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GRAVITY EFFECTS ON FLAME SPREADING OVER SOLID SURFACES

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16. Abstract

An experimental program was conducted to determine the effects of gravity on the spreading of a flame over a solid combustible surface. Flame propagation rates were measured from specimens of thin cellulose acetate sheets burning in both normal gravity (1 g) and reduced gravity (0 g) environments; the specimens were burned in various quiescent mixtures of oxygen, helium, argon, and nitrogen. A correlation for normal gravity and reduced gravity burning was obtained based on theoretical models of previous investigators.

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GRAVITY EFFECTS ON FLAME SPREADING OVER SOLID SURFACES

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SUMMARY

An experimental program was conducted to investigate the effects of gravity on flame propagation over a combustible solid. Flame spread rates were measured from cellulose acetate specimens that were 0.0025, 0.0051, and 0.0122 centimeter thick. The specimens were burned in various quiescent environments of pure oxygen, oxygen-helium, oxygen-argon, and oxygen-nitrogen mixtures in both normal and reduced gravity. The mixture concentration ranged from pure oxygen to 40 percent by volume oxygen - 60 percent by volume diluent at 3.45 newtons per square centimeter (5 psia). The pure oxygen tests were also run at 10.14 and 27.6 newtons per square centimeter (14.7 and 40 psia). All tests were conducted in the Lewis Research Center's 5.0- and 2.25-second drop tower facilities.

The results indicate that argon and nitrogen were more effective in retarding the flame spread rate under all test conditions. Flame spread rate was found to depend on pressure in a minor way ($\approx P^{0.1}$) in both normal and reduced gravity. A reduced gravity flame spread rate correlation was obtained using a prediction which neglected the effects of buoyancy (previously presented in the literature). By extending this model to include buoyancy effects, a normal gravity correlation was also determined.

INTRODUCTION

In an effort to reduce the fire hazard associated with oxygen-enriched atmospheres, several investigators have taken the approach of studying the mechanism of flame spreading over a combustible solid. A better understanding of the parameters controlling the rate of flame propagation can lead to new developments in fire safety techniques (ref. 1).

In some earlier work (refs. 2 and 3), the addition of a diluent gas to the oxygen rich mixture was found to retard the flame spread rate. These studies also supplied information needed to determine the effects of oxygen concentration and pressure on the burning process; thickness of material was also found to influence the burning rate. With this information, theoretical models were proposed in which the flame spread rate was dependent on gas phase properties as well as properties of the solid fuel. In DeRis's (ref. 4) model for thermally thin behaving materials (material is considered thermally thin when temperature gradients within are negligible), the flame spread rate was inversely proportional to the fuel bed thickness and independent of initial pressure. Lastrina's thermally thin model (ref. 5) also predicted the thickness effect but showed a slight pressure dependency on propagation rate. Other reported findings on flame spreading are given in references 6 to 13.

From the standpoint of fires occurring in space, the effects of gravity become important considerations. At the Lewis Research Center several programs have been conducted to obtain burning characteristics of solid materials in a reduced gravity environment (refs. 14 to 16). In reference 17 a minor effect of pressure (of the order of $P^{0.1}$) on flame spread rate over a thin material was found to exist in reduced gravity as well as in normal gravity. Furthermore, the ratio of normal to reduced gravity spread rates plotted against thickness indicated a definite pattern or correlation existing between these variables. Other work on gravity effects on fires is presented in references 18 to 23.

This report presents additional data on the burning characteristics of a solid in reduced gravity. Gas phase parameters (oxygen concentration, thermal conductivity, specific heat, and total pressure) were varied, and specimens of cellulose acetate were burned in normal and reduced gravity environments. Comparisons were made with the reduced gravity data and the thermally thin model presented by Lastrina (ref. 5). A relation for normal gravity was then obtained from an extension of Lastrina's analysis to include free convection.

SYMBOLS

A	arrhenius pre-exponential factor
B	empirical constants in correlating equations
C	molar concentration
c	dimensionless molar concentration
c_p	specific heat
E	activation energy
F	functional dependence
G	Brokaw factor (ref. 26)

g	acceleration of gravity
k	thermal conductivity
M	mean molecular weight, g/mole
P	pressure
Q_c	heat released per unit of fuel burned
R	gas constant
T	temperature
$\overline{T}$	characteristic temperature in gas phase, $(T_{AF} + T_o)/2$
ΔT_{AF}	$T_{AF} - T_o$
t	dimensionless gas phase temperature
U	gas phase velocity
U_a	characteristic gas phase velocity
u	dimensionless gas phase velocity
V	flame spread rate
X	mole fraction
Y	distance perpendicular to solid surface
y	dimensionless distance perpendicular to solid surface
ρ	density
τ	material thickness

Subscripts:

AF	adiabatic flame
B	solid surface
f	fuel
g	gas
o	ambient conditions away from flame zone
ox	oxidant
R	reciprocal mole-fraction average for mixture (ref. 26)
s	solid

APPARATUS AND PROCEDURE

Test Facility

Most of the experimental data presented in this report were obtained in the Lewis Research Center's Zero Gravity Facility. Five seconds of reduced gravity is obtained by allowing the experiment to free fall in a vacuum through a distance of 122.5 meters. There are no external guide wires or electrical cables used, and the effective maximum gravitational acceleration acting on the experiment is estimated to be of the order of 10^{-5} g's. A complete description of the facility is given in reference 15.

Experimental Apparatus

The standard module used in the zero gravity facility in which the experiment and supporting equipment are attached is shown in figure 1(a).

The spherical tanks at the top section are part of a CO_2 fire extinguishment system which was used as a safety precaution at the completion of each test. The bulk of the experiment is in the central part of the module and consists of a combustion chamber, two high speed cameras, a specimen holder and ignitor, an electrical control box, and the plumbing system used to fill and evacuate the chamber. Chamber pressure and temperature were measured and recorded using a telemetry system located in the upper cone of the module.

The combustion chamber was made of stainless steel and had an internal volume of approximately 1×10^5 cubic centimeters. Two motion picture cameras operating at a nominal speed of 400 frames per second were used to photograph the burning sample, one from a vertical view and another from a side view. A timing light generator provided calibrated traces on the edge of the film in 0.01-second increments. The specimen holder shown in figure 1(b) was simply four threaded rods mounted to a stainless steel base plate. A 5.5 centimeter square specimen was then fastened to the rods at each corner as shown in the figure. The nichrome wire ignitor was positioned below the specimen making contact near the specimen's geometric center. The base plate located in the lower section of the combustion chamber is shown in figure 1(c).

Test Materials

The fuel specimens used were cellulose acetate samples that were 0.0025, 0.0051, and 0.0122 centimeter thick. These materials were clear transparent sheets with a high gloss finish (further identified by MIL SPEC LP-504).

The gas mixtures were obtained commercially premixed with each component certified by the manufacturer to be correct to within 0.5 percent of their nominal values. This was verified experimentally with an analytical mass spectrometer. The water vapor in each mixture was also less than 5 ppm.

Test Procedure

Prior to each run, the combustion chamber was wiped clean of any residue left from the previous run. The material was mounted in the holder and installed in the chamber. The chamber was then sealed, evacuated, filled with helium to atmospheric pressure, and purged for a short time. Following this, the chamber was reevacuated and filled with the desired gas mixture. Gas samples were taken from the chamber to verify that the mixture was within ±0.5 percent of the required values.

Data Reduction

The burning samples were photographed on high speed film which was then examined on a motion picture analyzer. Flame spread rates were obtained by measuring the displacement of the flame front from the center, or ignition point of the material, as a function of time. Displacement against time curves were drawn, and their slopes were calculated to obtain the average flame spread rates. The estimated error involved in measuring the displacements was ±0.05 centimeter, which resulted in a maximum error in burning rates of 3 percent. The flame spread rates in each direction of travel were essentially the same for a specified material and gravity level.

RESULTS AND DISCUSSION

Flame Spread Rate Data

A summary of the data obtained is presented in table I. The initials NT indicate the conditions for which no test was conducted, while NL indicates transient flame spreading results. In the latter, measurements of flame displacement as a function of time indicated a nonlinear behavior over the duration of the tests. There also were several tests where a stable flame could not be established. Rather, after ignition and an initial flash the fire was extinguished. These cases are designated on the table by NB.

In general, the data indicate that the flame spread rate decreases as gravity is decreased, fuel thickness is increased, pressure is decreased, and oxygen mole fraction is decreased. A closer examination of the effect of the particular dilutent gas on the flame spread rate is shown in figure 2 for the 0.0051-centimeter-thick material in both normal and zero gravities. It can be seen that all the diluents contributed to retarding the flame spread rate. Nitrogen was the most effective retardant, helium the least effective, and argon was intermediate between the two. Similar normal gravity results reported in the literature attribute the retarding effect to the properties of the diluent gas. Of primary interest here, however, is that the change in the spreading behavior with diluent in zero gravity is the same as in normal gravity.

Data Correlation

Flame spread theories. - There are presently two major predictions for the rate at which a flame spreads on a solid surface. Magee and his coworkers (ref. 24) have derived expressions for both thin ($V = F(\tau)$) and thick ($V \neq F(\tau)$) materials considering both solid and gas phase processes. A transient conduction problem is treated in the solid, while in the gas attention is focused on an "ignition region" which is dominated by diffusion and chemical reaction. A rigorous solution of the governing coupled differential equations was not attempted. Rather, a local heat balance approach was adopted which resulted in a solution which predicts the general functional dependence of flame spread rate on solid and gas phase parameters. DeRis (ref. 4) has also considered this problem but from a slightly different point of view. The process he has modeled is a diffusion flame propagating over a solid against an air stream. Assuming the flame is diffusion controlled isolates the combustion processes to a sheet and permits an exact solution of the governing equations. Although there are considerable conceptual differences in the gas phase between the models proposed by Magee and DeRis, Magee (ref. 24), with a few assumptions, has shown the derived expressions for thin and thick materials, respectively, to be equivalent. Magee's prediction for a thermally thin material, which is applicable to this work, is

$$V \cong \frac{k_g Q_c X_{ox} F(P, X_{ox})}{\rho_S c_{P,s} c_{P,g} \tau (T_B - T_o)} \qquad (1)$$

As is obvious from equation (1) by the absence of a gravity term, the affects of buoyancy driven convection on flame spread rate were not considered in the model.

Effects of pressure. - The authors in an earlier report investigated the effects of pressure on flame spread rate in normal and zero gravity in pure oxygen environments.

It was experimentally determined that the effect of pressure in zero gravity was the same as in normal gravity. Using equation (1) as a basis for correlating the data, it was argued that $V \cong F(P)/(T_B - T_o)$ only. The rationale behind this was that the same material was burned in all the tests ($Q_c/\rho_s c_{P,s}$ = constant), that all the tests were conducted in 100 percent oxygen ($X_{ox} = 1$), and that the ratio $k_g/c_{P,g}$ was approximately the same, assuming it was evaluated at the same mean temperature between the flame temperature and the surroundings. A graph of $V(T_B - T_o)$ against pressure is shown in figure 3 for both normal and zero gravity. In addition to the data from reference 17, the tests conducted at 27.6 newtons per square centimeter (40 psia) in the present work are also presented.

Lastrina in reference 5 has indicated that for thermally thin cellulosic materials there is a slight ($\sim P^{0.1}$) effect of pressure on the flame spread rate. The results in figure 3 show this same general pressure dependence for the tests conducted at the lower pressures (<27.6 N/cm^2). Lastrina also determined (in ref. 5) that for a given specimen in a specific environment an increase in pressure results in a change in the flame spreading behavior from a thermally thin to a thermally thick material. This is reflected, according to the models, in a change in the pressure dependence of the flame spread rate. For cellulosic materials, Lastrina found the change to be from $V \sim P^{0.1}$ to $V \sim P^{0.63}$. Similarly, Magee (ref. 24) experimentally determined that the flame spread rate on thick cellulose acetate specimens depended on pressure to the 0.72 power ($V \sim P^{0.72}$). The dotted curves in figure 3, which have been faired between the low pressure and supercritical data, also indicate this general behavior. That is, the exponent of the pressure term P increases from 0.1 to some larger value as evidenced by the increasing scope of the faired lines as pressure increases.

In summary, the low pressure data indicate that the flame spread rate is varying with pressure in both normal and zero gravity only slightly ($V \sim P^{0.1}$) as would be expected for a thermally thin material. The results for the supercritical environment show a greater dependence on pressure, suggesting the transition to a thermally thick behavior.

Reduced gravity correlation. - The equations for flame spread rate which have been developed to date are actually zero gravity predictions because buoyancy has been ignored in these models. The data herein, therefore, provide the first test of the adequacy of these equations. Since the same material was burned in all the tests, and considering only the low pressure data, the terms Q_c, ρ_s, $c_{P,s}$, and $T_B - T_o$ remain essentially constant in equation (1). The term $F(P, X_{ox})$ can also be further simplified to $P^{0.1}F(X_{ox})$ based on the previous discussions on the effects of pressure. Equation (1) becomes

$$V_{0g} \propto \frac{k_g P^{0.1} X_{ox} F(X_{ox})}{c_{P,g} \tau} \tag{2}$$

In evaluating the terms in this equation, the fluid properties were assumed to be those of the surrounding environment and were evaluated at ambient temperature. Details on the fluid properties calculations are presented in the appendix.

A least squares analysis of all the data was carried out using equation (2) to determine the power dependence of the oxygen mole fraction $X_{ox,o}$; it was found to be $X_{ox,o}^{1.3}$. A cross plot of the reduced-gravity flame spread rate against the correlating parameters in equation (2) is presented in figure 4. The solid line is the least squares curve through the data.

The correlation is generally adequate. Examination of figure 4 reveals, however, a small effect of thickness that has not been completely accounted for in the correlation. The data points for the 0.0025-centimeter-thick specimens are consistently above the correlating line. A further check on this behavior was made by plotting the flame spread rate against the thickness for the 3.45 newtons per square centimeter (5 psia) data. Results for the pure oxygen and oxygen-nitrogen data are presented in figure 5. The dashed line represents a τ^{-1} relation that has been faired through the pure oxygen data while the solid lines indicate an approximate $\tau^{-3/2}$ dependence. The graph indicates that a τ^{-1} relation adequately describes the behavior of the two thickest materials. However, the regularity with which the thinnest specimen shows a greater dependence cannot be ignored. Certainly, more zero gravity data with very thin specimens are required to investigate this deviation from the predicted thermally thin behavior. However, since the primary objective of this study is a better understanding of gravity effects, the acceptability of equation (8) in generally representing the zero gravity behavior will be assumed.

Gravity effects. - An assessment of the gravitational effects can be made by comparing the reduced and normal gravity flame spread rates. The term indicative of these effects is the fractional change in flame spread rate between reduced and normal gravity:

$$\frac{V_{1g} - V_{0g}}{V_{0g}} \tag{3}$$

A correlation of this term is sought as a function of a parameter characteristic of the buoyancy effects. This parameter can be obtained from the governing equations for the gas phase. If the equations from reference 5 are used with added convection terms, the energy equation is

$$\rho_g c_{P,g} U \frac{\partial T}{\partial Y} = k_g \frac{\partial^2 T}{\partial Y^2} + Q_c C_f C_{ox} A \exp\left(-\frac{E}{RT}\right) \tag{4}$$

The variables can be nondimensionalized in terms of characteristic quantities such that

$$u = \frac{U}{U_a};\ t = \frac{T}{\overline{T}};\ y = \frac{Y}{\tau};\ c_f = \frac{C_f}{CX_{ox}};\ c_{ox} = \frac{C_{ox}}{CX_{ox}} \tag{5}$$

Inserting equations (5) into equation (4) yields

$$\rho_g c_{P,g} \left(\frac{U_a \overline{T}}{\tau}\right) u \frac{\partial t}{\partial y} = k_g \left(\frac{\overline{T}}{\tau^2}\right) \frac{\partial^2 t}{\partial y^2} + Q_c C^2 X_{ox}^2 c_f c_{ox} A \exp\left(-\frac{E}{R\overline{T}t}\right) \tag{6}$$

Assuming that conduction and convection effects are of equal order of magnitude,

$$U_a \cong \frac{k_g}{\rho_g c_{P,g} \tau}$$

Equation (6) simplifies to

$$\left(\frac{U_a^2 \rho_g^2 c_{P,g}^2 \overline{T}}{k_g}\right)\left(u \frac{\partial t}{\partial y} - \frac{\partial^2 t}{\partial y^2}\right) = (Q_c A C^2 X_{ox}^2) c_f c_{ox} \exp\left(-\frac{E}{R\overline{T}t}\right) \tag{7}$$

One would expect the conduction effects to be important in this process (see ref. 5). The fact that the buoyancy processes are equally as important, at least for the present tests, is borne out by investigating the numerical value of equation (3) (i.e., it ranges between 0.20 and 1.65). A value for the characteristic velocity U_a can be obtained by considering the momentum equation in Boussinesq form in which inertia and gravitational terms are assumed to be of equal order of magnitude or

$$U_a^2 = \frac{\tau g\, \Delta T_{AF}}{\overline{T}}$$

Inserting this into equation (7) together with $C = \rho_g/M$ and rearranging terms such that the source terms are of unit order of magnitude result in

$$\left(\frac{g\ \Delta T_{AF}\tau}{Q_c A k_g}\right)\left(\frac{Mc_{P,g}}{X_{ox}}\right)^2\left(u\ \frac{\partial t}{\partial y} - \frac{\partial^2 t}{\partial y^2}\right) = c_f c_{ox}\ \exp\left(-\ \frac{E}{R\bar{T}t}\right) \tag{8}$$

For the tests conducted, g, Q_c, and A remained fixed. Temperature measurements in the flame were not made so an accurate calculation for T_{AF} is difficult. Therefore, ΔT_{AF} is assumed to be approximately the same for all tests With these simplifications, the correlating parameter becomes

$$\left(\frac{Mc_{P,g}}{X_{ox}}\right)^2 \frac{\tau}{k_g} \tag{9}$$

The results of the correlation are presented in figure 6. It is apparent from this figure that there is a definite trend in the data with the correlating parameter. Considering that the term ΔT_{AF} was assumed constant and that the fluid properties were evaluated at ambient conditions rather than at some mean temperature, the results are very promising. In order to determine the power dependence of the correlating parameter, a least squares analysis was conducted and found to be approximately 2/3. The least squares line representing this dependence is shown in figure 6. Therefore, the general form of the correlating equation is

$$\frac{V_{1g} - V_{0g}}{V_{0g}} \propto \left[\left(\frac{M_o c_{P,g,o}}{X_{ox,o}}\right)^2 \frac{\tau}{k_{g,o}}\right]^{2/3} \tag{10}$$

Normal gravity correlation. - In seeking a correlation of the normal gravity data, an equation of the form

$$V_{1g} \cong V_{0g}\left[1 + F(g)\right] \tag{11}$$

is used. This type of equation has been used to correlate results for other burning processes such as droplets (ref. 25). The success of equation (10) in correlating the gravity effects also substantiates this approach since it can be transposed to the same form. Substituting equation (2) into equation (11) and assuming F(g) may be represented by equation (9) gives the result

$$V_{1g} \cong B_1 \frac{k_{g,o} P^{0.1} X_{ox,o}^{1.3}}{C_{P,g,o} \tau} \left[1 + B_2 \left(\frac{C_{P,g,o}^2 M_o^2 \tau}{X_{ox,o}^2 k_{g,o}} \right)^{2/3} \right] \tag{12}$$

The constants B_1 and B_2 were obtained from figures 4 and 6. Figure 7 shows the measured normal gravity flame spread rates plotted against equation (12). There is a small size effect, as would be expected, since the reduced gravity correlation showed that tendency. However, the overall adequacy of the correlation is apparent.

SUMMARY OF RESULTS

Flame propagation test results were obtained by burning cellulose acetate specimens (sheet thicknesses, 0.0025, 0.0051, and 0.0122 cm) in quiescent mixtures of gaseous oxygen, oxygen-helium, oxygen-argon, and oxygen-nitrogen over a pressure range of 3.45 to 634 newtons per square centimeter. The specimens were burned in both normal (1 g) and reduced (0 g) gravity environments. The results are as follows:

1. In both normal and reduced gravity the effect of adding an inert gas to a pure oxygen environment to minimize flame spread showed helium to be less effective than argon or nitrogen; nitrogen appeared to be most effective in retarding the burning rate. The observed differences between the three inert gases was less than 1 order of magnitude.

2. In both normal and reduced gravity the flame spread rate over a thin material varies with pressure of the order of $P^{0.1}$.

3. The reduced gravity data for flame spread rate was adequately correlated using Lastrina's thermally thin model which neglected the effects of buoyancy. The resulting equation is

$$V_{0g} \cong \frac{k_{g,o} P^{0.1} X_{ox,o}^{1.3}}{c_{P,g,o} \tau}$$

4. A parameter indicative of the importance of gravity effects was obtained from the governing equations:

$$\left(\frac{g \, \Delta T_{AF} \tau}{Q_c A k_{g,o}} \right) \left(\frac{M_o c_{P,g,o}}{X_{ox,o}} \right)^2$$

The fractional increase in flame spread rate between normal and gravity conditions was successfully correlated in terms of a form of this parameter or

$$\frac{V_{1g} - V_{0g}}{V_{0g}} \cong \left[\left(\frac{c_{P,g,o}M_o}{X_{ox,o}}\right)^2 \frac{\tau}{k_{g,o}}\right]^{2/3}$$

5. The normal gravity data were successfully correlated by an equation of the form

$$V_{1g} \cong V_{0g}\left[1 + F(g)\right]$$

where

$$V_{0g} = \text{Constant} \times \frac{k_{g,o}P^{0.1}X_{ox,o}^{1.3}}{c_{P,g,o}\tau}$$

and

$$F(g) = \text{Constant} \times \left[\left(\frac{c_{P,g,o}M_o}{X_{ox,o}}\right)^2 \frac{\tau}{k_{g,o}}\right]^{2/3}$$

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APPENDIX - PROCEDURE FOR CALCULATING GAS MIXTURE PROPERTIES

Table II presents the fluid properties used to evaluate the correlating equations. These values were calculated for each property as follows.

Thermal Conductivity

The equation for the thermal conductivity of a gaseous mixture (from ref. 26) is

$$k_g = Gk_m + (1 - G)k_R$$

where

$$k_m = X_{ox}k_{ox} + (1 - X_{ox})k_{diluent}$$

$$k_R^{-1} = \frac{X_{ox}}{k_{ox}} + \frac{(1 - X_{ox})}{k_{diluent}}$$

and G is tabulated in reference 26. The values of k_{ox} and $k_{diluent}$ are also obtained from references 26 and 27.

Specific Heat

The equation for the specific heat of a gaseous mixture (from ref. 28) is

$$c_{P,g} = X_{ox}\left(\frac{M_{ox}}{M_{mix}}\right)c_{P,ox} + (1 - X_{ox})\left(\frac{M_{diluent}}{M_{mix}}\right)c_{P,diluent}$$

The values of $c_{P,ox}$ and $c_{P,diluent}$ are zero pressure values also obtained from reference 28.

Molecular Weight

The equation for the molecular weight of a gaseous mixture (from ref. 29) is

$$M = X_{ox}M_{ox} + (1 - X_{ox})M_{diluent}$$

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TABLE I. - SUMMARY OF FLAME SPREAD RATE DATA

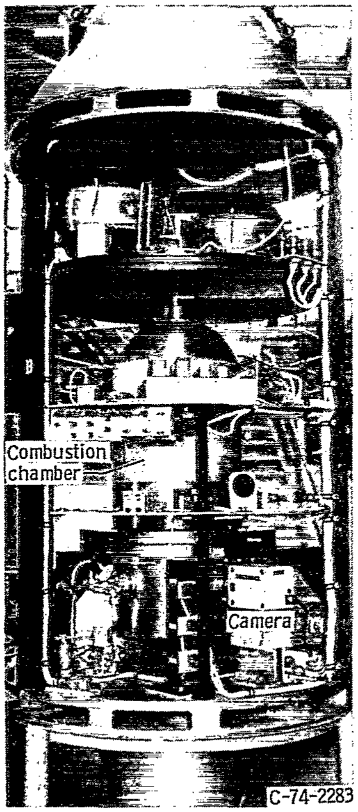
Gaseous mixtures			Flame spread rate, cm/sec					
Pressure, N/cm^2	Temperature, $^{\circ}C$	Constituents, vol %	Specimen thickness, cm					
			0.0025		0.0051		0.0122	
			Normal gravity	Reduced gravity	Normal gravity	Reduced gravity	Normal gravity	Reduced gravity
[a]3.45	20	$100O_2$	6.70	5.58	3.03	2.04	1.72	0.90
[a]10.14	20	↓	7.0	5.5	3.2	2.0	1.9	1.2
27.6	20	↓	7.63	6.33	4.02	2.40	NT[b]	NT
[a]634	-118	↓	10.2	9.7	7.8	4.9	3.35	1.76
3.45	20	$80O_2$-20He	6.47	4.73	2.79	1.92	1.56	.90
↓	↓	$80O_2$-20A	5.80	4.73	2.66	1.76	1.34	.78
↓	↓	$80O_2$-$20N_2$	5.82	4.32	2.63	1.62	1.37	.79
↓	↓	$60O_2$-40He	5.36	3.92	2.34	1.52	1.28	.55
↓	↓	$60O_2$-40A	4.72	3.28	2.20	1.27	.86	NL[c]
↓	↓	$60O_2$-$40N_2$	4.89	3.17	2.00	1.17	NL	.45
↓	↓	$50O_2$-$50N_2$	NT	NT	1.98	.79	NB[d]	NT
↓	↓	$40O_2$-60He	4.44	NB	2.24	NT	NB	↓
↓	↓	$40O_2$-60A	3.33	1.69	1.5	NL	NB	↓
↓	↓	$40O_2$-$60N_2$	3.11	1.43	1.43	.54	NT	↓

[a]Data from ref. 17.
[b]Not tested, NT.
[c]Nonlinear, NL.
[d]No burn, NB.

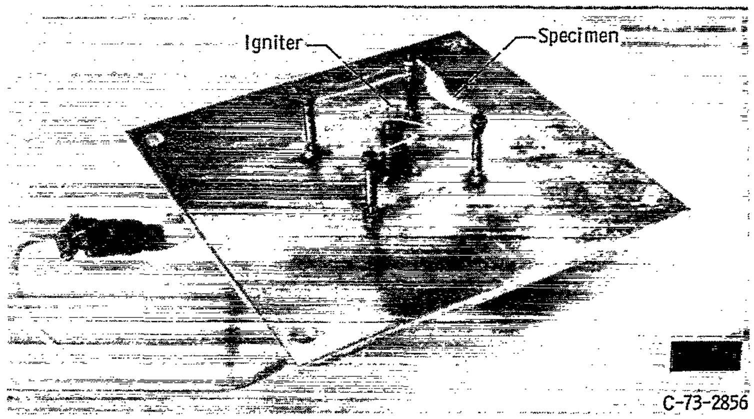
TABLE II. - FLUID PROPERTIES

[All properties evaluated at 20° C.]

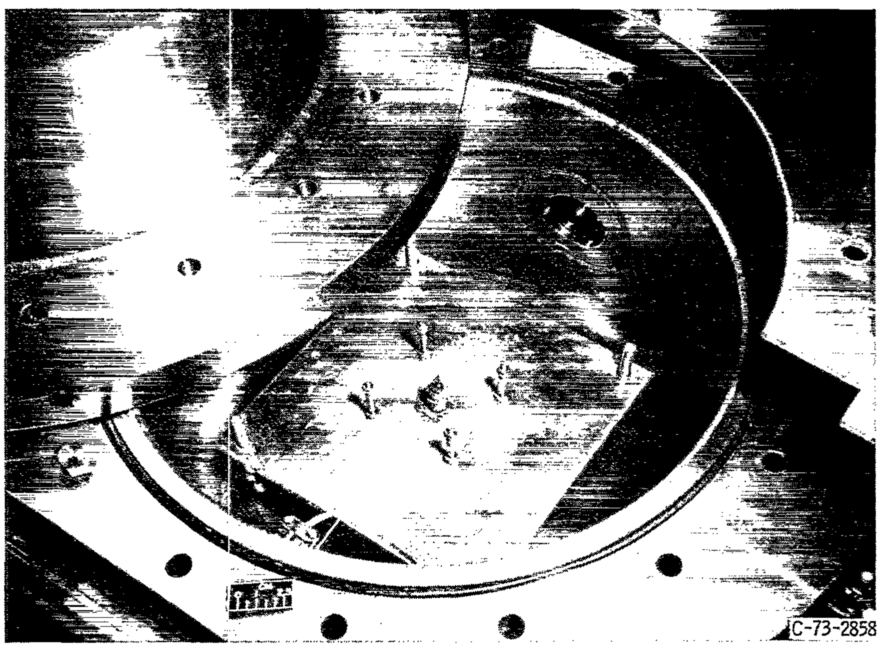
Environmental constituents, vol %	Pressure, N/cm^2	Molecular weight, M_o, g/mole	Specific heat, $c_{P,g,o}$, cal/g-K	Thermal conductivity, $k_{g,o}$, cal/cm-sec-K
$100O_2$	3.45	32.00	0.219	6.27×10^{-5}
$100O_2$	10.14	32.00	.219	6.28
$100O_2$	27.6	32.00	.219	6.32
$80O_2$-20He	3.45	26.40	.250	9.21
$60O_2$-40He	↓	20.80	.299	12.95
$40O_2$-60He	↓	15.20	.380	18.10
$80O_2$-20Ar	↓	33.58	.196	5.78
$60O_2$-40Ar	↓	35.16	.176	5.31
$40O_2$-60Ar	↓	36.74	.157	4.88
$80O_2$-$20N_2$	↓	31.20	.225	6.24
$60O_2$-$40N_2$	↓	30.40	.230	6.22
$50O_2$-$50N_2$	↓	30.00	.233	6.20
$40O_2$-$60N_2$	↓	29.60	.236	6.19



(a) Test rig.



(b) Specimen holder.



(c) Holder positioned in combustion chamber.

Figure 1. - Experimental apparatus.

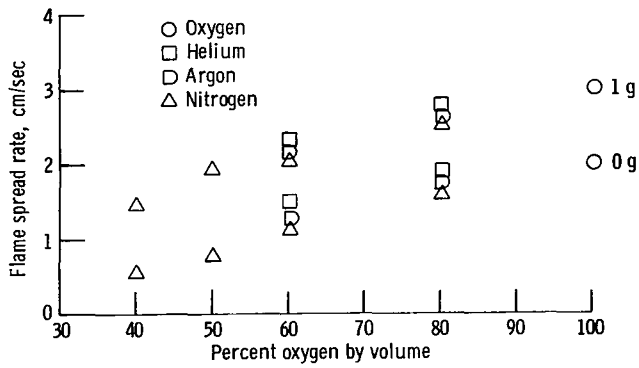


Figure 2. - Flame spread rate as function of oxygen concentration for 0.0051-centimeter-thick specimen.

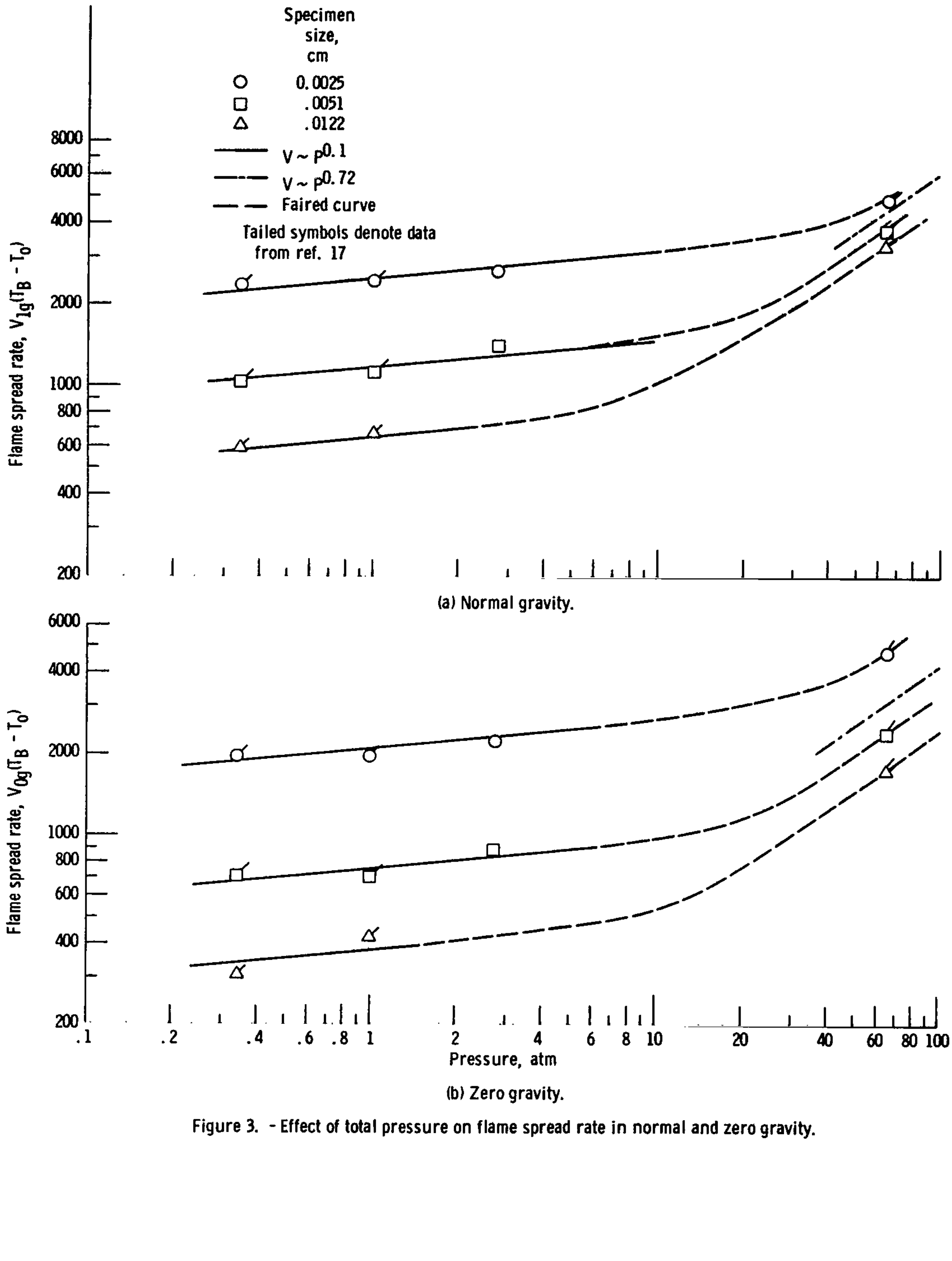


Figure 3. - Effect of total pressure on flame spread rate in normal and zero gravity.

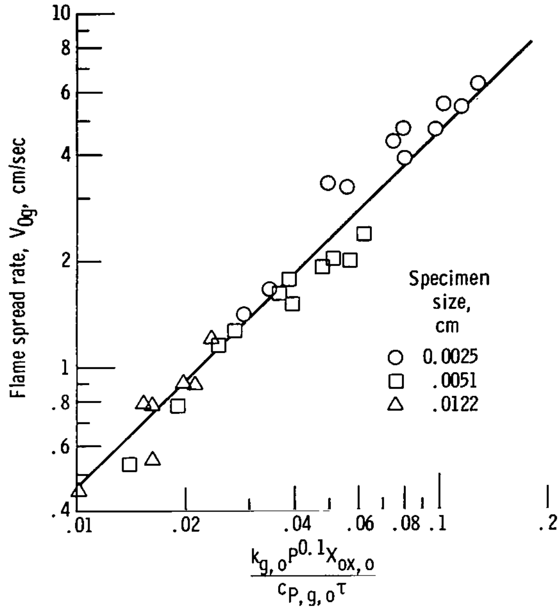


Figure 4. - Zero gravity correlation of flame spread rate for thermally thin materials.

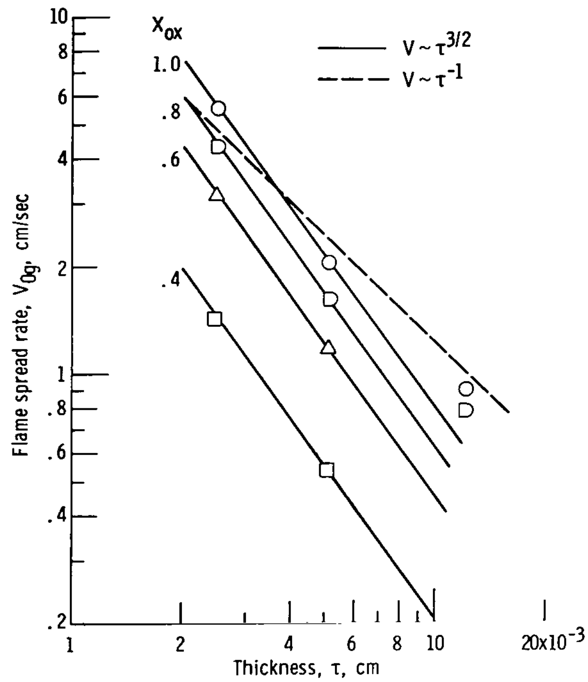


Figure 5. - Effect of thickness on flame spread rate in zero gravity for oxygen and nitrogen-oxygen environments.

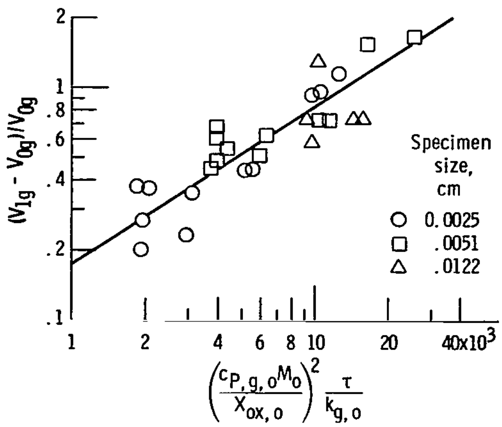


Figure 6. - Effect of gravity on flame spread rate for thermally thin materials.

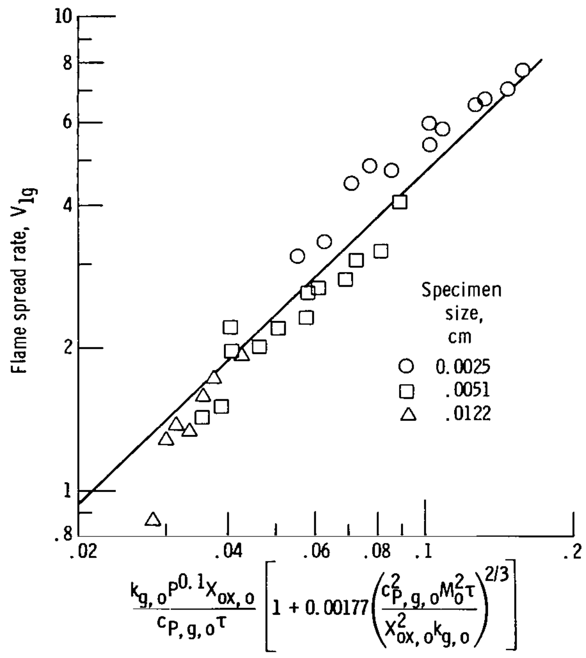


Figure 7. - Normal gravity correlation of flame spread rate for thermally thin material.

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