TECHNICAL NOTE TN 314-N-8-69 12 AUGUST, 1969

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ABSTRACT

The results of tests investigating the effect of acceleration on the "downward" burning of vertically oriented spacecraft materials in a pure oxygen (16.5 psia) environment indicate that the burning rate is heat transfer limited. At low acceleration levels (0 to 3 g) free convection tends to cool the fuel material ahead of the flame front, thus decreasing the burning rate. At higher acceleration levels (3 to 5 g) flowing melt and migrating burning particles preheat the fuel material ahead of the flame front, thus increasing the burning rate.

The results of tests investigating the effect of acceleration on horizontally oriented cotton specimens, in various environments, indicate that burning rates increase with acceleration level approximately as predicted by a theoretical model proposed by Reference 10.

1.0 INTRODUCTION

Recently tests (References 1 through 7) have been performed on the effect of gravity upon burning rate and related perameters of materials of interest to the aerospace program. The present note attempts to summarize these results and put them in a form suitable for forming a basis of an analytical study of these phenomena.

Furthermore computer oriented theoretical studies have also been performed (Reference 9 and 13). Consideration of these valuable contributions must also be included to insure full utilization of all pertinent material in the formation of an analytical model.

The above mentioned tests were performed to determine the effect of body forces, caused by high acceleration levels, on the burning rates of various spacecraft materials. These high acceleration levels (radial acceleration) were obtained using a centrifuge.

In these tests two orientations of the fuel specimen were investigated.

1. Specimen oriented parallel to the radial acceleration vector with flame propagation in the direction of the body force vector or away from the axis of rotation (quasi-vertical orientation with "downward" burning), Figure 1. For this orientation the radial acceleration, a_r, was varied between 0 and 15 g (References 1-6).
2. Specimen oriented perpendicular to the resultant of the radial acceleration and the gravity acceleration

vectors (horizontal orientation). For this orientation the resultant accleration, a, was varied between 0 and 5 g (Reference 7).

The test procedure for the quasi-vertical orientation is described in References 1 and 2. The burning rates for a variety of non-metallic materials were measured in an environment of pure oxygen at 16.5 psia. The burning rates were obtained using thermocouple rakes and motion pictures. The test procedure for the horizontal orientation is described in Reference 7. In these tests the burning of cotton cloth in environments of pure oxygen, helium-oxygen and nitrogen-oxygen mixtures at total pressures of from 3.5 to 14.7 psia was investigated. The burning rates were obtained using motion pictures.

2.0 EXPERIMENTAL RESULTS

2.1 Quasi-vertical Orientation

The results of the experiments on the "downward" burning of fuel specimen in the quasi-vertical orientation can be catergorized as follows:

a. Materials which self-extinguish for radial accelerations greater than 1 g (viz., Teflon, Teflon-coated fiberglass, asbestos fabric, Kel-F-Film and Beta fiberglass).

b. Materials (Table 1) whose burning rates can be characterized by the general relationship of Figure 2.

c. Materials whose burning rate increased with radial acceleration at a rate significantly greater than the general relationship of Figure 2.

Of the thirteen tests reported by References 1 through 6 the results of six fell into the first category, six fell into the second cateogry, and one fell into the third, (viz., Nylon Parapax Fabric, Reference 6).

Several of the materials in the first category would not support combustion under static conditions (no radial acceleration). For the majority of the materials in this category the burning rate decreased to zero as the radial acceleration increased from 0 to 3 g. For these material it appeared that the cooling due to free convection, which increases as the radial acceleration level increases, prevented the fuel material from being heated to the ignition temperature (Eg., Reference 6).

The results of the tests on the materials (Table 1) of the second category are shown in Figure 2. The average of the burning rates for all of the materials in this category, normalized to the static condition, is shown for the radial acceleration levels, a_r, from 0 to 15 g. In addition, the range of the mean rates for the individual tests is shown. Initially, as the radial acceleration is increased from zero, the burning rate decreases reaching a minimum value for an acceleration level of about 1 or 2 g. This decrease is attributed to the cooling of the fuel material by free convection. As the acceleration level is increased beyond approximately 2 g, the burning rate increases due to the flow of melt and the random migration of burning or hot, burned particles which preheats the fuel material at a greater rate than bouyancy force induced convective cooling (eg., References 5 and 6).

For Nylon Parapax Fabric, the only material in the third category, the burning rate increased from 0.436 in/sec. at staic conditions to 6.14 in./sec. at an acceleration level of 15 g (Reference 6). For these tests the scatter of the data was very large (the range was about twice the mean rate). This material had a tendency to disintegrate under the combined action of combustion and body forces and the flame propogation was apparently due primarily to the migration of burning particles (Reference 6).

2.2 Horizontal Orientation

The results of experiments on the burning of cotton cloth in a horizontal orientation are shown in Figure 3. The burning rate, normalized to the burning rate at a = 1g, is shown for acceleration levels, a, from 0 to 5 g. The environmental conditions for these tests are described in Table 2.

Reference 7 states (but gives no supporting data) that above acceleration levels of 5 g, the burning rate approaches a constant value. They attribute the increase in burning rate with increasing acceleration level to the increased supply of oxygen.

3.0 DISCUSSION

3.1 Quasi-vertical Orientation

An order-of-magnitude analysis, Appendix A, indicates that for conditions typical of the tests described in References 1 through 6, the burning rate is heat transfer limited as opposed to oxygen mass transfer limited. Assuming that heat transfer is the rate determining process, the analysis of Appendix B indicates that for the "downward" burning of a vertical fuel specimen the burning rate should decrease as the acceleration level increases. From Figure 2 it can be seen that this occurs at low acceleration levels. The increase in burning rate at high acceleration levels is attributed to preheating of the fuel by the flow of melt and by the migration of burning and/or burned particles

The above discussion helps to substantiate the explanation of the burning rate variation presented by References 1 through 6. One can conclude that a desirable quality for spacecraft materials, subjected to "downward" burning in a vertical orientation is good integrity of the char (i.e., no flowing melt or migrating particles) under the combined effects of combustion and large body forces.

The analysis of Appendix B also indicates that for "upward" burning of materials in a vertical orientation the burning rate will increase with acceleration level due to the increased preheating of fuel material by free convection. The quality of integrity, described above, would have little effect on the "upward" burning rate. Reference 8 points out the "upward" flame propogation in the vertical orientation is the most severe case and the analysis of Reference 9 indicates that "upward" propogation rates are about twice as large as "downward" rates at an acceleration level of 1 g. In view of the above observations and conclusions, the results presented in Figure 2, and the fact that such a phenomena is likely, it appears that an understanding of and control of "upward" flame propogation will be important in order to reduce fire hazards at high acceleration levels. Horizontal burning is of lesser importance while downward burning would, of the three categories, be of least importance in general.

3.2 Horizontal Orientation

A preliminary analysis (Reference 10) indicates that the burning rate for horizontally oriented specimen should be proportional to the acceleration level raised to the one-fourth power. The data of Reference 7 was fitted, by the method of least squares to a relationship of this type, Figure 3.

It is interesting to note that Reference 7 claims the burning rates tend to approach a constant as the acceleration level increases above 5 g although no such experiments are reported. A possible explanation for this is the burning rate, which is mass transfer limited at the low acceleration levels, becomes heat transfer limited at the higher acceleration levels. Furthermore, if the power law of Reference 10 is correct, then much larger g level increases are required to produce a significant change in burning rates when the g level exceeds 5.

4.0 REFERENCES

1. Whitaker, D.H., "Effects of Acceleration upon Combustion Rate Test," NASA MCS White Sands Test Facility,TP-WSTF-111A Test Report Number 1, 18 August 1967.

2. Whitaker, D.H., "Effects of Acceleration upon Combustion Rate Test," NASA MSC White Sands Test Facility, TP-WSTF-111A Test Report Number 2, 13 October 1967.

3. Whitaker, D.H., "Effects of Acceleration upon Combustion Rate Test," NASA MSC White Sands Test Facility, TP-WSTF-111A Test Report 3, 29 November 1967.

4. Whitaker, D.H., "Effects of Acceleration upon Combustion Rate Test," NASA MSC White Sands Test Facility, TP-WSTF-111A Test Report 4, 29 November 1967.

5. Whitaker, D.H., "Effects of Acceleration upon Combustion Rate Test," NASA MSC White Sands Test Facility, TP-WSTF-111A Test Report 5, April 1968.

6. Whitaker, D.H., "Effects of Acceleration upon Combustion Rate Test," NASA MSC White Sands Test Facility, TP-WSTF-111A Test Report 4, July 1968

7. Neustein, R.A., "The Effect of Atmosphere Selection and Gravity on Burning Rate and Ignition Temperature," McDonnell Douglas Astronautics Company, Santa Monica, California, DAC 62431, October 1968.

8. Huggett, C., "Combustion Processes in the Aerospace Environment," paper presented at the Spring Meeting of the Aerospace Medical Association, Miama, Florida, 1968.

9. __________ "Thermal Combustion Hazzard Model," a report prepared under Government Contract NASw-410 by General Electric Company, Apollo Systems Department, Houston, Texas, December 2, 1968.

10. Adelberg, M., "Effect of Gravity and Free Stream Velocity Upon Combustion Rate of Space Cabin Materials," Adelberg Research and Development TN 176-D-33-11-67, Sherman Oaks, California, November 30, 1967.

11. Lees, L., "Convective Heat Transfer With Mass Addition and Chemical Reactions," Recent Advances in Heat and Mass Transfer (J. P. Hartnett, editor), McGraw-Hill, 1961.

12. Eckert, E.R.G. and R.M.Drake, Heat and Mass Transfer, McGraw-Hill, 1959.

13. Von Elbe, G. et. al. "Quantitative Guidance For Material Control To Minimize Fire Hazards In Spacecraft" (Preliminary Draft of Task I Report), September 5, 1967, Atlantic Research Corporation Alexandria, Virginia.

TABLE 1

SPACECRAFT MATERIALS TESTED FOR THE EFFECT OF ACCELERATION ON "DOWNWARD" BURNING RATE

Material	Burning Rate, $a_r=0$ (in/sec.)	Reference
Nomex Standard	0.35	(1)
Nomex Standard	0.39	(2)
Aluminized Mylar	1.44	(3)
Nomex Fabric	0.273	(5)
Neoprene Coated Nylon	0.785	(5)
Kapton Aluminized	1.60	(6)

TABLE 2

ENVIRONMENTAL CONDITIONS FOR THE BURNING RATE TESTS OF HORIZONTALLY ORIENTED COTTON CLOTH (REFERENCE 7)

PRESSURE (PSIA)	COMPOSITION	BURNING RATE AT 1 g (in/sec)	CODE FOR FIGURE 3
3.5	100% O_2	0.46	×
5.0	100% O_2	0.50	+
5.0	70% O_2 30% He	0.44	○
5.0	70% O_2 30% N_2	0.37	●
7.0	50% O_2 50% He	0.34	△
7.0	50% O_2 50% N_2	0.25	▲
10.0	35% O_2 65% He	0.27	□
10.0	35% O_2 65% N_2	0.17	■

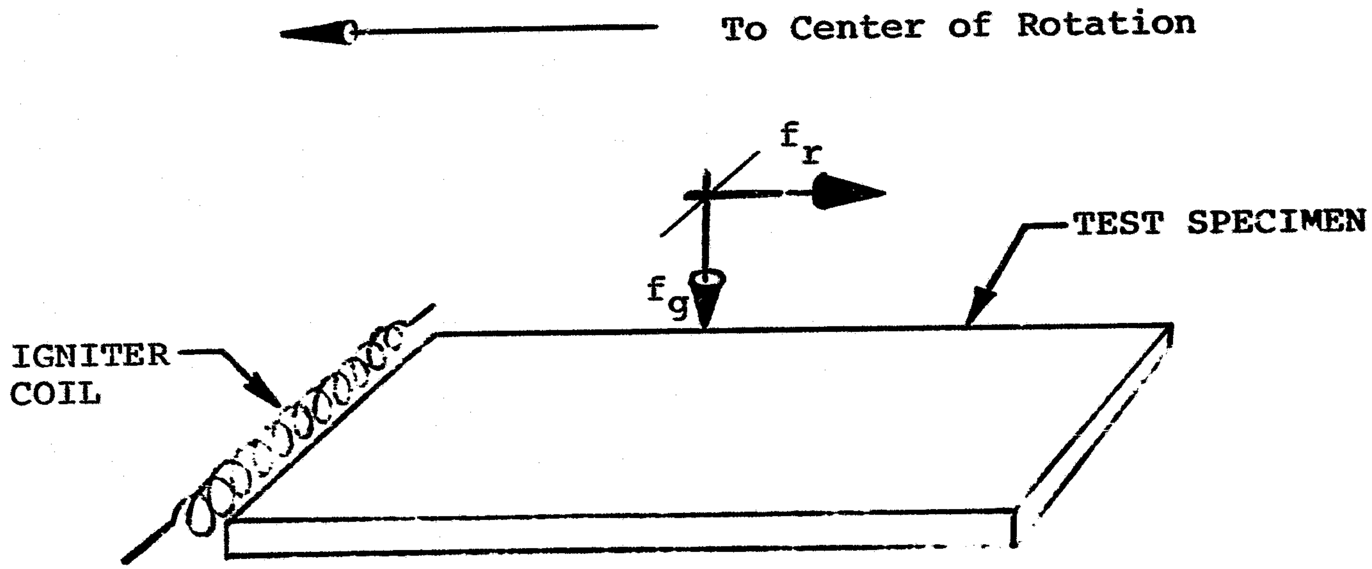


FIGURE 1. THE EXPERIMENTAL ARRANGEMENT FOR THE "DOWNWARD" BURNING RATE TESTS OF REFERENCES 1 THROUGH 6. (f_g is the body force due to gravity and equals 32.17 lb/slug. f_r is the body force due to the radial acceleration, a_r, caused by the action of the centrifuge. For the tests discussed, $0 \leq a_r \leq 15$ g's.)

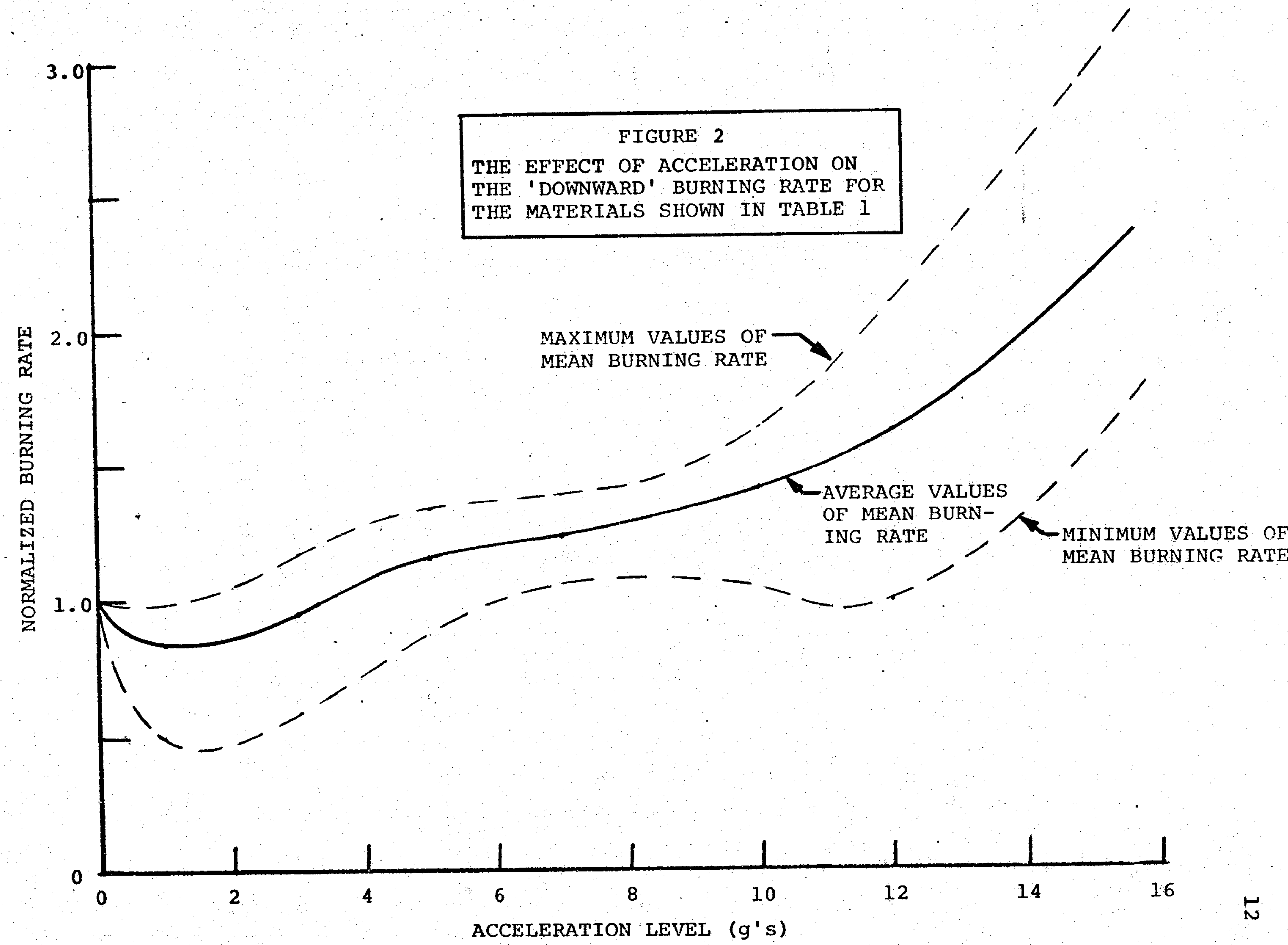
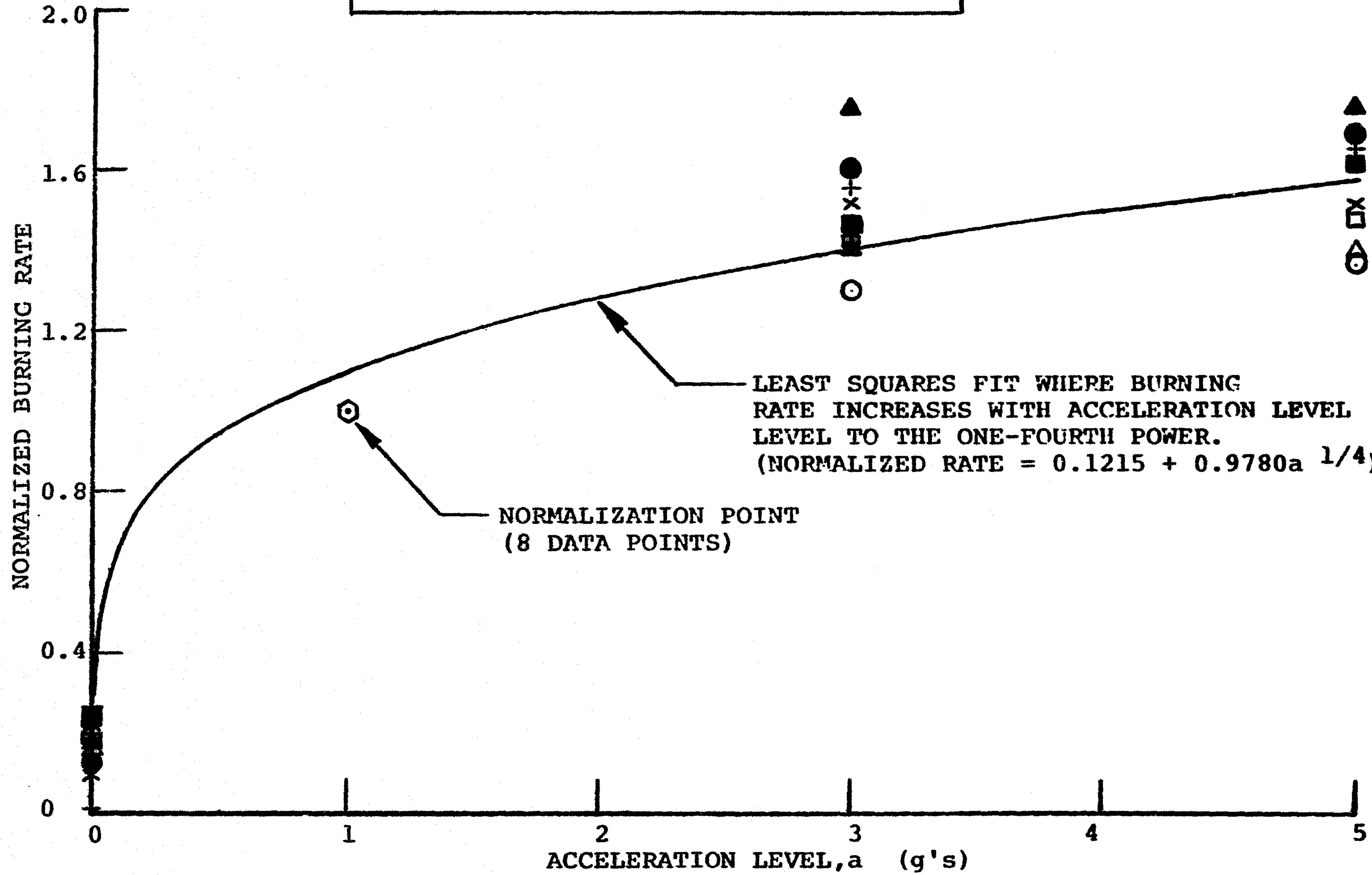


FIGURE 2
THE EFFECT OF ACCELERATION ON THE 'DOWNWARD' BURNING RATE FOR THE MATERIALS SHOWN IN TABLE 1

FIGURE 3

THE EFFECT OF ACCELERATION ON THE BURNING RATE OF COTTON CLOTH IN A HORIZONTAL ORIENTATION (SEE TABLE 2)



APPENDIX A

AN ORDER-OF-MAGNITUDE ANALYSIS OF THE CONSERVATION OF SPECIES EQUATION FOR A FREE CONVECTION SYSTEM

The purpose of this analysis is to present a justification for the assumption that the burning rate of non-metallic samples, vertically oriented, in a pure oxygen environment with "free" convection, is heat transfer limited.

The conversation of species equation for two-dimensional constant property boundary layer flow of a binary mixture can be written (Reference 11) as follows.

$$\rho u \frac{\partial w}{\partial x} + \rho v \frac{\partial w}{\partial y} = \rho D \frac{\partial^2 w}{\partial x^2} + \overset{\circ}{w} \qquad \text{...(A-1)}$$

where ρ = density

x,y = spatial coordinates parallel to and perpendicular, respectively, the surface.

u,v = x and y components of the velocity, respectively.

w = mass concentration of a particular species.

D = binary diffusion coefficient.

$\overset{\circ}{w}$ = volumetric rate of production by chemical reaction of a particular species.

Define the following dimensionless variables:

$$\tilde{\overset{\circ}{w}} = \overset{\circ}{w}/\overline{\overset{\circ}{w}}, \quad \tilde{w} = w/\overline{w}, \quad \tilde{x} = x/L, \quad \tilde{y} = y/\delta, \quad \tilde{u} = u/\overline{u}, \quad \tilde{v} = v/\overline{v} \qquad \text{...(A-2)}$$

where L = characteristic length of surface.

$\delta = L(GrPr)^{-\frac{1}{4}}$ is characteristic boundary layer thickness for free convection systems.

$\overline{u} = \alpha\sqrt{GrPr}/L$ is a characteristic x-component velocity in a free convection system.

$\bar{v} = \alpha\delta\sqrt{GrPr}/L^2$ is a characteristic y-component velocity as determined from the global continuity equation.

$\bar{w}$ = concentration of species in the mainstream.

= thermal diffusivity.

Gr = Grashoff number.

Pr = Prandtl number.

$\bar{\dot{w}}$ = characteristic species production rate.

Introducing equation (A-2) into equation (A-1) one obtains

$$\rho\frac{\bar{w}\alpha\sqrt{GrPr}}{L^2}\left[\tilde{u}\frac{\partial\tilde{w}}{\partial\tilde{x}} + \tilde{v}\frac{\partial\tilde{w}}{\partial\tilde{y}}\right] = \rho\frac{D\bar{w}\sqrt{GrPr}}{L^2}\frac{\partial^2\tilde{w}}{\partial\tilde{y}^2} + \bar{\dot{w}}\tilde{\dot{w}} \qquad \ldots(A\text{-}3)$$

Dividing equation (A-3) by the coefficient of the term on the left hand side one obtains

$$\tilde{u}\frac{\partial\tilde{w}}{\partial\tilde{x}} + \tilde{v}\frac{\partial\tilde{w}}{\partial\tilde{y}} = \frac{1}{Le}\frac{\partial^2\tilde{w}}{\partial\tilde{y}^2} + Da^1\,\tilde{\dot{w}} \qquad \ldots(A\text{-}4)$$

where Le = Lewis number = α/D

Da^1 = First Damköhler number for free convection (ratio of the rate of species produced by chemical reaction to the rate of species transferred by free convection),

= $\bar{\dot{w}}\delta/\rho\bar{w}\bar{u} = \bar{\dot{w}}L^2/\rho\bar{w}\alpha\,(GrPr)^{3/4}$ where it is assumed that the flame thickness is the same order of magnitude as the boundary layer thickness.

In equation (A-4), if $Da^1 > 1$ the flame propagation rate is mass transfer limited (provided Le ~ 1) while if $Da^1 < 1$ it is heat transfer limited.

For the combustion of vertical sheets of nonmetallic solids in a pure oxygen environment under the influence of free convection the following data are representative:

$\bar{\dot{w}} \sim 2\text{x}10^5$ lbm/cu.ft.hr (about 1 gm/sec.cc)

$\alpha \sim 2$ sq.ft./hr.

$\bar{w} \sim 0.1$ lbm/cu.ft. (16.5 psia and 600° R)

$L \sim 0.5$ ft.

$GrPr \sim 10^8$

For the above data the first Damköhler number is

$Da^1 \sim 0.25.$

For the above conditions the combustion rate is not oxygen mass transfer limited. Since the reaction would not normally be reaction rate limited one can conclude that the burning rate is heat transfer limited.

APPENDIX B

THE EFFECT OF ACCELERATION LEVEL ON THE BURNING RATE OF A VERTICAL PLATE

A schematic diagram of the "downward" burning of a vertical specimen is shown in Figure 4-A. If the process is heat transfer limited then the burning rate can be derived by making a heat balance on the volume element of length dx of the unburned material. The rate of increase of internal energy is equal to the net rate of heat transfer to the element. That is,

$$\rho_s (b t dx) c \frac{\partial T}{\partial \tau} = (q_r - q_c) b dx + k t b \frac{\partial^2 T}{\partial x^2} + \rho b t c \frac{\partial T}{\partial x} dx \qquad \text{...(B-1)}$$

where

ρ_s = density of the fuel material.

btdx = volume of the element having length dx.

c = heat capacity of the fuel.

T = temperature.

τ = time

x = spatial coordinate (referenced to the moving burning zone).

q_r = net radiant heat flux to the surface of the element.

q_c = the net convective heat flux from the surface of the element.

k = the thermal conductivity of the fuel.

V = the burning rate (eg., in./sec.)

b = specimen width

Assuming quasi-steady state (i.e., V = constant and $\frac{\partial T}{\partial \tau} = 0$ in the moving coordinate system),

$$V = \frac{tk\frac{\partial^2 T}{\partial y^2} + q_r - q_c}{-\rho c t \frac{\partial T}{\partial x}} \qquad \text{...(B-2)}$$

For a long specimen the terms in equation (B-2) are more dependent upon the distance from the flame zone, x, than upon the distance from the bottom of the specimen. Of the terms in this equation, only q_c depends upon the acceleration level, a. This relationship is of the form (Reference 12)

$$q_c = Ka^{1/4} \qquad \text{...(B-3)}$$

where K is not dependent upon the acceleration level. Thus,

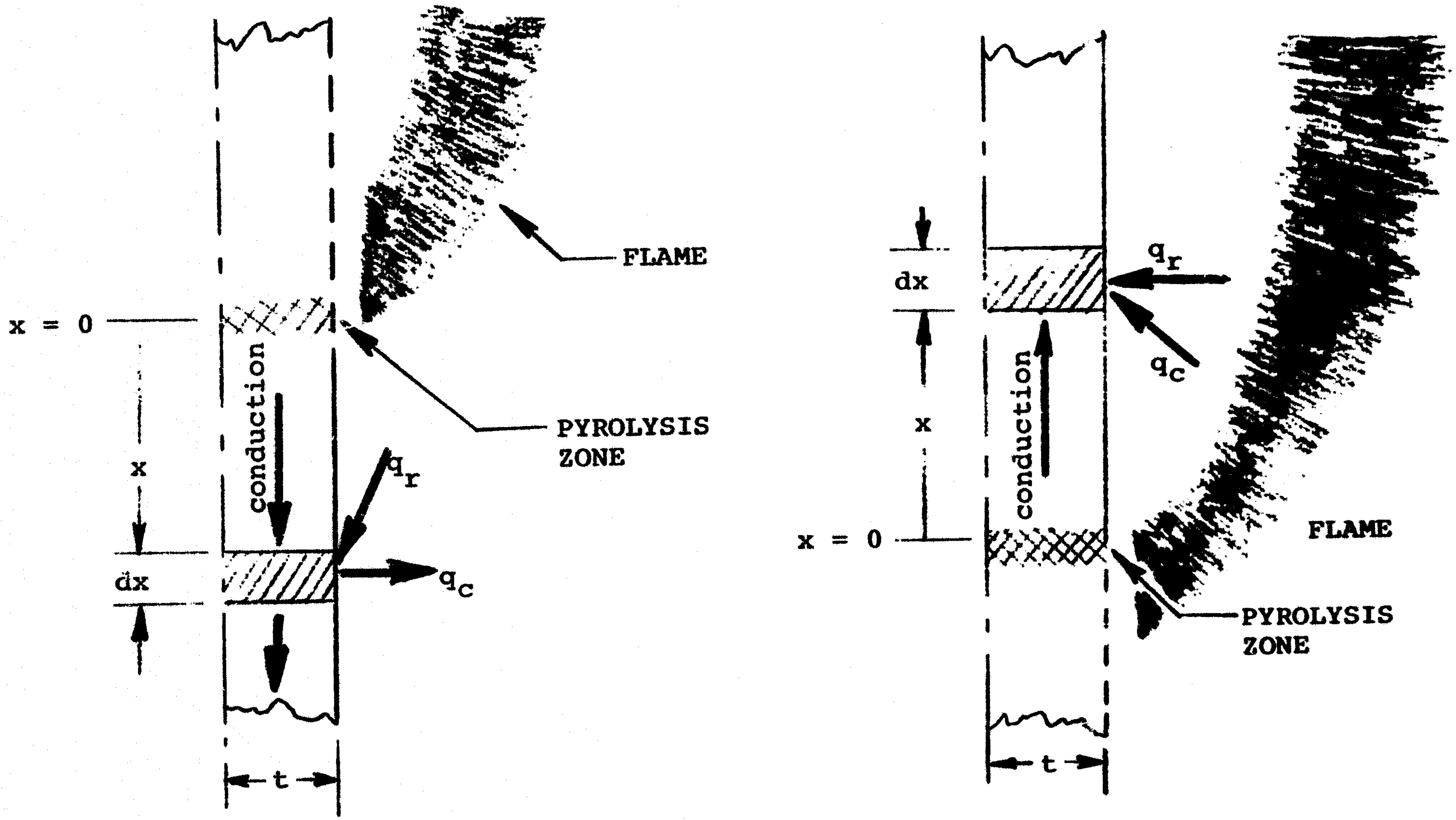
$$V = \frac{-1}{\rho c t \frac{\partial T}{\partial x}} \left(tk\frac{\partial^2 T}{\partial y^2} + q_r - K a^{1/4} \right) \qquad \text{...(B-4)}$$

Equation (B-4) predicts that the burning rate should decrease as the acceleration level increases.

For the case of "upward" burning, Figure 4-B, the burning rate becomes

$$V = \frac{-1}{\rho c + \frac{\partial T}{\partial y}} \left(tk \frac{\partial^2 T}{\partial y^2} + q_r + K a^{1/4} \right) \qquad \ldots (B-5)$$

and should increase as acceleration level increases. The burning rate for "upward" burning will be much greater than that for "downward" burning since the convection tends to heat, not cool, the unburned fuel and since the radiation view factor from the unburned fuel to the hot gases is much greater.



4-A "DOWNWARD" BURNING

4-B "UPWARD" BURNING

FIGURE 4. SCHEMATIC DIAGRAM OF BURNING SPECIMEN IN VERTIC.. ORIENTATION (In both cases the x-origin moves at the burning rate. I.E., a moving coordinat system.)