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EFFECT OF PRESSURE ON A BURNING SOLID IN LOW-GRAVITY

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Introduction

Venting, or depressurization, has been discussed as a possible technique for extinguishing fires on aircraft [1] and spacecraft [2,3]. Fire suppression plans for the International Space Station Alpha (ISSA) discuss the use of depressurization as a method for extinguishing fires [4]. In the case of an uncontrollable fire, the affected compartment would be vented from an initial pressure of 1.0 atm (14.7 psia) to a final pressure 0.33 atm (4.8 psia) within 10 minutes [4]. However, the lack of low pressure flammability data for solid materials in a low-gravity environment presents an uncertainty for the use of the venting technique. There are also transient effects that need to be considered. It is possible that the flows induced by the venting could intensify the fire. This occurred during flammability tests conducted on board Skylab [5]. In addition, the extinction pressure could be a function of the depressurization rate. Studies conducted with solid propellants have shown that if the pressure is reduced quickly enough, the pressure at extinction will be greater than the steady-state extinction limit [6]. This project, which was started in 1992, is examining both the quasi steady-state and transient effects of pressure reduction on a burning solid in low-gravity. This research will provide low-g extinguishment data upon which policies and practices can be formulated for fire safety in orbiting spacecraft.

Hardware & Procedures

Cast polymethyl methacrylate (PMMA) cylinders 1.9 cm in diameter and 2.5 cm in length were burned in these experiments. The cylindrical geometry was selected as a model system because two distinct flow regions exist when cylinders are placed in a flow: a forward stagnation point and a wake (re-circulating) region. The difference between flame stabilization and extinction characteristics in low and high speed flows can be important in venting extinction [7- 11]. The tests were conducted in a 25 cm diameter combustion chamber (50 cm in height) in which a forced flow of air, with velocities ranging from 5 to 20 cm/sec, was generated. (The axis of the cylinders was perpendicular to the flow.) Steel disks (1.9 cm dia) were placed at the ends of the cylinders to prevent end flames. Images were recorded on video tape using two color video cameras. A computer controlled the experiment and sampled pressure, temperature, volumetric flow rates, and acceleration data. Combustion was initiated using a hot wire ignitor.

A thermocouple was inserted along the cylinder axis with the junction at the center of the cylinder. This temperature was used as an indication of the change in the bulk solid temperature. The temperature of a thick solid can influence the flammability limits. In a quasi-steady gas-phase theoretical model [9], which was developed for this problem, a non-dimensional parameter (Φ) was defined to be the ratio of the heat conducted into the solid to that from the gas phase:

$$\Phi = \frac{-\lambda_S \left(\frac{\partial T}{\partial n}\right)_S}{-\lambda_G \left(\frac{\partial T}{\partial n}\right)_G}$$

This term has been demonstrated to be an important parameter determining the flammability of a PMMA cylinder in zero-gravity with a forced flow of air [9,10]. This model shows that as the solid center temperature increases, the value of Φ decreases. The relationship between the solid center temperature and Φ for a PMMA cylinder (1.9 cm dia) is shown in Figure 1. The solid-phase temperature was computed using a transient heat conduction model for a cylindrical geometry with a step change in the surface temperature: $t < 0$, $T(r) = 300$ K; $t > 0$, $T(r=R) = 700$ K. The gas-phase temperature gradient was calculated using an interface energy balance that included surface radiative loss, latent heat of vaporization, and heat conducted into the solid interior. In the limit of a solid heated to near the vaporization temperature, Φ would be approximately zero.

In these experiments, the sample was ignited, and depressurization was initiated at a pre-determined solid center temperature. (In most cases, this was 320 K.) The rate of depressurization was controlled using a PID controller that monitored the chamber pressure and controlled the outlet valve. The pressure was reduced until the flame was extinguished.

A series of tests was conducted to examine the velocity increase within the combustion chamber during depressurization. In the tests the forced flow velocity ranged from 10 to 18 cm/sec, the depressurization rate was 1.0 atmosphere per minute, the initial pressure was 1.0 atmosphere, and the final pressure was 0.5 atmospheres. The velocity was measured with a hot wire anemometer probe that was inserted into the center of the combustion chamber. During depressurization, the measured velocity increased by less than 2 cm/sec.

Low gravity data at low pressures was obtained on board the NASA Lewis Research Center's Lear Jet. In flight, the aircraft followed a Keplerian trajectory that produced approximately 20 seconds of low-g [12]. Accelerations on the order of $\pm$ 0.02 g's were measured during the low-g portion of the trajectory. The periods of low-g were preceded and followed by periods of high-g: + 2 to 3 g's. Because the time needed to establish combustion is longer than the entire low-g period, the samples were ignited in 1g, prior to the low-g trajectory. Reduced pressure on board the aircraft was obtained via an overboard vent line: atmospheric pressure at altitude (~ 30,000 ft.) provided the low pressure source.

Normal Gravity Results

The parameters for these experiments included: forced flow velocity, depressurization rate, and initial pressure. The forced flow was set at 10 or 20 cm/sec and the depressurization rate varied from 0.2 to 1.5 atmospheres per minute. The initial pressures ranged from 1.0 atm down to 0.4 atm.

Figure 2 is a plot of the solid center temperature at extinction and the computed value of Φ (at extinction) versus the extinction pressure. For high initial pressures and low depressurization rates (0.2 atm/min), the resulting temperature at extinction was high (> 500 K; $\Phi < 0.23$). The resulting longer period of burning raised the solid temperature increasing its flammability, as indicated by the decreasing value of Φ. Since the material was more flammable, a reduced pressure (0.07 atm) was required to cause extinction. For tests with a lower initial pressure or a high depressurization rate ($\geq$ 0.5 atm/min), the solid had less time to absorb heat from the flame, so the center temperature was less than 450 K ($\Phi > 0.27$) at extinction. (Extinction pressures varied from 0.1 to 0.3 atm.) Thus, these results provide a flammability boundary dependent on the solid (center) temperature and pressure.

There were distinct changes in the flame shape during the experiments. (Figure 3) Initially, the flame had a tear-drop shape (envelope flame) and a whitish-yellow color. (Figure 3A) As the pressure was reduced, the flame tip length was reduced, and the flame developed an elliptical shape. In addition, the flame color changed to a dim blue. (Figure 3B) As the pressure was reduced further, the flame blew-off at the forward stagnation point. This was followed by a period of oscillations, as the flame tried to re-attach itself. Eventually, the flame receded, forming a wake flame. (Figure 3C) As the pressure was reduced slightly, the flame extinguished.

In this test, the depressurization rate was 0.3 atmospheres/minute. In tests with depressurization rates on the order of 1.5 atmospheres/minute a wake flame did not form after the flame was blown-off the forward stagnation point. In these cases, the short burning times may not have permitted the upper surface temperature profile to increase to the point at which it could sustain combustion.

Low-gravity Results

Two types of experiments were conducted: constant and variable pressure. In both types of experiment, the samples were ignited at pressures ranging from 0.7 to 1.0 atmospheres. In the constant pressure experiments the pressure was reduced to the test condition after ignition, but prior to the beginning of the low-g-interval; the pressure was kept constant during the period of low-g. In the variable pressure tests, the pressure was kept constant until the low-g interval, at which point the combustion chamber was depressurized. The pressure range examined was 1.0 to 0.4 atm, with the lower pressure limit a result of the vent line capacity.

Twenty-six constant pressure extinction tests were conducted with a forced flow of 10 cm/sec in air. During low-g the solid- phase center temperature did not vary significantly, indicating little change in the solid-phase temperature profile. Since the solid-phase thermal diffusion time was on the order of 350 seconds, and the gas-phase time scales (conduction and convection) were on the order of 1 second, these experiments were considered to be quasi-steady. As noted in a previous paper [10], there were distinct changes in the flame's shape from 1g to low-g (Figure 4); at the same pressure (0.8 atm) and with the same forced flow (10 cm/sec), the low-g flame did not have the characteristic 1g plume, and the flame's color changed to a dim blue.

In these experiments, the quasi-steady nature of the flame was disturbed by perturbations about the mean g-level (g-jitter). These perturbations are associated with vibrations in the aircraft due to engine noise, air turbulence, and trajectory control. The perturbations were typically on the order of 10 to 40 milli-g's (10^{-2} to $4x10^{-2}$ g's). Since the mean g-level during the low-g portion of the trajectory was typically on the order of 1 to 10 milli-g's (10^{-3} to 10^{-2} g's), the perturbations created periods of positive and negative-g. The effect of g-jitter was noticeable in the visible flame thickness at the forward stagnation point. In figure 5, this thickness is plotted with the g-level as a function of time. As the g-level decreased, the flame thickness increased, most likely because changes in the net velocity affected the heat and mass transfer balances within the flame. The flame extinguished after 1.5 seconds of sustained negative-g, as shown in the right edge of the figure. The rapid decrease in the flame thickness denotes extinction.

The pressure and solid center temperature data for these experiments is plotted in Figure 6. Note that there were numerous experiments in which the flame extinguished. In all of these cases, the flame was disturbed by a sustained period of negative-g on the order of 30 milli-g's ($3x10^{-2}$ g's). At this g-level the induced buoyant velocity was on the order of 10 cm/sec. Since the induced velocity opposed the forced flow during a period of negative-g, the local velocity would have approached zero in tests with a forced flow of 10 cm/sec. Previous experiments [13] have indicated that this material is not flammable in air in a quiescent low-g environment. Thus, during negative-g the near zero air velocity weakened the flame. The weakened flame was not able to recover when the g-level began to increase and extinguished as shown in Figure 5.

A method for minimizing the effect of g-jitter would be to increase the forced flow velocity. The induced buoyant velocity would then be a smaller percentage of the forced flow. During a period of negative-g, the induced flow would still oppose the forced flow, however, the local velocity would not approach zero. Work in progress suggests that this method is effective in reducing the effects of g-jitter on the flame.

For cases in which g-jitter did not significantly affect the flames, extinction did not occur. This indicates that the pressures and solid center temperatures tested were above the low-g flammability limit. A recent numerical study agrees with this result [9]. This study examined the burning of PMMA cylinders in low-g with a forced flow and determined that the flammability limit was a function of the solid sub-surface temperature gradient. As the solid center temperature increased, the percentage of energy conducted into the solid interior from the flame (Φ) decreased. Since the solid was at a higher temperature, it required less energy from the flame to create the fuel vapor. Thus, in cases with reduced pressure and increased solid temperatures, the solid was able to produce fuel vapor, even though the reaction rate of the flame was reduced. Because of this, a cylinder at higher bulk temperatures sustained combustion at lower pressures. The limiting case was when the entire solid was near the vaporization temperature: Φ near zero. The low pressure limit with a 10 cm/sec forced flow of air, as reported in the numerical study, was approximately 0.12 atm (1.7 psia) [9].

In the transient experiments, the chamber pressure was reduced during low-g. Six cases were run, with depressurization rates ranging from 0.5 to 1.2 atm/min. The final pressures ranged from 0.67 to 0.42 atm. The flames were not extinguished during these tests. Additionally, there was no visible intensification or diminishment of the flames.

Conclusions

The 1g experimental results presented in this paper comprise a pressure - temperature flammability boundary for constant % oxygen, forced flow velocity, and g-level. As the bulk solid temperature increased, the low pressure limit decreased. (Figure 2.) When the solid temperature was sufficiently high, as measured by the solid center temperature and Φ, the low-pressure limit was quite low (< 0.1 atm).

The low-g experimental results to date did not produce a flammability boundary, but they illustrate the effects that g-jitter can have on a flame. In these experiments, g-jitter extinguished flames in conditions that have been observed to be flammable without jitter and which were predicted to be flammable [9]. Future experiments will continue to examine methods for limiting the effects of g-jitter.

The inability to determine the low pressure flammability limit in low-g was caused by limitations in the hardware; the lower pressure limit was a result of the vent line capacity. Further low-g experiments at pressures below 0.4 atm (5.9 psia) are planned. The current estimate for the low-g flammability limit with flow is below the final venting pressure for space station (4.8 psia). However, current plans for the ISSA are to turn off forced air circulation, vent to 4.8 psia, and then close the vent valve providing a quiescent low-g environment in which the flame should extinguish. However, during the time required to attain the quiescent condition, the fire may continue to burn.

During the low-g transient experiments, there was no visible intensification of the flames. This was due to the small increase in the velocity due to the venting. An intensification of the flames in the Skylab experiments [5] was due to a large change in velocity during depressurization; the Skylab experiments were conducted in a quiescent chamber with a pressure of 5.2 psia (0.35 atm) and an oxygen concentration of 65% [5]. Thus, during venting of the space station, there may or may not be an intensification of the fire, depending on the flame location and it's position relative to the vent port(s).

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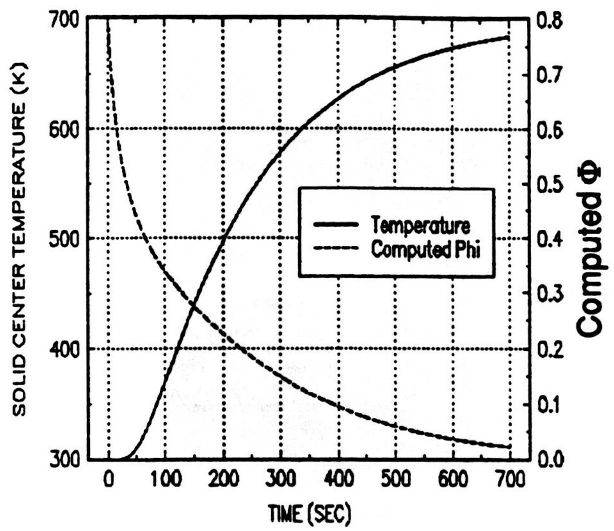


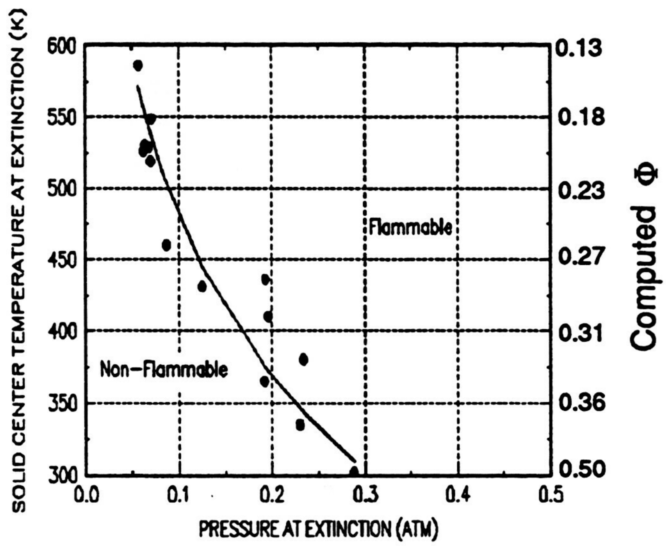
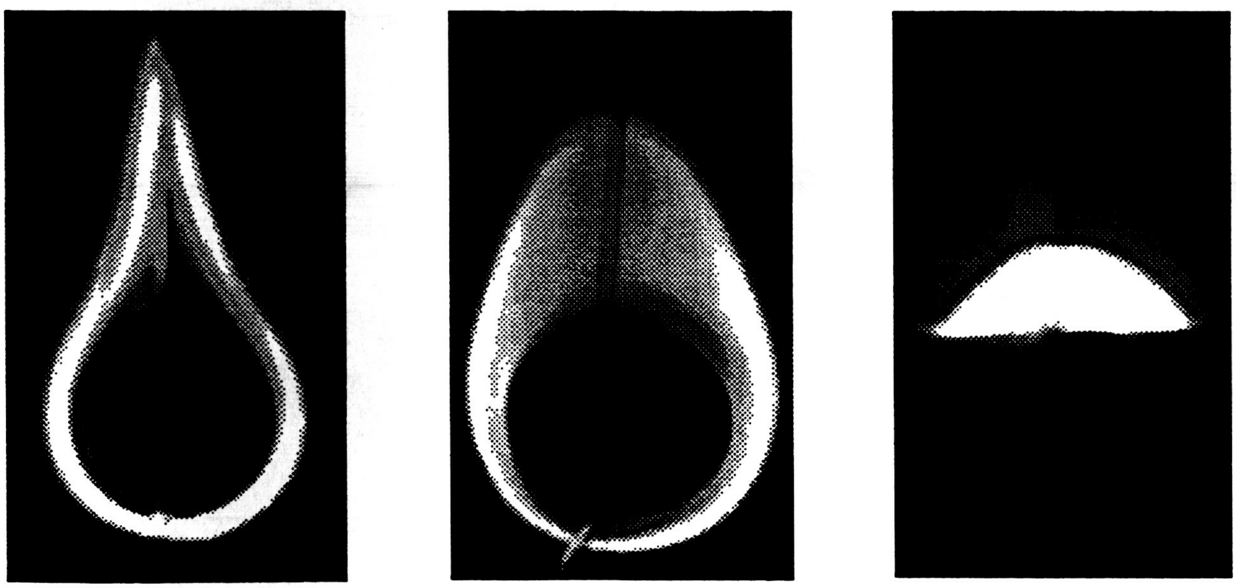


Figure 1 - Computed Solid Center Temperature and Computed Φ vs. Time
(Surface Temperature = 700K)

Figure 2 - Solid Center Temperature and Computed Φ vs. Pressure at Extinction in normal gravity
(forced flow of 10 cm/sec in air)

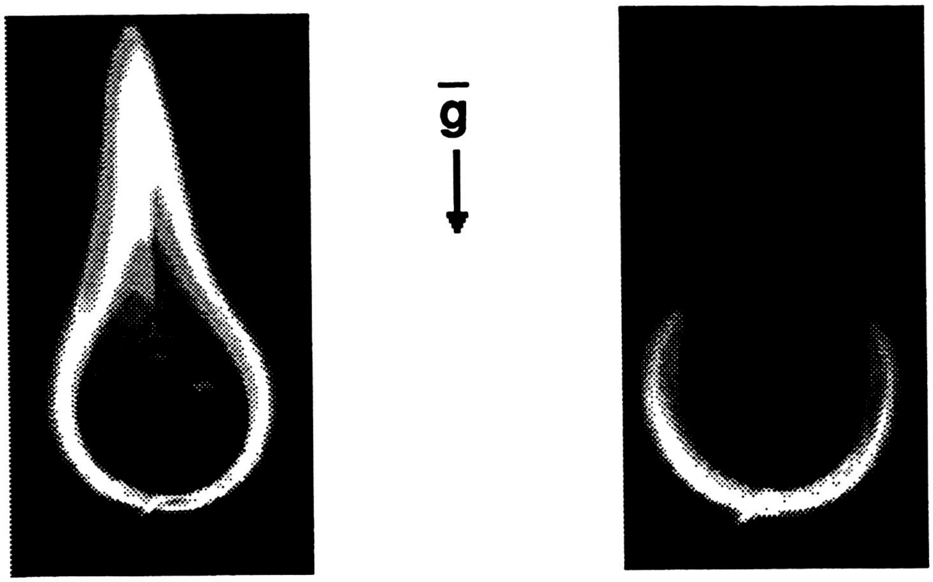


(A) P = 0.98 ATM
T = 307 K
t = 93 sec

(B) P = 0.11 ATM
T = 510 K
t = 301 sec

(C) P = 0.07 ATM
T = 526 K
t = 322 sec

Figure 3 - Visible Flame in normal gravity with a forced flow of 10 cm/sec in air
(ignition occurred at t = 34 seconds)



(A) 1g
T = 298 K

(B) Low-g
T = 303 K

Figure 4 - Comparison of 1g and Low-g Visible Flames

Constant Chamber Pressure (0.8 atm) with a forced flow of 10 cm/sec in air

(Initial Solid Center Temperature = 295 K)

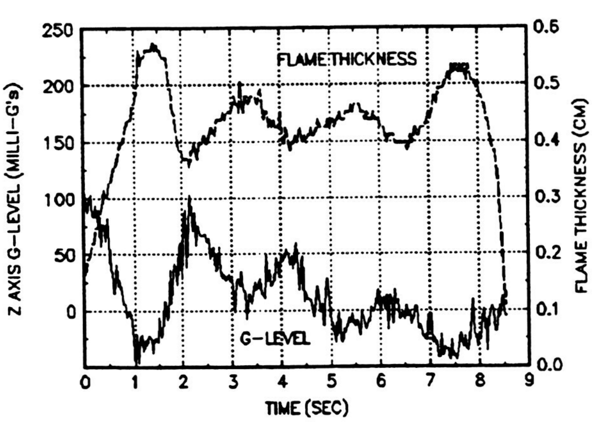


Figure 5

Flame Thickness & G-level vs. Time

Pressure = 0.79 atm
Solid Center Temperature = 303 K

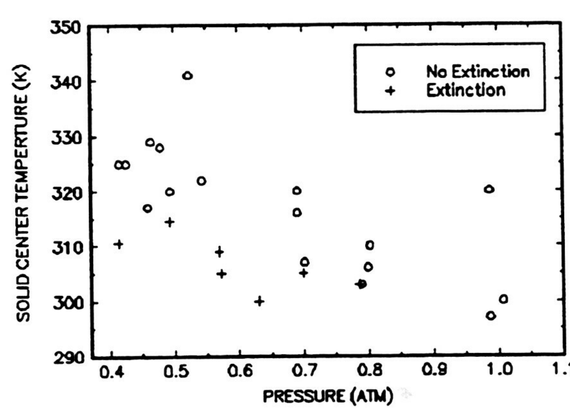


Figure 6

Solid Center Temperature vs. Pressure in Low-g (Lear Jet) with a Forced Flow of 10 cm/sec in air (subject to g-jitter)