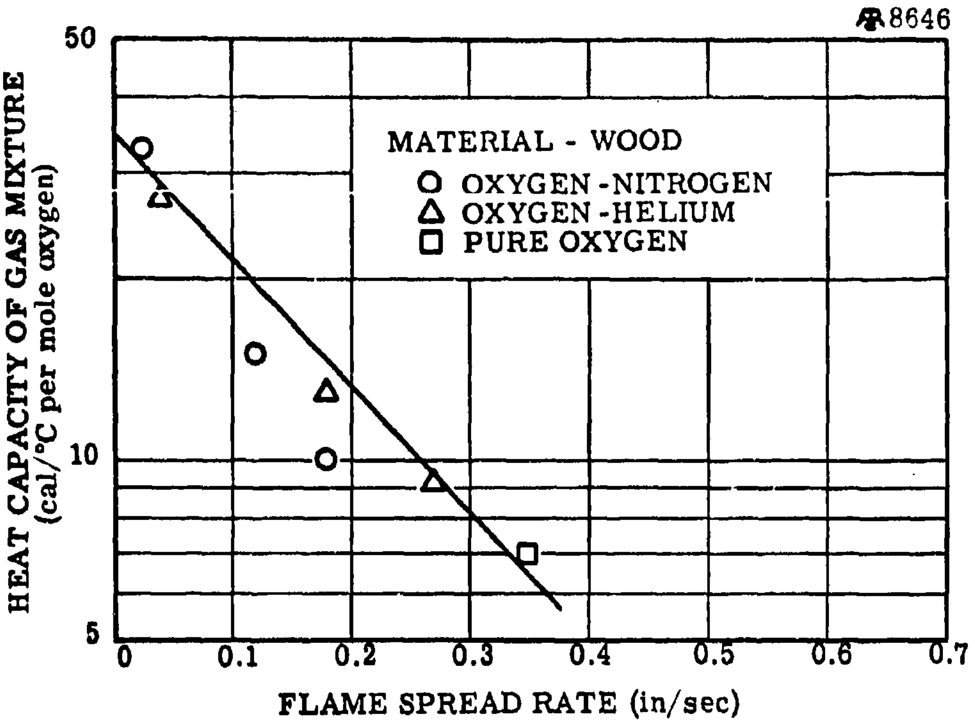


Figure 1. Flame Spread Rate Versus Heat Capacity of Atmosphere.

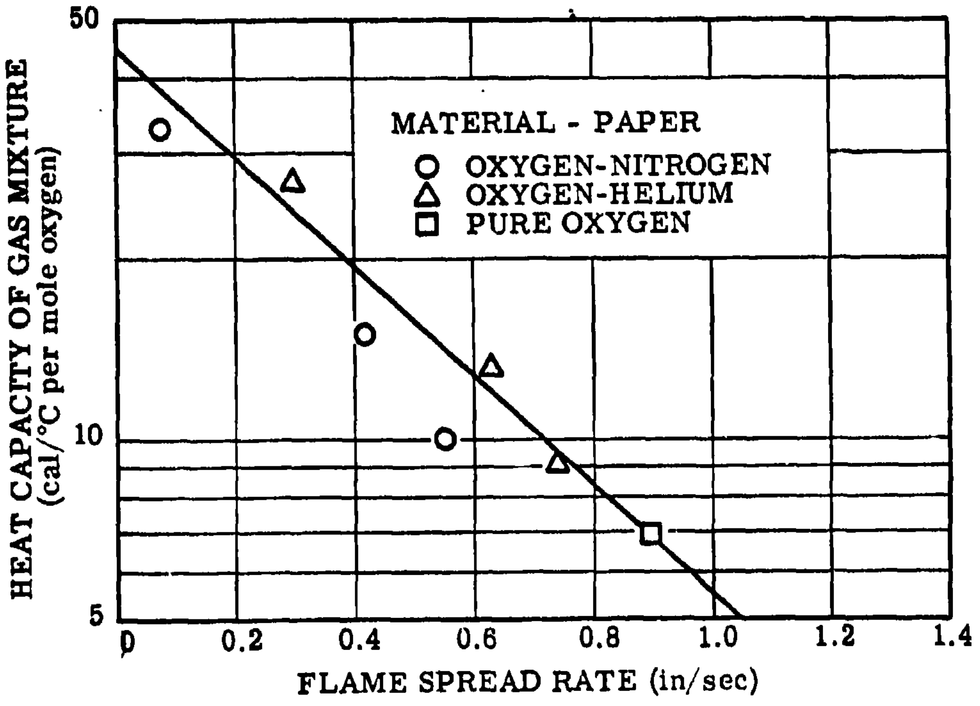


Figure 2. Flame Spread Rate Versus Heat Capacity of Atmosphere.

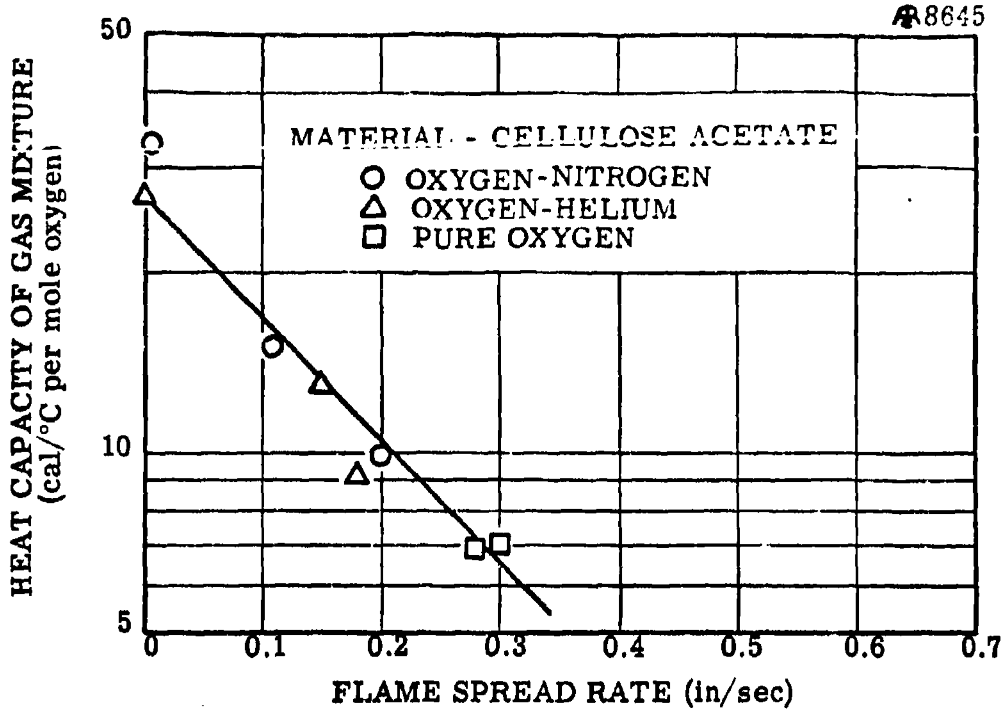


Figure 3. Flame Spread Rate Versus Heat Capacity of Atmosphere.

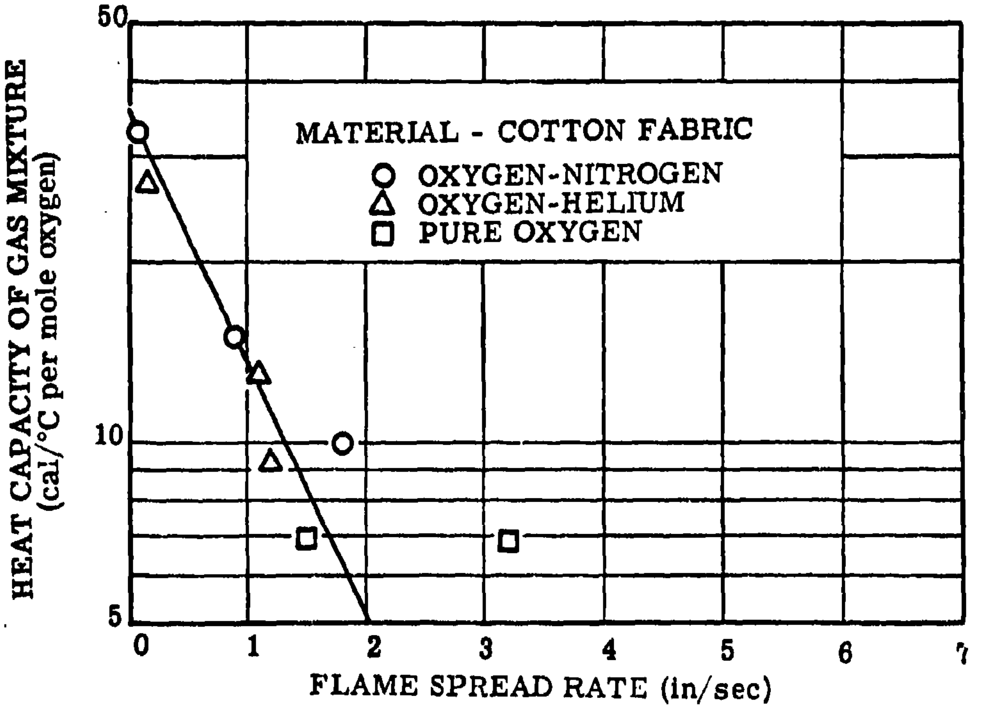


Figure 4. Flame Spread Rate Versus Heat Capacity of Atmosphere.

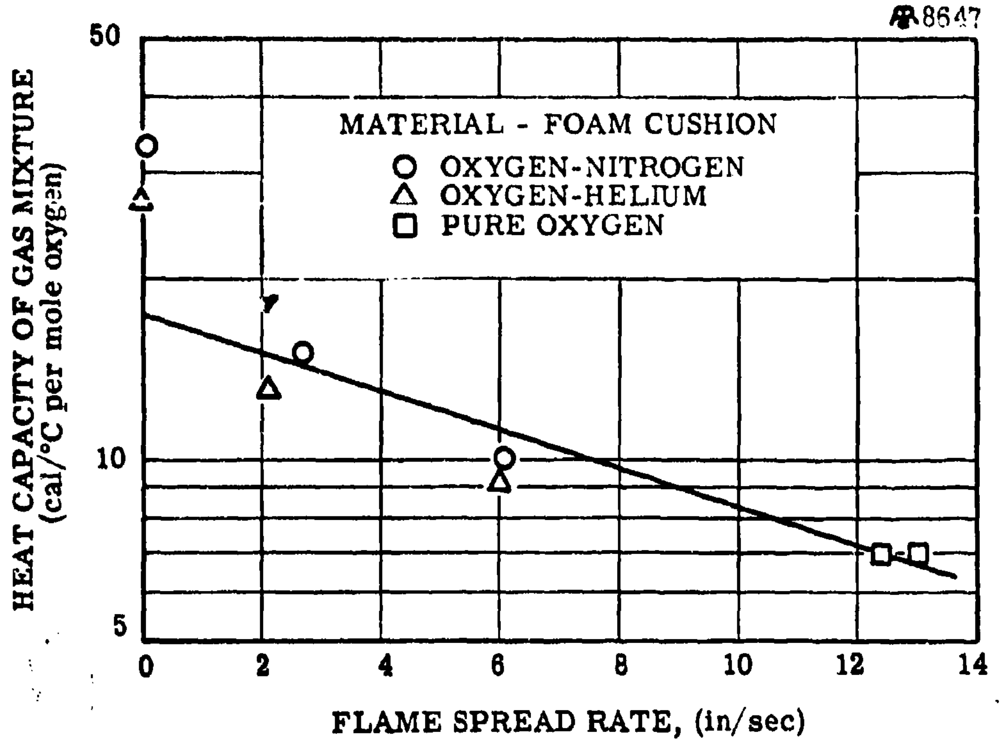


Figure 5. Flame Spread Rate Versus Heat Capacity of Atmosphere.

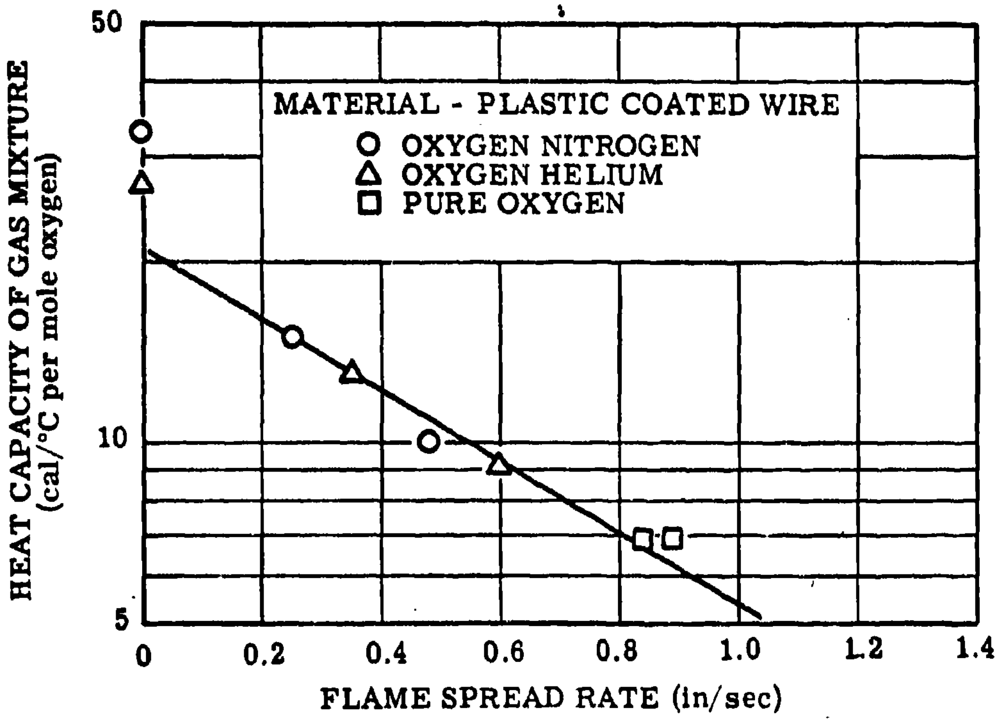


Figure 6. Flame Spread Rate Versus Heat Capacity of Atmosphere.

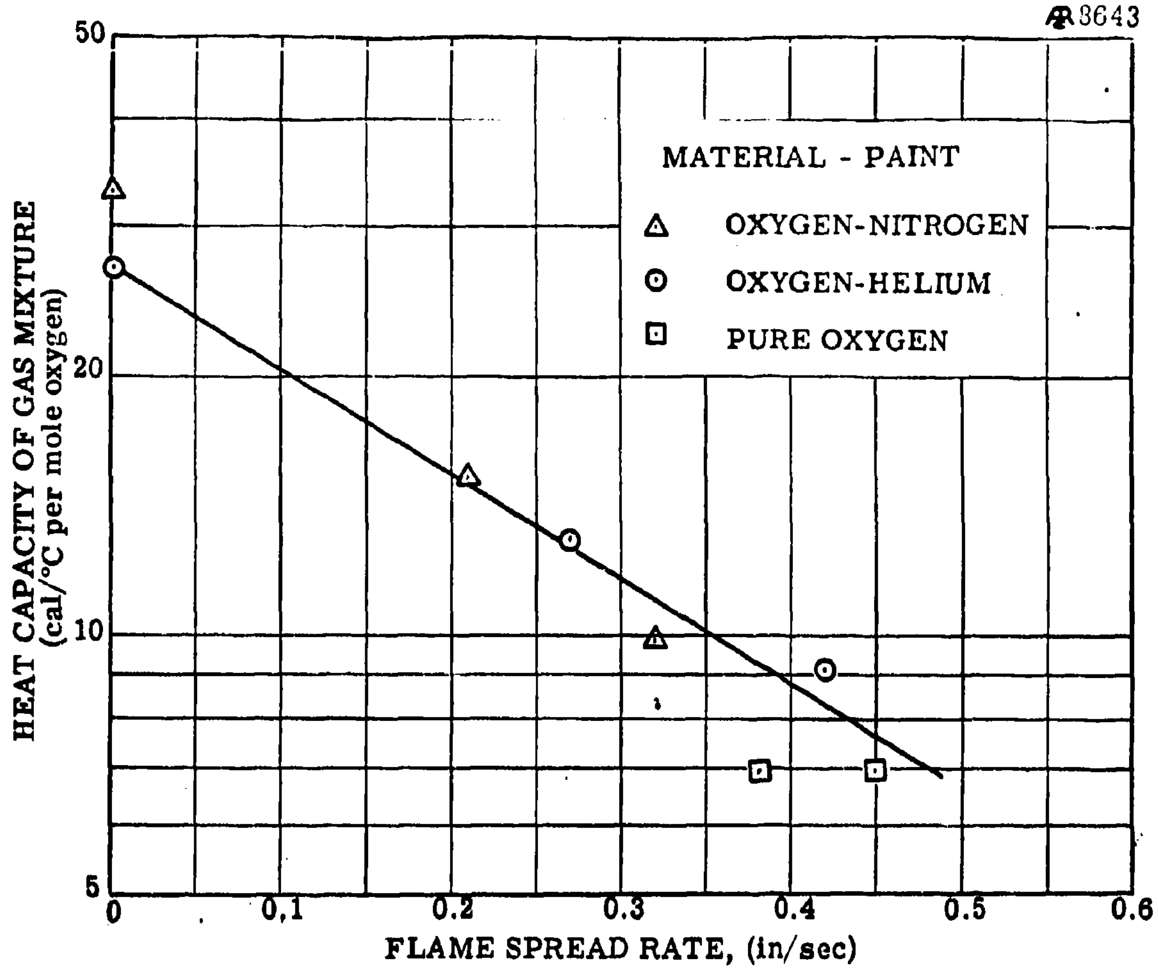


Figure 7. Flame Spread Rate Versus Heat Capacity of Atmosphere.

Table III

Properties of Gas Mixtures 25°C

Gas Mixture	Heat Capacity cal./mole °C	Heat Capacity cal./mole O_2 °C	Thermal Conductivity cal./(cm.^{2}) (sec) (°C/cm.)	Thermal Diffusivity at Test Condition cm.^{2}/sec.	Partial Press. of Oxygen at Test Cond. mm. Hg.
21% O_2-79% N_2	6.96	33.1	5.8×10^{-5}	0.186	160
20% O_2-80% He	5.38	26.9	24.0×10^{-5}	0.995	152
46% O_2-54% N_2	6.99	15.2	5.8×10^{-5}	0.372	175
46% O_2-54% He	5.90	12.8	15.6×10^{-5}	1.178	175
70% O_2-30% N_2	7.01	10.0	5.9×10^{-5}	0.567	181
70% O_2-30% He	6.41	9.2	10.5×10^{-5}	1.092	181
100% O_2	7.02	7.0	5.9×10^{-5}	0.567	258

which the atmosphere ceases to support flame spread. This correlation is expressed as

$$\log \frac{(C_p)_{crit.}}{\left[C_{p(O_2)} + n\, C_{p(x)}\right]} = kr \qquad (1)$$

where n is the number of moles of inert gas per mole of oxygen, k is a slope factor which appears to be slightly dependent on the nature of the inert gas, and r is the flame spread rate.

Values of the critical heat capacities, corresponding to zero flame spread rate for the various test materials, are given in table IV. These were obtained from figures 1 to 7. Also given in the table are the concentrations of inert diluents (nitrogen or helium) required to provide an atmosphere with the critical heat capacity. It is apparent that higher concentrations of helium than of nitrogen would be required to give an equivalent degree of protection from fire hazards.

Cellulose acetate and the foam cushion material showed a very slow propagation rate in air even though the critical heat capacity value was exceeded. The mechanism of propagation of this smoldering combustion probably involves heterogeneous reactions and is quite different from the gas phase flame propagation reaction.

Ignition energies

The energies required to ignite the materials in the various atmospheres are shown in table V. The value reported is the average of four different determinations. The average deviation is also shown.

In all cases more energy was required to ignite the materials in the 20% oxygen-80% helium mixture than in air or pure oxygen. A slightly larger amount of energy was required to ignite fabric, wire and the paint sample in helium-oxygen atmospheres than in nitrogen-oxygen atmospheres. In the case of wood and paper this damping effect was not evident in the mixtures containing more than 20% oxygen.

Table IV

Critical Flame Spread Conditions

Material	$C_{p(crit.)}$ cal./°C mole O_2	Critical Inert Diluent Concentration mole % N_2	mole % He
Wood	35.0	80.2	84.8
Paper	45.0	84.5	88.4
Cellulose Acetate	27.0	73.3	80.1
Cotton Fabric	36.0	80.6	85.4
Foam Cushion	17.5	60.3	68.0
Plastic Coated Wire	21.2	65.0	74.0
Painted Surface	27.0	73.3	80.1

Table V

Energy Required for Ignition of Materials in Various Atmospheres using a Radiant Flux of 13.2 cal./cm.^{2} sec.

Atmosphere	Air	20% O_2 80% He	46% O_2 54% N_2	46% O_2 54% He	70% O_2 30% N_2	70% O_2 30% He	100% O_2
Pressure, mm Hg	760	760	380	380	258	258	258
			Energy, cal./cm.^{2}				
Wood	25 ±1	109 ±11	25 ±2	24 ±0.5	25 ±1	22 ±1	23 ±1
Paper	32 ±1	39 ±0.5	25 ±2	26 ±0.5	26 ±0.5	25 ±0.5	25 ±1
Cotton Fabric	13 ±0.5	NI	12 ±0.5	17 ±0.5	15 ±0.5	16 ±0.5	15 ±0.5
Plastic Wire	20 ±1	NI	16 ±1	NI	17 ±1	46 ±1	16 ±1
Painted Surface	30 ±1	NI	56 ±5	70 ±4	61 ±3	57 ±5	36 ±1

During the determination of flame spread rates it was noted that it was much more difficult to ignite the materials with the hot wire igniter in the helium atmospheres than in the nitrogen atmospheres. This was due not only to the fact that more energy was required to ignite the material but also because the convective heat transfer from the wire was greater in the helium atmospheres than in the nitrogen atmospheres. As a result, the temperature of the wire was lower in the helium atmospheres. The calculated wire temperature for the 20% oxygen-80% helium atmosphere was approximately 400°F lower than the temperature in air when the same voltage was applied across the wire.

In the case of ignition by radiation, the incident energy supplied to the sample is unaffected by the atmospheric composition but energy loss from the sample surface will be greater for the helium containing atmospheres because of their higher thermal diffusivities. This probably accounts for the slight increase in the observed ignition energy in the helium-oxygen mixtures.

IV. DISCUSSION OF RESULTS

Flame spread rates

The mechanism of flame spread comprises a very complex interplay of diffusion, heat transfer and chemical processes in the fuel material and in the ambient gas phase. The subject has hitherto not received significant attention in the literature. In our previous report we have therefore limited ourselves to a qualitative description of flame spread in terms of pyrolysis and gas-phase combustion processes. We shall now attempt to arrive at a more quantitatively oriented description by means of a simplified model of the flame spread mechanism.

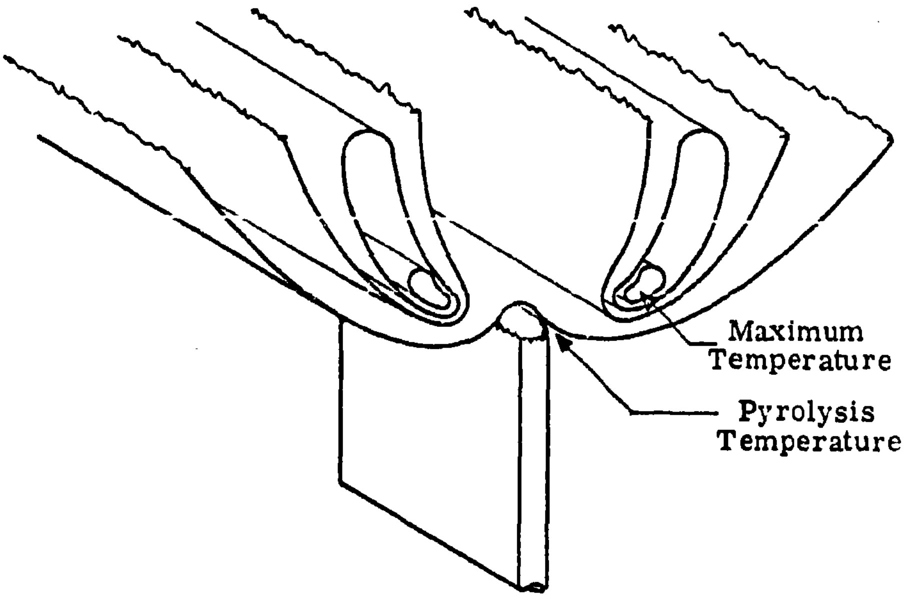
It is common experience in combustion theory that the choice of simplifying assumptions is quite risky. The literature is replete with examples of mathematically impressive combustion theories that bear little relation to actuality. Realistic treatments are generally based on fortunate experimental discoveries which show some unexpected simplicity in the relation between various combustion parameters. In the present case three such discoveries are now available.

(1) The flame spread rate of a sheet of combustible material, held vertically and ignited at the upper edge, is inversely proportional to its thickness over a considerable range of thickness (see previous report).

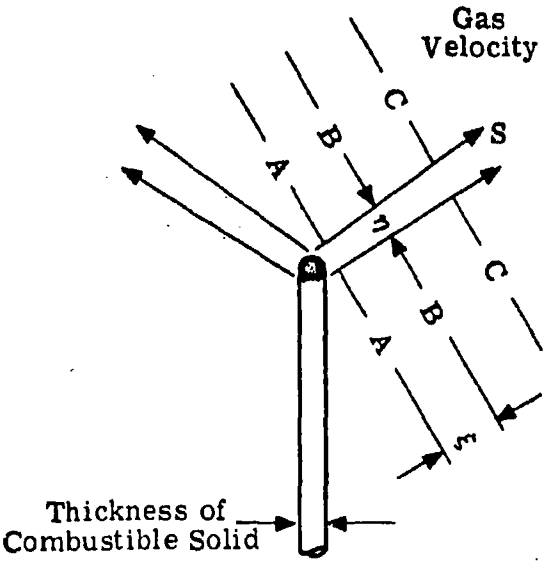
(2) The flame spread rate is independent of pressure.

(3) A correlation exists between the flame spread rate and the heat capacity of the gas mixture per mole of oxygen, approximately of the form shown in equation (1).

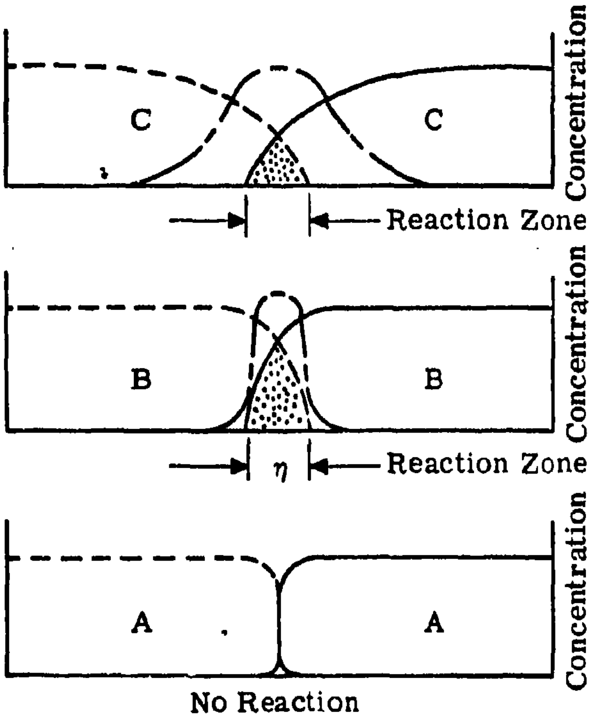
Reference is made to the schematic sketches of figure 8. The temperature in the flame above the burning edge of a combustible sheet is indicated in figure 8a. Figure 8b shows the combustible pyrolysis gas flowing away from the burning edge and interdiffusing with the ambient atmosphere. The diffusion flux of fuel meets the diffusion flux of oxygen to form a blue flame, the bluish glow being due to spectral emission from OH and hydrocarbon fragments such as CH and CC. The blue-flame



(a) Isothermal Surfaces Above the Burning Edge of a Sheet of Combustible Solid.



(b) Flow Lines in Diffusion Zone.



(c) Concentration Profiles in Diffusion Zone.

———— Oxygen
– – – – – – – Pyrolysis Gas
———- - ———— Product Gas

zone is bounded on the fuel side by a surface in which the oxygen concentration is zero, and on the oxygen side by a surface in which the fuel concentration is zero. Inside the zone heat is released at a rate determined by the fuel and oxygen concentrations and by the temperature. Rapid reaction demands high levels of concentration and temperature. The temperature field is maintained by the balance between the rate of heat release and the rate of heat loss by conduction across the zone boundaries. The rate of heat release is a high-order (exponential) function of temperature whereas the rate of heat loss is proportional to the temperature gradient across the zone boundaries. The steepness of this gradient is in inverse ratio to the distance between the zone boundaries. It follows from well-known principles of combustion theory that the zone must have some minimal width in order to maintain a thermal balance. If the width is smaller than this minimum, no thermal balance can exist and the blue flame is quenched. This quenching condition applies to the early stage of contact of the pyrolysis gas with the atmosphere, as the flow passes through the plane A-A in figure 8b.

A volume element of gas passing through plane A-A acquires a concentration profile as shown at the bottom of figure 8c, too narrow to support the flame reaction zone. In plane B-B the width has increased sufficiently to support the flame. Subsequently the fuel and oxygen concentrations decrease due to dilution by the inert reaction products CO_2 and H_2O, as illustrated for plane C-C; thus, the rate of heat release decreases and the temperature decreases. The temperature is a maximum at the onset of the blue flame, in plane B-B.

In summary, our model considers the blue flame to be a narrow stationary combustion wave supported by a flow of fuel/oxygen mixture. The fuel gas is generated by pyrolysis induced by feed-back of heat from the wave to the solid fuel. The combustible mixture is generated by interdiffusion of fuel gas and oxygen prior to the entry into the wave. There is a minimal width, η, which is analogous to the quenching distance in premixed flames and which determines the width of the diffusion zone required for flame support. Diffusion and heat conduction are considered to be the rate-controlling processes, eliminating chemical reaction rates from the model.

On this basis we formulate an equation describing the balance between the chemical energy of the diffusing oxygen and the heat released in the wave, another equation describing the balance between heat conduction and convection in the gas phase, and a third equation describing the conduction-convection balance between the gas and solid phase including the pyrolysis process. It is pointless, at this stage, to set down these equations in a form more refined than required by a crude dimensional analysis showing the gross features of the dependence of the flame spread rate on the various parameters. Thus, we take the number of moles of oxygen that diffuse into the fuel stream between the planes A-A and B-B per unit time to be

$$\xi D \frac{N_{O_2}}{\eta/2},$$

where ξ is the distance between planes A-A and B-B, D is the diffusion coefficient, N_{O_2} is the number of moles per unit volume in the ambient atmosphere, and η the width of the diffusion zone at B-B. The average width of the diffusion zone is taken to be $\eta/2$ and the oxygen concentration is considered to decrease from N_{O_2} to zero across the zone, so that $N_{O_2}/(\eta/2)$ represents a rough average of the concentration gradient. In the steady state an equal number of moles O_2 is transported per unit time by mass flow through the area of width η in plane B-B, where the oxygen reacts and releases the heat Q per mole. This heat raises the temperature of the stream to T_m, so that

$$\xi D \frac{N_{O_2}}{\eta/2} Q = \eta c \rho T_m S \qquad (2)$$

where c and ρ are the specific heat and density, respectively, of the gas, and S is the stream velocity. Heat flows by conduction from B-B to A-A and is transported by convection from A-A to B-B. In the steady state the conductive flux and the convective counterflux are equal; taking the flow to be substantially one-dimensional we write

$$k \, dT/d\xi = c\rho TS, \qquad (3)$$

where k is the heat conductivity of the gas, and integrating between the limits ($\xi = 0$, $T = T_p$) in plane A-A and (ξ, T_m) in plane B-B we obtain

$$\log \frac{T_m}{T_p} = \frac{c\rho}{k} S \xi. \tag{4}$$

The solid-fuel sheet moves with respect to the plane A-A at the flame-spread rate r, carrying the heat

$$c_s \rho_s T_p \times rd$$

toward A-A per unit time. c_s and ρ_s are the specific heat and density of the solid, d is the sheet thickness, and T_p is the pyrolysis temperature at which the solid disintegrates into gas. The pyrolysis reaction is exothermic, releasing the heat q_s per unit volume of solid. Thus, as the fuel sheet approaches the plane A-A it gains the heat q_s rd per unit time plus the heat that flows by conduction through plane A-A into the sheet. The latter heat flow is $\eta k(dT/d\xi)_{\xi = 0} = c\rho T_p \times S\eta$. In the steady state, therefore,

$$c\rho T_p \times S\eta = (C_s \rho_x T_p - q_s) \times rd \tag{5}$$

Combining equations (2), (4) and (5) and writing $N_{O_2} = f_{O_2} \rho/M$, where f_{O_2} is the mole fraction of oxygen and M the average molecular weight of the gas, one obtains

$$\log \frac{T_m}{T_p} = \frac{(c_s \rho_s - q_s/T_p)^2 \, MT_m}{2 \, k\rho D \, f_{O_2} \, Q} \, r^2 d^2 \tag{6}$$

or

$$r = \frac{1}{d(c_s \rho_s - q_s/T_p)} \sqrt{\frac{Q}{M} \, \frac{k\rho D}{T_m} \, f_{O_2} \, \log \frac{T_m}{T_p}} \tag{7}$$

Equation (7) states correctly that the flame spread rate is inversely proportional to the sheet thickness and independent of pressure. The density ρ is $\sim p$ and the diffusivity D is $\sim 1/p$ so that the product ρD is independent of pressure, as are the heat conductivity k and all other parameters in the equation. This agreement between theory and experiment lends strong support to the model assumptions and in particular to the assumption that diffusion and heat conduction are in particular to the assumption that diffusion and heat conduction are the rate-controlling processes in flame spread. There seems to be no alternative concepts that would permit one to arrive at this agreement, indicating that a more refined theory would still have to be based on a set of equations (2), (4), and (5). We may therefore conclude that our understanding of the flame spread mechanism in principle rests on a rather firm basis.

We are in a much weaker position when we attempt to use equations (6) or (7) for predicting absolute rates or effects of mixture composition. Here we meet with difficulties in assigning realistic values to the various parameters. To begin with, the temperature T_m is not well-defined. According to equation (2) T_m is the flame temperature for adiabatic combustion; however, this is only an upper bound for T_m because the combustion is not adiabatic.[3] T_m is nevertheless commensurate to the adiabatic flame temperature and will change similarly with mixture composition; it decreases in inverse ratio to the heat capacity of the mixture per mole of oxygen. The relation can be specified with precision only for the adiabatic flame temperature T_f of a stoichiometric fuel/oxygen mixture, viz., $T_f = \Delta H/(m_{CO_2} + m_{H_2O}\, c_{H_2O} + m_{inert}\, c_{inert} +$ dissociation terms) where $\Delta H = Q$ is the heat of combustion per mole of oxygen (about 105 kcal/mole) and m is the number of moles of the indicated molecular species per mole of oxygen in the original (unburned) mixture. We take roughly,

$$T_m \sim 1/c_{p(O_2)} + m_{inert}\, c_{p(inert)})$$

and thus transform equation (6) into an equation resembling equation (1).

The flame spread rate enters as r^2 instead of r; this is offset to some extent by the parallel change of f_{O_2} in the denominator. We shall not attempt to elaborate further on this correlation, one important deterrent being the difficulty of assigning realistic values to the diffusivity D. We deal here with the diffusion of an oxygen/inert gas mixture into a fuel gas of unknown composition, which seems to be an unmanageable problem at this time. It should be pointed out, however, that the much larger flame spread rate in helium-oxygen atmospheres as compared to nitrogen-oxygen atmospheres is attributable primarily to the higher thermal conductivities and presumably also higher diffusivities of the helium mixtures, and only secondarily to the higher flame temperatures associated with the lower heat capacity of helium.

Of interest is the condition $T_m = T_p$, corresponding to log (T_m/T_p) = log 1 = 0 and, hence, r = 0. Taken at face value, this means that at some critical inert-gas dilution of the atmosphere the flame temperature drops to the level of the pyrolysis temperature so that heat transfer to the solid becomes insufficient to maintain the pyrolysis process and the combustion ceases. This may be an acceptable interpretation of the extinction limit, except that it does not allow an identification of the temperature T_p with observed threshold pyrolysis temperatures, which for wood, for example, are of the order of 700°C - too low for any kind of flame. It may be suggested that a more refined definition of the extinction limit should allow for the rate of evolution of pyrolysis gas; that is, below some critical rate various dissipative processes take crontol which are not considered in the present model.

From this analysis, we would predict that polyatomic gases would be more effective in reducing flame spread rates than monatomic or diatomic gases because of their higher volumetric heat capacities. A gas such as CF_4 should be highly effective in preventing flame propagation. Physiological activity and high density, however, might prevent its use in life support systems.

The only previously reported attempt to relate heterogeneous burning rates to the properties of the inert gas diluent is that of Chianta and Stoll (2). They conclude that the "damping effect" of the diluent is due solely to the mass of diluent present and predict that the monatomic gases of high molecular weight would be very effective on a volumetric basis. Our results suggest that they would be much less effective than polyatomic gases of the same molecular weight.

Ignition

The ignition of a combustible solid organic material requires first that the surface temperature be brough to a level where rapid pyrolysis occurs, generating gaseous products which form a flammable mixture with the ambient atmosphere close to the surface; and, second, that a sufficiently intense ignition source be present to ignite this flammable mixture. The rate of the condensed phase pyrolysis reaction will depend only on temperature and will be independent of the nature of the gaseous atmosphere. The flammability limits of the fuel/oxygen mixture and the energy necessary for ignition of the mixture will be affected only slightly by the presence of diluents in the concentration range considered here. Consequently, we should expect only a small effect of atmospheric composition on <u>ignition energy</u>.(3)

On the other hand, the nature of the gaseous atmosphere may have a profound effect on the <u>ease of ignition</u>, depending on the way in which the ignition energy source is applied to the sample. We have noted that hot wire ignition was more difficult in the atmospheres containing helium than in those containing nitrogen. This is attributed to the lower equilibrium temperature reached by the ignition wire in the helium atmosphere at constant voltage, rather than to any change in the ignition characteristics of the sample. When the ignition energy was furnished by a radiation source, however, the energy flux was independent of the composition of the atmosphere. In the case of a sample material with low specific surface and low thermal diffusivity (wood) energy loss to the atmosphere during the ignition process was negligible and the ignition energy was indopendent of the composition of the atmosphere (table V). As the specific surface increased (paper, cotton fabric) energy loss to the atmosphere increased also. This was most apparent in the helium containing atmospheres with high thermal conductivity and high thermal diffusivity, resulting in a significant increase in the <u>apparent</u> ignition energies. In the case of a thin layer of combustible material on a support with a high thermal diffusivity (plastic coated wire, painted surface) energy loss became even greater and ignition became difficult or impossible in the helium containing atmospheres.

The use of helium in a spacecraft atmosphere can be expected to reduce the probability of ignition from certain classes of ignition sources, e.g., overheated electrical circuits. This effect is achieved, however, through a more rapid dissipation of energy that prevents the attainment of a critical ignition temperature rather than through any effect on the ignition process per se. The beneficial effect may be nullified by designs which prevent ready heat dissipation.

V. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Flame spread rates over the surface of combustible solids are reduced by the presence of an inert diluent in the atmosphere.

Nitrogen is more effective than helium in reducing flame spread rates.

The rate of flame spread can be correlated with the specific heat of the atmosphere per mole of oxygen. A critical value for this quantity can be found for each material above which flame propagation ceases.

The rate of flame spread at constant atmospheric composition is approximately independent of pressure over the range studied (258 to 760 mm. Hg).

The ignition energy for a combustible material is approximately independent of the composition of the atmosphere within the flammable range.

The apparent ignition energy is strongly dependent on the thermal dissipative characteristics of the atmosphere and the mechanism by which the ignition energy is supplied.

Recommendations

Further work is needed to verify the theoretical correlation developed in this report.

Atmospheres containing polyatomic gas diluents should be investigated for theoretical and practical reasons.

A wider range of combustible materials should be studied. Correlations of critical heat capacities of the atmosphere with thermal and thermodynamic properties of the material should be sought.

REFERENCES

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2. Chianta, M.A., and A.M. Stoll. Effect of oxygen enriched atmospheres on the burning rate of fabrics. Aerospace Medicine 35:870-873, (1964).

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APPENDIX

Gas compositions

The gas mixtures used in this investigation were analyzed and found to be within one-half percent of the specified compositions. The results of the analyses are presented below.

Nominal Composition (Volume Percent)	Actual Composition (Volume Percent)
20% O_2 - 80% He	19.85% O_2 - 80.15% He
46% O_2 - 54% He	45.82% O_2 - 54.18% He
70% O_2 - 30% He	69.70% O_2 - 30.30% He
46% O_2 - 54% N_2	45.85% O_2 - 54.15% N_2
70% O_2 - 30% N_2	69.50% O_2 - 30.50% N_2

Description of combustibles

Cellulose acetate $(C_{12}H_{16}O_8)_n$. Samples of this material are one-half inch wide, one quarter inch thick and three inches long were cut from a clear class A sheet meeting Federal Specification LC-169.

Cotton fabric. Samples of this material were cut from a shirt of a type normally worn by medical technicians. It was supplied by the School of Aerospace Medicine and weighed 4.8 oz./sq. yd.

Foam cushion material. This material was supplied by the School of Aerospace Medicine. It had a fine open pore structure. Samples one-half inch wide and one-quarter inch thick were used in the flame spread rate studies.

Paint. This material, designated Capon EA4-269 Ivory finish, was manufactured by the Coast Paint and Lacquer Company of Houston, Texas, and supplied by the School of Aerospace Medicine. An 0.004-inch thick coating was applied to an 0.008-inch thick aluminum strip which had been primed with an 0.004-inch thick coating of Capon EA-216 chromate primer. The samples were allowed to air dry for at least thirty days before being tested.

Paper. One-half inch wide strips were cut from an ordinary 3 x 5 inch file card. The thickness of the card was 0.008 inches.

Wire, Mil W76B. These samples were supplied by the School of Aerospace Medicine. They were manufactured by the Belden Wire Company of Chicago, Illinois, as their No. 8522-1000, MW-C-18-16-W. The wire is a 16-strand conductor with an 0.020-inch insulation, presumably polyvinyl chloride.

Wood. These samples were standard tounge depressors, 3/4-inch wide and 0.066-inches thick, made from northern hardwood. Samples of uniform color were selected.