CANDLE FLAMES IN MICROGRAVITY: USML-1 RESULTS -- 1 YEAR LATER

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ABSTRACT

Here we report on the sustained behavior of a candle flame in microgravity determined in the glovebox facility aboard the First United States Microgravity Laboratory. In a quiescent, microgravity environment, diffusive transport becomes the dominant mode of heat and mass transfer; whether the diffusive transport rate is fast enough to sustain low-gravity candle flames in air was unknown prior to this series of about 10 tests.

After an initial transient in which soot is observed, the microgravity candle flame in air becomes and remains hemispherical and blue (apparently soot-free) with a large flame standoff distance. Near flame extinction, spontaneous flame oscillations are regularly observed; these are explained as a flashback of flame through a premixed combustible gas followed by a retreat owed to flame quenching. The frequency of oscillations can be related to diffusive transport rates, and not to residual buoyant convective flow. The fact that the flame tip is the last point of the flame to survive suggests that it is the location of maximum fuel reactivity; this is unlike normal gravity, where the location of maximum fuel reactivity is the flame base.

The flame color, size, and shape behaved in a quasi-steady manner; the finite size of the glovebox, combined with the restricted passages of the candlebox, inhibited the observation of true steady-state burning. Nonetheless, through calculations, and inference from the series of shuttle tests, it is concluded that a candle can burn indefinitely in a large-enough ambient of air in microgravity.

After igniting one candle, a second candle in close proximity could not be lit. This may be due to wax coating the wick and/or local oxygen depletion around the second, unlit candle. Post-mission testing suggests that simultaneous ignition may overcome these behaviors and enable both candles to be ignited.

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INTRODUCTION

The candle flame has fascinated scientists for over three hundred and fifty years. The first recorded experimental investigations into candle flames were by Dr. Robert Hooke in 1672 (Birch, 1757). He used the candle flame to investigate the nature of combustion, discovering, among other things, the function of oxygen, performing the first schlieren experiment (using candles as both the light and object sources), and observing what is now known as buoyant convection. Dr. Hooke recorded this last observation as "...besides the flame and smoke of a candle there is a continual stream rising up from it distinct from the air". In beginning a famous series of lectures and candle experiments in the 1830's and 1840's, Sir Michael Faraday stated "There is no better, there is no more open door by which you can enter into the study of natural philosophy (science) than by considering the phenomena of a candle...(Faraday, reprint 1988)." Since the time of Faraday's lectures, the burning of a candle has often been used to illustrate some of the complicated physico-chemical processes occurring in a flame [Walker (1978), Gaydon and Wolfhard (1979), Lyons (1985)]. Recently candles have been used to study flame flicker (Buckmaster and Peters, 1986), spontaneous, near-extinction flame oscillations (Chan and T'ien, 1978), electric field effects (Carleton and Weinberg, 1989) and enhanced gravitational effects on flames (Villermaux and Durox, 1993).

Despite the frequency with which a candle flame is used in combustion science, no computational model of its behavior is available. Qualitatively, of course, various aspects of candle burning have been understood for centuries (for a history of candle making and candles, see Sherman, 1993). The flame surface represents the location where fuel vapor and oxygen mix at high temperature and react exothermically. Radiative and conductive heat transfer from the flame melts the wax (typically a C20 to C35 hydrocarbon) at the candle base. The liquid wax rises by capillary action up the wick, bringing it into closer proximity to the flame. This close proximity causes the liquid wax to vaporize. The wax vapors then diffuse toward the flame surface, breaking down into smaller hydrocarbons enroute. Oxygen from the general atmosphere migrates toward the flame surface by diffusion and convection. The survival and location of the flame surface is determined by the requirement that all these processes balance continuously.

In normal gravity, buoyant convection develops due to the hot, less dense combustion products. This has several effects: (a) the hot products are carried away by buoyancy and fresh oxygen is carried toward the flame zone; (b) solid particles of soot form in the region between the flame and the wick and are convected upward, where they burn off, yielding the bright yellow tip of the flame; and (c) in overcoming the loss of heat due to buoyant convection, the flame anchors itself close to the wick. The combination of these effects causes the flame to be shaped like a tear drop. Near the flame tip, the convective velocities are estimated to be between 30 and 90 cm/sec.

Therefore, one of the essential elements needed to explain the shape, size, and color of candle flames is the presence of buoyant-induced convective flow which affects the heat and mass transfer processes. Questions are frequently asked regarding candle flame behavior if buoyancy forces are greatly reduced. In a quiescent, microgravity environment, diffusive transport becomes the dominant mode of heat and mass transfer; diffusive transport velocities are on the order of 1 cm/sec, and at this rate, most combustion systems become less flammable. Whether this transport rate is fast enough to sustain low-gravity candle flames in air was unknown prior to these tests. It should also be noted that the candle flame in low gravity is one which provides a potential for a steady, non-propagating, non-convective, diffusion flame, and as such it is a model system.

Chung and Law (Chung and Law, 1986) used low pressure in an attempt to minimize buoyancy driven flows in combusting systems. Low pressure, however, obviates the use of better-understood chemical kinetics, since an elevated oxygen concentration is required to prevent flame extinction. Furthermore, diffusive transport rates decrease and the mean free molecular path increases (which broadens the reaction zone thickness) as pressure is reduced. Finally, low pressure is not expected to diminish the convective flows to a negligible level for candle flames in air (see Appendix 1) despite a near-spherical flame shape.

Compared with those in normal gravity in the same atmospheric conditions, both the low-pressure and the low-gravity candle flames (described below) are different in that: (a) the shape is approximately spherical rather than elongated and (b) the main reaction zone, as indicated by the visible blue region, is much farther away from the wick. This distance, referred to as the flame standoff distance here, Rs, gives an indication of the magnitude of the heat flux from the flame to the liquid fuel in the wick. In normal gravity and 1 atm pressure, this distance is about 1 mm at the base of the flame; in low gravity or low pressure, it is about 5 mm. Thus the candle in low gravity or pressure produces a flame of much lower power (smaller wax mass burning rate per unit wick surface area) and, based on the diminished soot content, a lower flame temperature. for the reduced pressure, normal gravity case (see Appendix 1).

I. PREVIOUS AND RELATED MICROGRAVITY TESTS

In preparing for the shuttle flight, we utilized both the NASA Lewis Zero Gravity Facility (Lekan, 1989) which offers reported acceleration levels less than 10^{-6} ge with very little jitter for a period of 5.2 sec during the free-fall drop, and the NASA Lewis Learjet. In the former tests, we examined the effects of oxygen concentration, and diluent type on flame behavior (Ross *et al*, 1991). The range of oxygen concentrations that were tested spanned the lowest to highest concentrations expected in Spacelab (19-25% O2). At 19%, the soot content appeared minimal. As the oxygen concentration was raised from test to test, the soot content, determined by the size and intensity of the yellow luminosity of the flame, increased. Regardless of the initial oxygen concentration, the luminosity of the soot diminished continuously throughout the time of the drop. In all cases, a blue outer rim remained, undiminished in intensity (based on visual observation). Because of the lack of convection and the presence of thermophoresis, the soot in low gravity is confined within the fuel-rich region defined by the blue zone. In normal gravity, soot convects across the blue reactive zone producing a much more luminous and larger, visible flame.

Also tested was the effect of ignition in 1ge versus microgravity. Ignited in 1ge, the flame's response to a change in gravitational level was immediate: within 0.04 sec after the drop start, the flame shape became nearly identical to its shape at the end of the drop. Thus, the sensitivity to g jitter is clearly apparent. Much more luminous soot was seen concentrated near the flame top, a residual effect of the 1g ignition and flame.

In the aircraft tests we conducted, as well as independent tests on NASA aircraft (Carleton and Weinberg, 1988), the residual acceleration level and jitter caused severe unsteadiness in the flames, which produced rapid soot flares and flame shape variations (Carleton, personal communication). The flames from our testing were elongated in the direction of the residual acceleration, very sooty, and often emitted smoke through an open tip. These differences from the drop-tower flames further showed how sensitive candle flames are to acceleration levels. Aircraft-based tests were also conducted with two candles (described below).

More recently (post-USML-1), tests were run in the 10 sec drop tower in Hokkaido, Japan; the results were consistent with the previously reported drop tower tests.

II. MOTIVATION FOR SHUTTLE FLIGHT TESTS

Extinction was not observed in any of the drop tower and aircraft experiments; in addition the soot content of the flames burning in air was still evolving at the end of the tests. A long duration, microgravity test then offered the possibility to determine the flame survivability, the sustained mass burning rate, and the flame behavior (e.g. flame oscillations) near extinction. Each of these phenomena was unknown. By having crew member involvement, thermocouple position could be changed to provide information about flame temperature at various locations around the flame surface, emulating the low pressure, normal gravity experiments. Also, the crew could manipulate the igniter or other variables to recover from unexpected events; this proved a vital feature of the candle flame experiments.

Flame interactions (two flames in near proximity) could also be observed. Because the apparent shape of the low-gravity candle flame is approximately spherical, its behavior may be analogous in some ways to low-gravity droplet combustion. It is of interest here to see, in a purely quiescent environment, how two neighboring flames behave; following Williams (Williams, 1985), one might expect the flames to merge when the distance between the base of each hemispherical candle flame is less then 2 times the flame radius, Rf. From a heat transfer perspective, the influence of neighboring flames will help promote and sustain burning, since the heat losses from the flames are reduced by each other's presence. From a mass transfer perspective, however, both flames compete for the same oxidizer, also required for combustion. It is not known *a priori* whether the rate and amount of fuel consumption, and flame(s) lifetime will increase or decrease. For closely spaced candles, where one single envelope flame is established around both wicks, can a stable flame exist since the stabilization point (discussed below) of both flames is effectively quenched? If not, at what separation distance do the interactions become such that a steady flame will exist? Here again, the advantage of a simple space shuttle experiment is apparent: the separation distance and system behavior of two flames may be much more easily adjusted by a trained crew member than by some automated process.

The purposes of the experiments therefore were: to determine if wick-stabilized flames (candles) can be sustained in a purely diffusive, i.e. quiescent, environment or in the presence of very slow, sub-buoyant convective flows; to determine the effect of these processes on the sustained burning rate, flame shape and color; to determine if near-extinction flame oscillations occur in the absence of buoyantly-induced flow; and, finally, to study interactions between two, closely spaced diffusion flames.

III. HARDWARE DESCRIPTION

There were two modules needed to run the experiment: a *candle parts box*, containing cables, igniter wires, candle holders, etc. and a *candlebox* in which the candle was mounted. As shown in fig. 1, the faces of the plastic candlebox are 11.4 cm by 11.4 cm by 0.95 cm thick. There were about 100 0.32 cm diameter holes in each of the six faces. The holes permitted fresh oxidizer to reach the candle but prevented a glove or other material from being accidentally ignited. The box itself provided thermal mass to keep both the combustion products diffusing through the holes and the candlebox itself from being above touch temperature limits.

A candle was normally mounted in the center of the right face. For the two candle experiment, a second candle, whose position was adjustable, was mounted in the center of the left face. Also on the right face of the candlebox was a Viton-covered opening through which the igniter was pushed. Shown also is a translation stage which was capable of moving one or two thermocouples through the flame to obtain temperature; this was not utilized in the experiments.

Candles of 4.75 mm diameter, roughly 1.2 cm long were used; the type of candle was 80% paraffin wax with 20% stearic acid ($C_{18}H_{36}O_2$), a paraffin to impart toughness and reduce the dripping characteristics. The melting temperature was about 68° C. The small size of the candles were to limit the available fuel to about 10 minutes of burning, and to guarantee that the experiment would not exceed Spacelab's maximum allowable concentrations of combustion products.

Ignition was via an electric-powered, hot-wire igniter. The igniter could only be activated if 2 switches, remotely located, were closed simultaneously and if an igniter wire was in place. A retractable shield was available to serve as a flame snuffer and to protect the bare wire in operations. The candlebox was permanently mounted on an aluminum stand 7.5 cm high to ensure its being centered in the glovebox. In the stand were thermocouple displays and electrical connectors. Magnets on the base of the stand held the candlebox to the bottom of the glovebox's working volume.

The flame(s) were observed in orthogonal views by video cameras and in one run by a 35 mm SLR camera (Nikon F4) containing ASA 1600 color film; the camera was operated using the intervalometer feature and aperture bracketing in order to be assured of proper timing between photos and film exposure, respectively. Electric power and video cameras were provided by the glovebox facility. The video data was either downlinked directly or stored on Spacelab video tapes, copies of which were provided after the mission. In addition, data was obtained from an accelerometer mounted to the underside of the floor of the glovebox working volume.

IV. OPERATIONAL SEQUENCE

During launch and reentry, the candlebox and candle parts box were stowed in a foam-padded drawer. In orbit, a payload crew member (either Dr. Bonnie Dunbar or Col. Carl Meade) placed the candlebox inside the glovebox; the candle parts box was attached to the outside of the glovebox. The crew member then removed from the candle parts box the candle(s) and igniter, and installs them inside the glovebox. After the electrical connections were made and verified, the crew set up the cameras focusing on a 2.5 cm x 2.5 cm area around the candle tip and on the thermocouple displays.

The crew member then activated the igniter and lighted the candle(s). Photography and temperature measurements continue until the flame burned to extinction. In some cases, the glovebox fan was then turned on to replenish the glovebox with Spacelab air. After about 1 minute, the next test proceeded.

V. DATA REDUCTION AND ANALYSIS

To ascertain the proper film development process, only 1 of the 4 rolls of color 35 mm film was developed and reviewed; following this review, the remaining rolls were developed. The video tapes were analyzed, frame by frame, on a digitized motion analyzer to determine the flame diameter and heights as functions of time from each test. Quantitative comparisons were made with normal gravity behavior. In addition, the 3-axis readings from the Space Acceleration Measurement System (SAMS) sensor head C (125 samples / sec) were superimposed on the video tapes to synchronize the flame and accelerations, and facilitate correlation. At the time of this writing, the acceleration data was still being analyzed. The log of thruster firings is also being analyzed for potential effects on flame behavior and acceleration traces. Spacelab data suggests that the ambient oxygen concentration was 21.7% in Spacelab; it is assumed that this was the initial concentration in the glovebox prior to the first ignition attempt for each test.

VI. RESULTS

About ten single-candle flame tests were run with the following results. Immediately after ignition, the candle flame was spherical with a bright yellow core. After 8-10 seconds, the yellow, presumably from soot, disappeared, and the flame became blue and hemispherical; these behaviors are consistent with the earlier, short-duration studies (Carleton and Weinberg, 1989; Ross et al, 1991) Typically, the candle flame reached a nearly steady diameter of 1.5 cm (fig. 2). The mass of liquified wax grew, however, and unlike normal gravity, did not drip off because of the small Bond Number ($\rho gl/\sigma$, where ρ is the liquid density, g is the acceleration level, l is the characteristic length, i.e. effective diameter of the liquid, and σ is the surface tension). The shape of the liquid mass was not spheroidal (as might be expected in low gravity), because of the wick and the likely presence of thermocapillary convection. The extent of liquified material also suggests that the influence of thermal conduction from the flame, overwhelmed by buoyant convection in normal gravity, extended much farther into the solid wax in the microgravity tests.

Figure 3 shows the flame diameter and height as a function of time for a single candle experiment. Figure 3a shows that the flame diameter decreases with time for the first ten seconds, after which it maintains a steady value until just prior to extinction. The flame height, shown in fig. 3b on the other hand changed continuously with time until extinction. Figure 3a is just for a single flame, the temporal behavior of each experiment was different. Some flames reached *steady-state* with respect to both diameter and height, and for some both the flame diameter and height changed continuously. The flame diameter and height increased with time for some flames and decreased with time for others. The flames remained soot-free throughout the flame lifetime. Extinction occurred between 40 and 60 seconds for all flames except one[1]. One flame had a lifetime of 105 seconds; this flame started and

[1] For comparative purposes, a candle of identical composition as those used in the shuttle tests was burned in normal gravity in the following manner: a vertical, downward burn orientation (flame above candle), no candlebox, a rectangular sealed box filled with air (21% oxygen) with a physical volume of 12 liters (just under one-half the glovebox volume), the same candle diameter but about 6 cm length. The candle flame survived for 205-220 sec, 2 to 5 times the shuttle results; the longer-lived flame in normal gravity, despite the available oxygen being half that of the full glovebox, illustrates how buoyant convection maintains steep oxygen and combustion product concentration gradients and thereby enhances the local supply of oxygen to the flame zone.

stayed smaller than normal (approximately 0.6 cm) for a long time because it stabilized on only a portion of the wick. This smaller but longer-lived flame, supported by models and discussion described below suggest that oxygen depletion in the candlebox and the overall glovebox volume, combined with ongoing heat losses (e.g. flame radiation to the environment; conduction into the solid), led to extinction.

Surprisingly, each candle flame oscillated spontaneously about 5 seconds before extinction. The flame symmetrically traced back and forth along the candle axis in each cycle (fig. 4). The oscillation had a frequency of about 1 Hz with an amplitude that started small and continued to grow until extinction.

Another surprising result was the inability to sequentially ignite two, proximate candles oriented to face each other on a common axis. The crew attempted ignition with various wick separation distances (4-12 mm), ignition sequences, and igniter locations. After successfully lighting the first candle, the second candle could never be ignited; at no time was a stable flame(s) attained simultaneously on both. In one test, a single candle was lit and allowed to burn to extinction near an unlit second candle. Initially, the single candle flame was not affected by the presence of the second candle. With time, the flame grew closer until its tip was quenched by the wick of the unlit candle, immediately after which the surviving part of the flame rotated asymmetrically around the axis and then extinguished.

For a fraction of a second during one experiment, the residual acceleration level changed from $O(10^{-6}g_e)$ to $O(10^{-3}g_e)$ due probably to a crew movement (a review of the log book on shuttle thruster firing shows that thrusters were not the source of the increased acceleration). Before and several seconds after, the flame was hemispherical and dim. During and shortly after the disturbance, the flame remained hemispherical but became much more luminous, presumably due to enhanced soot production and burnout caused by a small buoyant flow. This appears to further demonstrate the sensitivity of even small flames to convection induced by seemingly benign accelerations; however given that this was the only occurrence of such behavior, it is difficult to state with certainty that this is the source. The acceleration environment was analyzed in terms of frequency content and mean-square spectral density (aka power spectral density). The 17 Hz dither for the shuttle antenna is readily apparent in the analysis. As expected, the flames do not appear to be responsive to the high-frequency components of acceleration.

Also in one test, flashes of flame appeared somewhat randomly in time and space. These were most likely a result of air bubbles trapped inside the solid wax. As the wax was heated and melted, these bubbles expanded and burst. The mixture of fuel vapor, satellite wax droplets, and air then ignited and quickly extinguished upon consumption of the fuel. The acceleration traces did not show any correlation with, i.e. response to, the appearances of the flashes.

VII. DISCUSSION

This investigation sought to provide some experimental evidence toward answering the commonly asked questions "will a candle burn indefinitely (or steadily[2]) in 'zero' gravity in a large volume of quiescent air." These types of questions are often asked because a greater accumulation of combustion products in the absence of buoyancy tends to make the candle less flammable. The classical theory for a spherically-shaped, diffusion flame, however, shows that steady combustion is possible in the absence of buoyancy if the chemical reaction kinetics are fast enough. The oxygen concentration profile, both at steady state, and in transition to steady state, for a spherical geometry are shown qualitatively on Figure 5. At the flame front itself ($r = Rf$), oxygen is completely consumed. The initially steep gradient in oxygen concentration (curve 1 in fig. 5) evolves as time continues, to a flatter gradient (curve 2), with oxygen depletion being apparent farther from the flame front. Eventually the oxygen concentration profile reaches steady state (bold curve) if the surroundings are effectively infinite. To experimentally test candle flammability in air in zero gravity, a long test duration is required because, in addition to the gas phase, the wick and the solid and liquid phases take substantial time to reach their steady states. Unfortunately, ambient oxygen depletion owed to the small glovebox volume and the candlebox complicates the test.

The flame lifetime in the glovebox was estimated, on the assumption that oxygen depletion leads to extinction, to understand the effects of the sealed volume. The estimate is based on solving (numerically) the transient, spherically-symmetric, species conservation equation for oxygen (Appendix 2). The boundary conditions are developed based on the assumption that the candle is a sink for oxygen, and there is no oxidizer flux at the glovebox wall. The analysis assumes a known constant wax mass burning rate, flame diameter (0.1 mg/sec and 1 cm respectively) and the product of the gas density and binary diffusion coefficient of oxygen into nitrogen is a constant (evaluated at 800 K). As shown on curve 4 on fig. 5, the non-infinite ambient suffers from ongoing oxygen depletion. Extinction occurs when the ambient can no longer supply the required oxidizer flux to the flame (curve 5).

The results show that for a candle burning in a spherical volume the approximate size of the glovebox, the flame lifetime will be on the order of three minutes. During this time, the ambient oxygen concentration is significantly depleted. The perforated candle box, however, serves as an impediment to oxygen diffusing to the flame. Modifying the analysis to account for the effect of the candle box shows that the flame lifetime decreases to on the order of 1 minute. During this time the oxygen concentration

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2 Steady state is achieved when the solid- (wax and wick), liquid-, and gas-phase behaviors become invariant with time. For candles burning in normal gravity, there are several initial transients, including the flame size, the wick lengths (the length coated in wax and the exposed length), and the volume of liquified wax. Eventually these reach a balance and the candle flame system is considered to be steady. Often stray air currents cause the flame to move about; also flame flicker is commonly observed in normal gravity. These variations from steady state are well-explained.

inside the candlebox decreases significantly while that outside the candlebox decreases only slightly. The analysis is admittedly not a comprehensive model of candle burning; specifically, the mass burning rate and flame radius may change as oxygen is depleted. This estimate supports the notion that flame extinction was caused by oxygen depletion. We also note, that the long-lived flame was small initially, thus consumed less oxygen, and this resulted in its significantly longer lifetime.

Despite the ability to obtain a true steady state being compromised by the sealed glovebox, we note that the gas phase was quasi-steady, since the flame was invariant over a characteristic gas-phase transport time (e.g. 1-3 x Rs^2/D, where Rs is the flame standoff distance, as previously defined, and D is the average molecular diffusion coefficient), and this time was much smaller than the characteristic time scale over which oxygen was depleted (e.g. Volume of glovebox / Volumetric rate of oxygen consumption, the latter quantity being estimated from equilibrium chemistry, a comparison of Rs in 1g and microgravity, and the known burning rates in normal gravity). Furthermore the flame survived the initial transient when heat loss into the solid is a maximum. Thus a single candle flame can survive indefinitely in zero gravity in air in a large-enough, quiescent, ambient air volume. This conclusion, admittedly, is reached through inference, rather than through experimental demonstration.

To discuss the actual mechanism of extinction, we define a local reactivity as the fuel vapor reaction rate per unit volume and note that it varies from point to point in the flame. Previous modeling results with similar flow configurations (Bergeson and T'ien, 1986) show that the maximum reactivity is located near the flame base for the normal gravity candle flame. The point of maximum reactivity serves as the flame stabilization region for the flame. In zero gravity, the visible flame is entirely blue and its shape is close to a hemisphere. The flame standoff distance is basically the same from any point in the flame. Based on the survival of the flame tip during oscillations, the response of the microgravity candle flame to the nearby, unlit candle, and previous temperature measurements of flames with similar shape and sizes (Chan and T'ien, 1978) one can deduce that in low-gravity the maximum reactivity is located at the top of the candle flame. Since the location of maximum reactivity is the strongest point in the flame, it is the last part to extinguish. In the shuttle experiment, oxygen is gradually depleted as the candle burns. With decreasing oxygen, the reactivity decreases everywhere. The base is the coolest part of the candle flame, hence the reactivity is the lowest and the flame base is the first point to extinguish.

Extinction of flames in normal gravity is usually due to blowoff (e.g. how one extinguishes a match) in which the residence time of fuel vapor in the reaction zone is too short compared to the chemical reaction time. The ratio of these times is known as a Damkohler number, and extinction corresponds to the condition when the Damkohler number falls below a critical value (Williams, 1979). In a quiescent, microgravity environment, the residence time becomes large, and this form of the

Damkohler number (based on adiabatic flame temperature) becomes large; therefore extinction must be due to a completely different mechanism (T'ien, 1986). Extinction in microgravity has sometimes been described as being caused by an accumulation of combustion products around the flame (e.g. Carleton and Weinberg, 1989), but this description, in isolation, is incomplete. Instead, we note that the chemical reaction time (and the rate of heat release), is indeed affected by the local oxygen concentration (linear dependence) which is coupled to the diffusive transport. However, the chemical reaction time and heat release are affected more strongly (exponential dependence) by the flame temperature. The peak candle flame temperature is less than the adiabatic flame temperature by ongoing conductive and radiative heat loss into the solid and to the surroundings. Flame extinction occurs when the lowered flame temperature, owed both to reduced oxygen transport rate and heat loss, decreases the rate of chemical heat release beyond that which can overcome the ongoing heat losses. At this point, chemical reaction effectively ceases.

The above discussion has concentrated on the importance of the gas phase, but the wick/liquid phase is also important in determining the characteristics of the candle flame. Since the fuel is evaporated from the surface of the wick, the mass burning rate of wax from the candle is a function of the length of exposed wick. In many instances (normal gravity) when a candle is first lit and the length of exposed wick is small and/or the mass of liquid wax is also small, the flames are small initially. As the burning proceeds, and the fuel heats up melting solid wax and exposing more wick the flame begins to grow until it reaches a steady-state size. While the wick dynamics cannot explain the significant differences between the normal gravity and reduced gravity flames, they can explain the differences between the different shuttle experiments. Specifically, even though the candles were nearly identical to start with, the length and severity of the ignition process created a different initial condition (length of exposed wick and/or mass of liquid wax) in each test. Also potentially contributing to the test-to-test variation was the variable oxygen concentration in the glovebox.

The flame oscillation before extinction is explained as a flame base retreat and flashback mechanism. As the ambient oxygen concentration decreases, the flame oscillations are initiated when the flame base begins to retreat. Because of their thermal inertia, the liquified wax and wick are still hot, so fuel vaporizes, and the fuel vapor and oxygen diffuse toward each other. Eventually a combustible mixture is formed and a rapid flashback of the flame occurs. This further depletes the ambient oxygen concentration, so that more of the base or weakest part of the flame (compared to the previous cycle) extinguishes, and the cycle repeats. The oscillations will continue, increasing in amplitude as the ambient oxygen is continuously depleted, until the ambient oxygen concentration becomes too low to sustain any part of the flame.

This type of oscillation has also been observed in candles in normal gravity at low pressure (0.14

atm). The frequencies of oscillation are different, however, 6-9 Hz in normal gravity, 0.14 atm versus 1 Hz in microgravity, 1 atm. Previously a buoyant convective flow, even at the low pressure condition, was suspected as being related to the oscillation cycle (Chan and T'ien, 1978). Analysis of the acceleration traces shows that oscillations occurred even in the "most quiet" environments on the shuttle, i.e. when there were no thruster firings and no obvious crew disturbances. At the measured background levels of 10^{-5} to 10^{-6} ge associated with these quiet periods, buoyant convection is estimated at much less than diffusive transport rates. Therefore buoyant convective flow does not appear to be required for the oscillation phenomena. Instead, we hypothesize that the different frequencies are due to the different diffusive transport rates (times) in the two environments and further assume that these transport rates are approximated by the time for fuel vapor transport from the wick to the flame surface. The time scale for diffusion is $1\text{-}3 \times Rs^2/D$; using measured values of Rs = 5.6 mm and 5 mm for µg and 1g, respectively, and an average molecular diffusion coefficient evaluated at 800 K for both, the estimated diffusion time is equal to 0.37 - 1.1 sec for the low-gravity flame and 0.04 - 0.12 sec for the normal gravity, 0.14 atm flame. The magnitude and the ratio of the two times (about 9) are in the range of the experimental data. The identification of time scales does not necessarily explain why oscillations have to occur; this requires a proper phase relationship between the involved processes. In addition, whether this observed oscillation is an instability (oscillation under constant environmental conditions) needs further investigation.

The inability to ignite two candles was somewhat surprising. The range of initial separation distances would produce near-optimal burning in normal gravity. Perhaps more significantly, aircraft-based testing, albeit limited, of the ignition procedure for two candles was successful. Since the candles were lighted *sequentially*, the first flame could have at least two undesirable effects on the unlit candle. First the heat from the first flame may have melted the wax of the unlit candle to the extent that the liquified wax coated the wick of the unlit candle; in this case, ignition is much more difficult to achieve, a result observed firsthand by the crew members. Second, and probably more likely, the wicks in microgravity were within 1 flame diameter, so the oxygen around the unlit candle may have been sufficiently depleted prior to ignition to be unable to support a flame. The aircraft tests did not reveal similar behavior because the residual acceleration level was higher (so residual convective flow provided oxygen locally and causing the large, first flame to promote ignition) and because the time between lighting the candles was greater in the space-based mission. Since the USML-1 mission, these were further investigated via experiments by D. Dietrich in the 10 sec drop tower in Hokkaido, Japan. To overcome both the deleterious possibilities, axially aligned candles were *simultaneously* ignited in the Hokkaido drop tests. At the same wick separation distance (about 1 cm) as in the shuttle tests, both candles were ignited and a merged, roughly elliptical flame was observed, whose temporal and spatial characteristics were still evolving (neither extinction nor steady state was seen) at the end of the drop. This occurred whether or not the candles were ignited in 1g and then dropped, or if they were ignited in microgravity.

VIII. RECOMMENDATIONS FOR FURTHER RESEARCH

The existing shuttle-based hardware performed extremely well, revealed several new behaviors, was developed in a very short period of time and cost literally *orders of magnitude less* than most shuttle investigations. Further tests nonetheless could be beneficial.

Perhaps most importantly, the candle flame behavior should be examined in an experiment where the rate of ambient oxygen depletion is significantly less than in the earlier experiment. This could be readily accomplished since the new glovebox facility is larger and since the safety of the experiment has now been demonstrated. Design and operations will be changed to enable the effect on oxygen diffusion by the perforated box to be minimized. This might mean a wire cage with much larger free passages, the elimination of the cage completely, or use of a larger, but similarly styled box with a larger open volume. This design would not only enable the tests described below, but would verify the flame lifetime calculations and explanations described above. It would also allow for steady state in the gas, liquid and solid phases to be reached.

The previous two-candle, shuttle-based tests were compromised both by the ignition procedure and the close, initial spacing of the candles (which was necessitated by the size of the glovebox and candlebox). With a greater separation distance and a simultaneous ignition, two independent flames should be observable. The preliminary tests in the Hokkaido drop tower verified this behavior. Again, the behavior of these flames was still evolving at the end of the 10 sec test period. Further shuttle testing could involve a much further separation distance, now available because of a larger glovebox volume. At least three kinds of flame interaction tests could be performed: (1) simultaneous ignition of on-axis candles at various separation distances, with the flames allowed to burn to completion; (2) simultaneous ignition of on-axis candles at various separation distances, followed by the slow translation of one candle flame toward the other; and (3) off-axis flame interactions. The existing hardware, in a new, larger perforated container can be utilized for all of these investigations.

One question regarding experimental operations on the shuttle which has emerged since the mission is that the ignition process took longer on the shuttle than in drop facilities and or aircraft. The reasons for this are not yet clear. Variables have been discounted [e.g. that the wicks were too short in the shuttle tests (unlikely, since they were the same length as used on the ground), or the igniter power from the glovebox was lessened in space (also unlikely since this was well-characterized)]. It is only recently realized that the ignition time and method may be an important variable in many, quiescent microgravity combustion experiments. The hot gas expansion associated with ignition may influence the observed flame behavior for far longer times than in normal gravity, where the ignition effect is swept away by buoyant convection. Hot gas expansion has been shown to influence flame spread behavior and even flame survivability (Ross, 1993). Since the mission, other igniter configurations than the one used on the shuttle tests have been examined, and it is believed that a simple change to a coiled wire should speed ignition and minimize the hot gas expansion effect.

The thermocouple measurements planned for USML-1 were never conducted, due to scheduling tradeoffs. These measurements would directly verify the location of maximum reactivity, and measure flame temperatures. Such measurements should be relatively accurate, since the flames are soot-free.

Finally, the effects of slow, controlled air flow over the candle flame can be examined. As noted above, these velocities would be between the diffusive transport velocities, estimated at about 1 cm/sec, and the buoyant convective velocities, estimated at 30-90 cm/sec, found on Earth. The effects of these flows on sooting behavior, flame lifetime, color, and temperature should be noted. Alternatively, various wick and candle diameters might be examined; Villermaux and Durox attributed gravitational effects on wick dynamics as having a significant influence on the flame position (relative to the wick) in their recently published, candle experiments conducted in a centrifuge.

CONCLUSIONS AND CONCLUDING REMARKS

The following conclusions were reached in this experiment.

The flame color, size, and shape behaved in a quasi-steady manner; the finite size of the glovebox, combined with the restricted passages of the candlebox, inhibited the observation of true steady-state burning. Nonetheless, through calculations, and inference from the series of shuttle tests, it is concluded that a candle can burn indefinitely in air in a large-enough, quiescent, microgravity environment.

After an initial transient in which soot is observed, the microgravity candle flame in air becomes and remains hemispherical and blue (apparently soot-free). During the time in which the candle burned, the mass of melted wax increased continuously, suggesting steady state had not yet been reached. The enlarged flame standoff distance, previously observed in drop tower tests, is maintained throughout the burning lifetime. Near extinction, spontaneous flame oscillations, explained as a flashback-quench phenomena, are regularly observed. The frequency of oscillations can be related to diffusive transport rates, and not to residual buoyant convective flow. The fact that the flame tip (the farthest from the solid wax) is the last point of the flame to survive suggests that it is the location of maximum reactivity; this is unlike normal gravity, where the location of maximum reactivity is the flame base.

Accelerations on the shuttle are generally below those which induce a significant buoyant flow for these low-momentum, and therefore very sensitive, flames. As such the shuttle environment should be amenable to several other microgravity combustion experiments. An isolated departure on the order of 10^{-3} ge from the background levels of acceleration appeared to cause temporary sooting of the candle flame.

Two candles in close proximity could not be lit sequentially. This was unlike the experience in aircraft testing, and shows that, at least for these flames, aircraft testing with bolted-down hardware is a poor surrogate for the shuttle. The inability to light both candles in the shuttle experiment may be due to wax coating the wick and / or local oxygen depletion around the second, unlit candle. Post-mission testing suggests that simultaneous ignition may overcome these behaviors and enable both candles to be ignited.

The actions of Bonnie Dunbar and Carl Meade proved vital to the success of these candle flame experiments. The unexpected difficulty in igniting the candles could not have been overcome with software and automation, or at least without years of expensive development of such processes. Instead, the crew took appropriate on-the-spot action which enabled us to observe sustained burning. In addition, the color still photographs proved especially valuable, since they revealed the liquified mass clinging to the wick (invisible on the video cameras).

This seemingly simple experiment has yielded widespread interest from disparate groups -- primary and secondary school students; physics, chemistry, and engineering professors; combustion scientists; and the popular media (Encyclopedia Britannica, Cable News Network, the Associated Press, CBS, and local newspapers). The results continue to engender debates amongst the investigators as well as the forementioned groups, and this may be the most gratifying part of the experience.

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Appendix 1

Estimating and Demonstrating Residual Convective Flow at Low Pressure in Normal Gravity

An order-of-magnitude analysis is made here to estimate the effect of reduced pressure on the buoyancy-induced velocity in air. The estimate can be based on a balance between gravitational force with either inertial or viscous terms in the momentum equation. Using inertia, we get

$$u_{iner} \sim \sqrt{gl\Delta\rho/\rho} \cong \sqrt{gl\Delta T/T}$$

where l is the height of the flame. It is clear that gas velocity is continuously accelerating and the highest velocity in the flame occurs at the flame tip. Using the viscous term, we get

$$u_{vis} \sim \delta^2 g \frac{\Delta\rho}{\mu} \cong \delta^2 \frac{g}{\mu}\rho\frac{\Delta T}{T}$$

where δ is the thickness of the viscous or thermal layer. The choice between eqn. (1) and eqn. (2) depends on the magnitude of the Grashof number:

$$Gr = \frac{\rho^2 l^3 g\Delta\rho}{\mu^2\rho}$$

When Gr > 1, a boundary layer type of flow exists and it is more appropriate to use eqn. (1) since the boundary layer thickness adjusts its magnitude such that u_{buoy} becomes comparable to u_{iner}. When Gr < 1, eqn. (2) gives a better estimate of the magnitude of buoyancy-induced velocity in the flame and δ can be taken as the flame standoff distance, Rs. The pressure dependence in eqs. (1-3) comes from l, Rs, and ρ. The dependence of flame height, l, on pressure can not be determined simply from flame photographs because, at different pressure levels, the soot production varies and masks the actual height of the flame. If we select the blue boundary to define flame height (extrapolation required for sooty flames), the dependence of l on pressure is weak for candle flames. On the other hand, Rs exhibits a strong pressure dependence. At the bottom of the flame, Rs is about 1 mm at 1 atm; everywhere around the flame Rs is about 5 mm at 0.14 atm. The density ρ is proportional to pressure, but $\Delta\rho/\rho$ is about 1 (actually about 0.8) over the pressure range of interest. Thus from eqns (1-3) u_{iner} is only weakly dependent on pressure, u_{vis} can actually increase with decreasing pressure (if the increase of δ^2 is greater than the decrease of ρ), and Gr will decrease with pressure. Evaluating μ and ρ at 900K, we find at normal gravity for a range of selected l:

l (cm)	p (atm)	Gr	$Gr^{0.5}$	u_{iner} (cm/s)
1	1	464	21.5	36
1	0.14	8.6	2.2	36
0.5	1	58	7.6	25.5
0.5	0.14	1.1	1.04	25.5

From this table, we see that, even at low pressure, Gr > 1 for l = 0.5 - 1 cm (the observed low pressure flame height). Using eqn. (1), the buoyantly-induced velocity is estimated at 25 - 36 cm/sec. Thus it appears that the flow is not diminished sufficiently over the tested range of pressure and oxygen concentration, and as such it does not simulate the low convective flow in reduced gravity.

In support of these estimates, a few simple experiments were performed. A low-pressure, normal gravity candle flame was established inside a candlebox identical to that flown in the shuttle, but *without a top* placed inside a large (over 500 *l*) chamber. A top was then placed on the candlebox, and the flame quickly extinguished. Similarly, a low-pressure candle flame was established in a chamber in normal gravity, and then the chamber was released into freefall in the NASA Lewis 2.2 sec drop tower. Shortly after entry into microgravity, the flame extinguished. These demonstrate a significant, residual convective flow was present even in low pressure.

The molecular mean free path, Λ, is proportional to T/P. As pressure is lowered seven-fold (from 1 atm to 0.14 atm), the flame temperature diminishes only slightly (about 10%). Thus, the reduction in pressure has a stronger effect than the reduction in temperature, and Λ increases by about a factor of 6. This will reduce the number of molecular collisions in the reaction zone and broaden the reaction zone thickness.

Appendix 2
Oxygen Depletion Calculations

The problem being considered is that of a spherically symmetric candle flame with radius R1 and mass burning rate $\dot{m}$ burning in a spherical container of radius R2 that allows no oxygen to enter. The following assumptions are made in the development of the model.

1.) Spherical symmetry.

2.) No oxidizer leaks through the flame and the flame burns at stoichiometry at an infinitesimally thin flame front. The radius of the flame front is R1.

3.) The problem is one of oxygen diffusing in air. Neglect the products of combustion.

5.) Body forces on the two species are the same.

6.) No thermal diffusion or thermosolutal effects.

7.) Constant pressure.

8.) The product of the density and the binary diffusion coefficient is a constant.

The following parameters are assumed to be known and are specified.

1.) The mass burning rate of the candle wax, $\dot{m}$. This parameter is also assumed to be constant. Knowing the wax mass burning rate and by assumption (2) allows the mass flux of oxygen to the candle flame to be determined. This is the boundary condition at the flame.

2.) The initial ambient oxygen concentration. This is the initial condition for the unsteady computation.

The species conservation for oxygen conservation is given as follows (Williams, 1985).

$$\frac{\partial Y_o}{\partial t} + v_o \bullet (\nabla_x Y_o) = \frac{w_i}{\rho} - \frac{\left[\nabla_x \bullet \left(\rho Y_o \overline{V}_i\right)\right]}{\rho}$$

By assumption (1) we can write the differential operators as.

$$\nabla_x \rightarrow \frac{\partial}{\partial r}\,,\ \nabla_x^2 \rightarrow \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right)$$

By assumptions (5), (6) and (7) Fick's law of diffusion is valid, and the product of the local oxygen mass fraction and diffusion velocity may be written as.

$$Y_o \overline{V}_o = -D(\nabla_x Y_o).$$

By assumption (8) the Stefan convective velocity may be written as

$$\dot{m} = 4\pi r^2 \rho v_o.$$

With this, the differential equation of oxygen conservation becomes

$$\frac{\partial Y_o}{\partial t} + v_o\frac{\partial Y_o}{\partial r} = \frac{D}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial Y_o}{\partial r}\right).$$

The initial and boundary conditions are:

at $t = 0, r$: $Y_O = Y_{O\infty}$

at $r = R1, t = t$: $\dfrac{\dot{m}}{\nu} = \left\{-4\pi r^2 \rho (v_o + \overline{V}_o) Y_o\right\}_{r=R1}$

at $r = R2, t = t$: $\left\{(v_o + \overline{V}_o) Y_o\right\}_{r=R2} = 0$

The second boundary condition expresses the fact that the oxidizer mass flux to the flame must occur in stoichiometric proportion to the mass burning rate of the candle. The last boundary condition shows that no oxygen can enter from the outside to the inside of the container. ν is the stoichiometric fuel to oxygen (not air) mass ratio. The equation, initial and boundary conditions are then non-dimensionalized as follows.

$$\tilde{r} = \frac{r}{R2}\,,\ \tau = \left(\frac{t}{R2^2/D}\right)$$

$$\frac{\partial Y_o}{\partial \tau} + \frac{\beta}{\tilde{r}^2}\frac{\partial Y_o}{\partial \tilde{r}} = \frac{1}{\tilde{r}^2}\frac{\partial}{\partial \tilde{r}}\left(\tilde{r}^2\frac{\partial Y_o}{\partial \tilde{r}}\right)$$

$$\beta = \gamma\delta\nu$$

$$\gamma = \frac{\dot{m}}{4\pi\rho(R1)D\nu}$$

$$\delta = \frac{R1}{R2}$$

at t=0, $\tilde{r} = \tilde{r}$: $Y_o = Y_{o\infty}$

at $t = \tau$, $\tilde{r} = \delta$: $\gamma\nu Y_o - \delta\frac{\partial Y_o}{\partial \tilde{r}} = -\gamma$

at t = t, $\tilde{r} = 1$: $\gamma\delta\nu Y_o - \frac{\partial Y_o}{\partial \tilde{r}} = 0$

The above system of equations was finite-differenced and solved for the oxygen mass fraction as a function of radial position and time. Only two parameters in the problem need to be specified, γ and δ. The following tabulation lists some of the values utilized.

$m = 1.4\ (10^{-7})$ kg/s

$D = 2.0\ (10^{-4})\ m^2/s$ (~1500 K)

R1 = 0.005 m

$\nu = 0.3$

$\rho = 0.25\ kg/m^3$ (~1500 K)

Resulting in: $\gamma = 0.15$

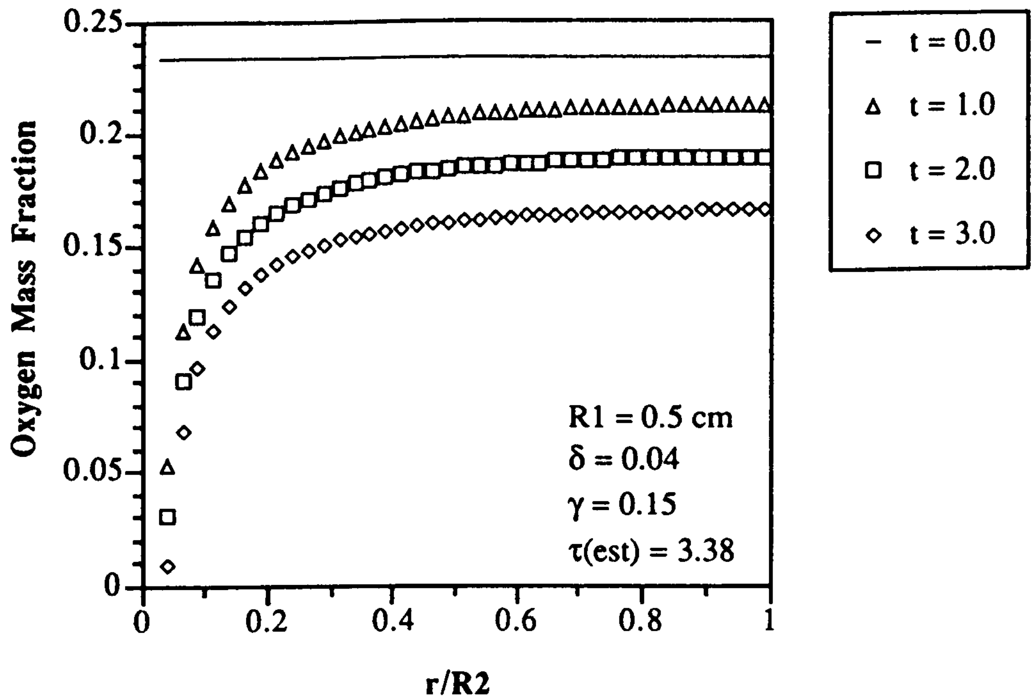
Using the outer dimension of the glovebox for R2, δ becomes

$\delta = 0.04$

The ambient mass fraction must also be input, and its value is :

$Y_{O\infty} = 0.232$

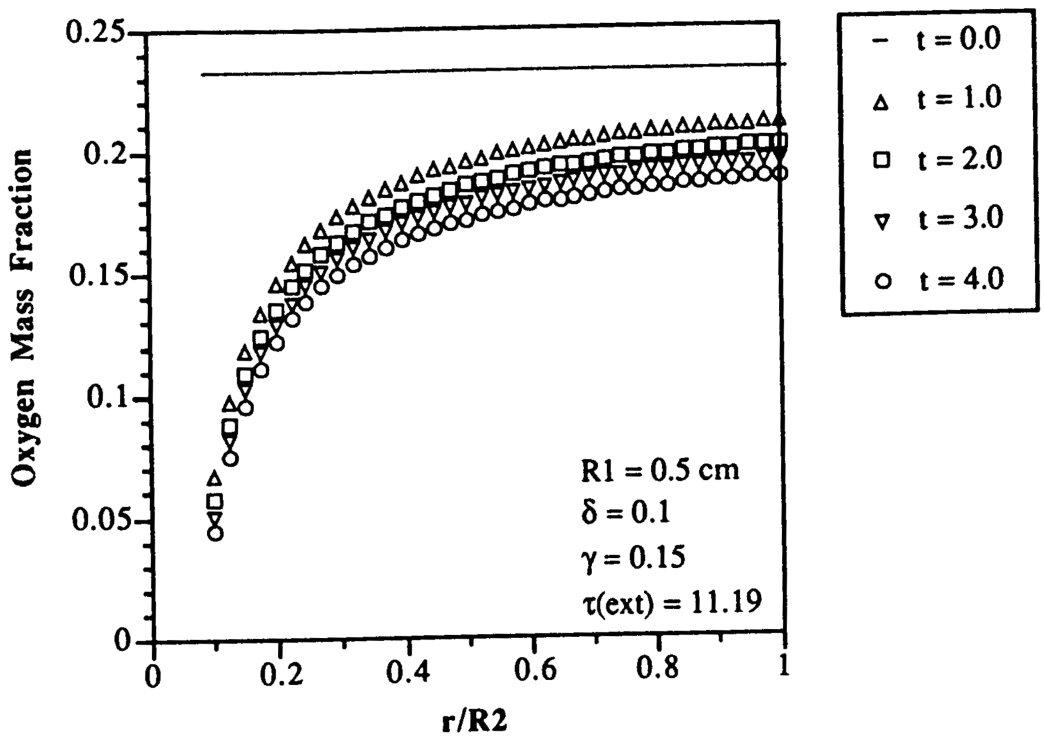
Results were compiled for different values of γ and a fixed δ. Below is a sample result for the oxygen mass fraction as a function of non-dimensional radius for δ=0.4 and γ=0.15. Extinction of the flame is defined as the time at which the oxygen mass fraction at the flame front is less than zero.



Converting to dimensional time using the given parameters shows that for the candle flame above the flame lifetime will be on the order of 4 minutes.

This result does not take into account the impediment to oxygen transport due to the candle box, so the analysis was modified to account the candle box. The surface area of the holes in the box comprised approximately 13% of the total surface area of the box. The model assumes that the candle flame is surrounded by a sphere with radius R2 with 13% free area for oxygen transport. This sphere is surrounded by another sphere with radius R3 in which the boundary condition is no oxygen transport. The spherically symmetric equations above are solved in the regions between R1-R2 and R2-R3 with the boundary conditions of known oxidizer flux at R1 and no oxidizer flux at R3. The interface between the two regions have equal and opposite fluxes; this is used to match the interfacial condition.

Below is a graph of the oxidizer mass fraction as a function of radius for the candle in the candle box surrounded by the glovebox (both times are non-dimensionalized by R2, but the value of R2 is different for the two figures).



The actual time of extinction corresponds to about 2 minutes in this case.

The time at which the oxygen concentration at the flame front, or the flame lifetime, is very sensitive to the value of γ, the non-dimensional mass burning rate. Small values of γ lead to large flame lifetimes, and large values of γ to smaller flame lifetimes. In a more complete model of the candle flame, the mass burning rate and flame radius would be 'outputs' as opposed to 'inputs'. The value of γ is also temperature dependent since ρD is a function of temperature ($\rho D \sim T^{1/2}$). For the γ used above we assumed the density of air and the binary diffusion coefficient of oxygen into air at a mean temperature of 1500 K.

A few words about flame size are in order. The analysis above shows that the oxygen transport to the candle flame is, to a first approximation, determined by γ. γ is not necessarily fixed during the lifetime of the flame. In other words, as oxygen is depleted, the non-dimensional mass burning rate of the candle will change. Given the definition of γ though, it is impossible to know, without a more complete model, how the flame will respond as oxygen is depleted. The mass burning rate of the candle may decrease, the flame radius may increase, only one may change, or both may change. Further analysis of the results of Ross et al. (1990), however, suggests that the near quasi-steady flame size was nearly independent of the oxygen concentration from a 19% to a 25% oxygen ambient. Thus, we conclude that changes in the flame size as a result of oxygen depletion would not necessarily be expected.

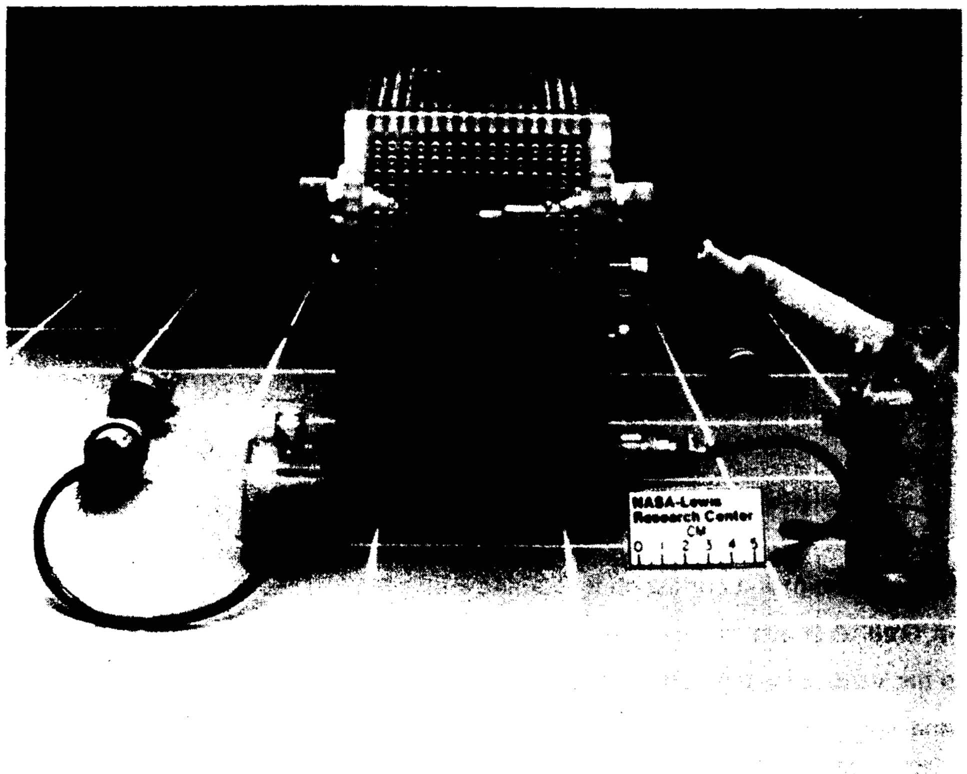


Figure 1 Hardware used in the Candle Flames in Microgravity experiment

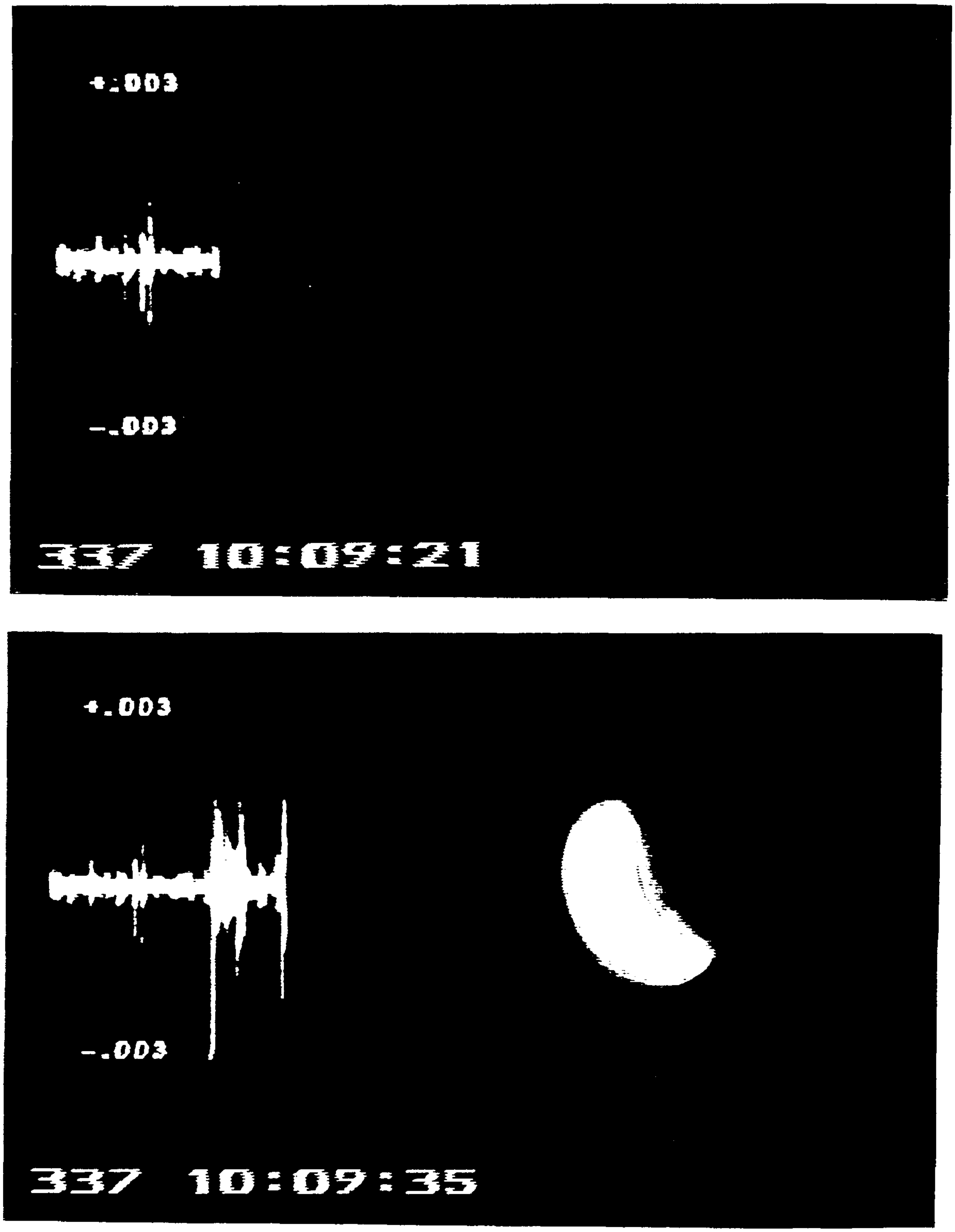


Figure 2 Candle flame in microgravity. On the right is the flame image. On the left is superimposed the SAMS acceleration data from the SAMS-x axis. The vertical scale is in m/sec^2, so divide by about 10 to obtain the value in terms of g_e. (a) Blue, hemispherical flame during quiet period; (b) 14 sec later, sooty flame apparently as a result of increased acceleration level.

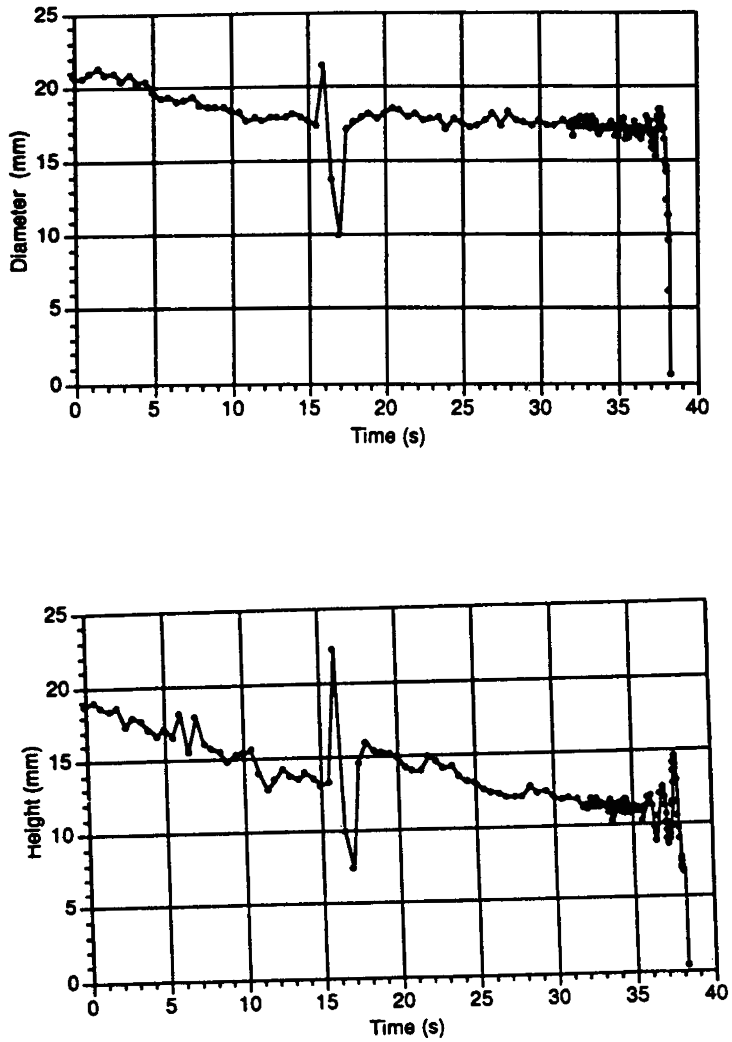


Figure 3 Evolution of flame shape (a) flame diameter; (b) flame height. Note the data showing a wide excursion at 17 sec is incorrect, a consequence of an error in the digitization of the motion analyzer.

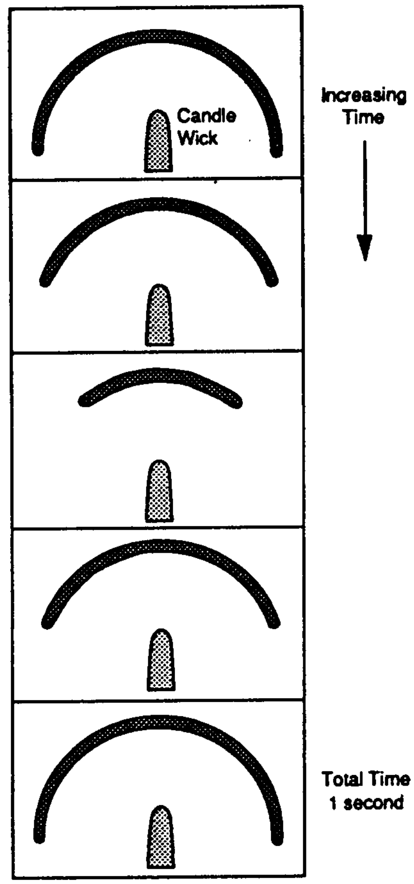


Figure 4 Near-extinction flame oscillations

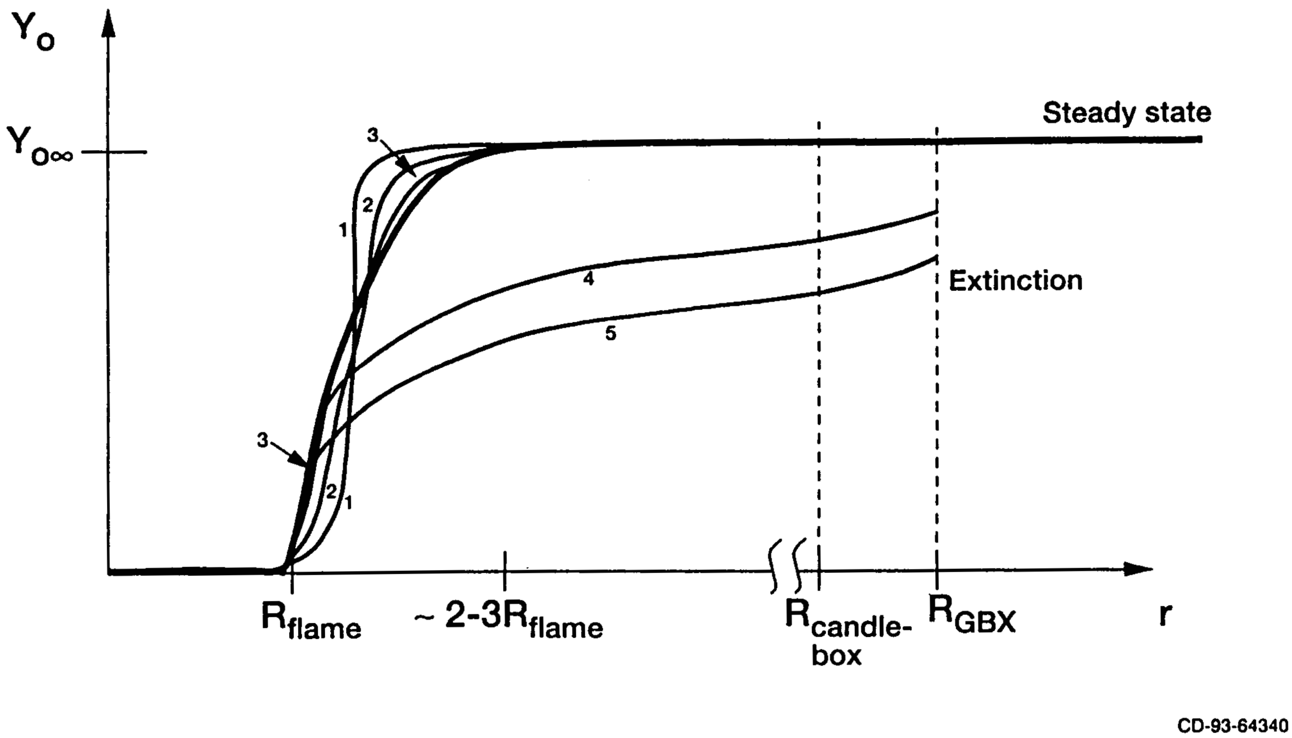


Figure 5 Oxygen concentration profile in the glovebox and at steady state in an infinite ambient with oxygen concentration $Y_{O\infty}$. Curve 1 shows the qualitative profile shortly after ignition, curve 2 at a slightly later time, curve 3 at a still later time, etc. Curves 4 and 5 show when the oxygen concentration in the far field has been somewhat depeleted.