MICROGRAVITY SMOLDERING COMBUSTION ON THE USML-1 SPACE SHUTTLE MISSION

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ABSTRACT

Preliminary results from an experimental study of the smolder characteristics of a porous combustible material (flexible polyurethane foam) in normal and microgravity are presented. The experiments, limited in fuel sample size and power available for ignition, show that the smolder process was primarily controlled by heat losses from the reaction to the surrounding environment. In microgravity, the reduced heat losses due to the absence of natural convection result in only slightly higher temperatures in the quiescent microgravity test than in normal gravity, but a dramatically larger production of combustion products in all microgravity tests. Particularly significant is the proportionately larger amount of carbon monoxide and light organic compounds produced in microgravity, despite comparable temperatures and similar char patterns. This excessive production of fuel-rich combustion products may be a generic characteristic of smoldering polyurethane in microgravity, with an associated increase in the toxic hazard of smolder in spacecraft.

INTRODUCTION

Smoldering is a non-flaming surface combustion reaction that takes place in the interior of porous combustible materials. A smolder reaction will propagate through the porous material if enough heat, generated by the reaction and any external source, is transferred to the unburnt fuel to initiate a smolder surface reaction. However, for the smolder reaction to be sustained, oxygen must also be transported to the reaction zone. The balance between the transport of oxidizer and the transport of energy determines the rate and characteristics of the reaction (Ohlemiller[1], Drysdale[2], Torero[3], Torero, et al.[4]). When the smolder conditions are such that the resulting smolder reaction is vigorous, its rate of propagation is directly proportional to the rate of oxygen supply. When it is weak, however, the rate of heat loss determines whether the reaction will continue to propagate or eventually extinguish (Dosanjh, et al.[5], Torero[3]; Torero, et al.[4]).

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Although smoldering is present in a variety of combustion processes, it is of particular interest in fire safety because of its role as a potential fire-initiation source. It can propagate slowly, undetected, for long periods of time, and suddenly undergo a transition to flaming. The products of smolder combustion themselves are toxic. Recently, with the planned establishment of a space station, there has been an increased interest in the study of smoldering in microgravity because of the potential danger of a smolder-initiated fire in remote facilities. The absence of gravity is expected to influence smoldering through its effect on the mass and heat transport within the smoldering material.

Although considerable work has been conducted to date on smoldering at normal gravity (reviews on the subject can be found in the works of Ohlemiller[1] and Drysdale[2]), very limited information is available on smolder in low gravity. This paper reports the first experimental study of smolder initiation in the extended period of microgravity that is available on the Space Shuttle. These tests are part of an ongoing broader program to study smolder in low gravity.

Cantwell and Fernandez-Pello[6,7], and Torero et al.[8], conducting experiments in a Drop Tower (NASA Lewis, 2.2 sec of ~10^{-5} g) and in KC-135 and Learjet aircraft following a parabolic trajectory (NASA, 20-25 sec ~10^{-2} g per parabola), made some preliminary observations of the effect of gravity changes on the smolder characteristics of polyurethane foam. However, due to the slow propagation of smolder, the short test periods provided only limited information about smoldering in microgravity.

These studies confirmed that in microgravity, as in normal gravity, smoldering is controlled by the balance between the oxygen supplied to the reaction zone and the heat transferred to and from the reaction zone to the virgin fuel ahead. The absence of gravity resulted in an enhancement of the fuel heating ahead of the reaction zone due to reduced natural convective cooling, but also resulted in a decrease in the smolder reaction temperature due to the reduction in oxygen supplied. From these works it was concluded that in microgravity, smoldering would be generally weaker than in normal gravity because of the reduction in the buoyancy-induced oxidizer flow. However, if smoldering occurred under conditions such that it is controlled by heat loss rather than oxidizer flow, then the reduction of convective heat loss in microgravity should result in increased temperatures and a resulting enhancement of the smolder process.

The present work attempts to provide further information about smoldering in a microgravity environment. To provide for extended periods of microgravity, a comprehensive smolder experiment was approved for testing on the Space Shuttle and is now under development. A preliminary set of tests were approved to specifically study the ignition and transition effects of low-gravity smolder. The Spacelab Glovebox on the United States Microgravity Laboratory mission, of the Space Shuttle Columbia, of June/July 1992 (USML-1, STS-50), was used for these preliminary tests. The use of the Glovebox limited the size of the fuel sample that could be tested and the power available for ignition, but had the advantage of much reduced costs and development time. Although the small sample size and low ignition power limits the amount of information to be obtained from these preliminary experiments, the primary objective was to investigate the ignition characteristics for smolder propagation in microgravity. This information would be very useful in the design of the comprehensive smolder experiment to be carried out at a later time in the Space Shuttle.

A series of comparative tests were also conducted in normal gravity. The normal and microgravity smolder characteristics were determined from interpretation of the available temperature histories obtained at several locations within the sample, visual inspection of the smoldered foam sample, and analysis of the post-combustion gases.

I. EXPERIMENT

A. Flight Hardware

The flight hardware consisted of four experiment modules, two data displays, a control box, and four cables. Each module contained a cylindrical foam sample, with an embedded igniter, and a fan to produce a forced flow in the longitudinal direction. A photograph of the assembled hardware, with one module, is presented in Figure 1. The test variables during the experiment were the igniter geometry and the convective environment. Through the use of an axial igniter (as in Figure 1) and a plate igniter, both radial and axial smolder were investigated. For each igniter geometry, a test was conducted in a quiescent environment and with a low-velocity air flow for a total of four test conditions, as shown in Table I.

Each experiment module was a sealed polycarbonate box, nominally 0.15 m x 0.15 m x 0.20 m, filled with dry air at one atmosphere pressure. The fuel consisted of a 50 mm diameter, 80 mm long cylinder of open-cell, unretarded, white flexible polyurethane foam, with a 26.5 Kg/m^3 density and 0.975 void fraction, which weighed 4 grams. The fuel sample was positioned axisymmetrically in a polycarbonate tube, 76 mm in diameter, that had a fan at one end to provide a convective flow past the sample. The fan was oriented to pull the air past the foam, and screens were placed at both ends of the cylinder to improve flow uniformity. For the quiescent tests, large sections of the tube were removed to provide free exchange of air throughout the module. Hot-wire measurements of the fan-induced air flow indicated that the velocity around the foam sample was of the order of 100 mm/sec. Indirect observations indicate that the fan also induces a localized flow through the foam. No measurements were made, however, of this internal flow. The plate and axial igniters were resistively-heated elements, consisting of nickel-chromium wire sheathed in ceramic.

The axial igniter was 95 mm long and 3 mm in diameter, but only 42 mm of its center section was heated. The plate igniter was 7 mm thick, 51 mm in diameter and was sandwiched in the foam, centered at 20 mm from the fan end of the fuel sample, such that the smolder wave propagated along the length of the sample in both directions away from the igniter. With the fan on, the air flow through the sample results in an opposed-flow smolder upstream of the igniter, and a forward-flow smolder in the downstream region. The axial igniter ignited the fuel sample along the centerline such that the smolder wave propagated radially outward toward the edges of the cylinder. The maximum igniter power was approximately 29 watts, due to Glovebox limits.

The foam sample was instrumented with six sheathed, cold-junction compensated, chromel-alumel thermocouples, 0.5 mm in sheath diameter, to measure the smolder reaction temperature and its propagation throughout the sample. A seventh thermocouple was used to measure the local gas-phase temperature outside the foam. The positions of the six thermocouples within the foam sample are indicated in Table II, for the modules with an axial igniter. The output of the thermocouples and the igniter current was recorded with a video camera through the use of two data displays (with four readings each). A second video camera viewed the side of the smoldering sample.

B. Experimental Procedure

Testing a single module at a time, the hardware was assembled by the crew member within the Glovebox. Prior to ignition, the fan was activated for those tests requiring air flow. The igniter was then energized and the current potentiometer was adjusted to the appropriate level. Power was applied for 10 to 24 minutes, depending on the test. The progress of the smolder reaction was observed for up to an hour through the temperature displays, the smoke production, and the discoloration or charring of the foam. After the test was completed, the hardware was disassembled and the module was stowed. The four planned smolder combustion tests were successfully conducted during the USML-1 mission, the first by Dr. Lawrence DeLucas, and the following three by Col. Carl Meade.

Following the mission, gas samples were drawn from the modules for analysis and the foam samples were removed for inspection. Normal-gravity tests were conducted in the flight hardware to allow comparison of the smolder characteristics in normal gravity and microgravity. These tests were identical to those conducted in space in regards to the igniter power, flow conditions, and time sequence. The comparison normal-gravity tests were conducted with the foam samples in a horizontal orientation, such that the gravity vector was perpendicular to the axis of the foam. Additional tests were performed with other foam orientations to observe the effect of gravity on the normal-gravity smolder.

The test nomenclature and specific test conditions are listed in Table I. The nomenclature used to describe the four tests is based on the order that the tests were conducted in during the USML-1 mission. During the first microgravity test (1.0), there was a malfunction which affected the display for thermocouples 5 to 7. During the mission, it was not clear whether the malfunction also affected the igniter current reading which was on the same display. The uncertainty about the igniter current and a concern about exceeding the Glovebox power limits prompted the authors to have Dr. DeLucas reduce the igniter power to a level determined from normal-gravity igniter characterization testing. However, the resulting heating rate was less than desired, so the igniter power was then increased to an intermediate level, bringing the heating rate to an acceptable level. The malfunction did not reoccur during the mission; it was later determined to be the result of a failed reference junction, for thermocouples 5 to 7, located on that single module. Tests 2.x to 4.x were all conducted with the maximum ignition power available from the Glovebox.

During test 2.0, the fan was shut off at approx. 8 minutes, per the nominal test procedure, because the measured igniter temperature fell below the desired level. The igniter temperatures also fell below the desired level in test 4.0, but at the authors instruction, Col. Meade kept the fan on, in order to simplify the interpretation of the results. As previously described, these procedures were duplicated in the comparison normal-gravity testing.

II. RESULTS

The test results are based on the temperature histories provided by the thermocouples, a visual inspection of the burnt foam samples, and the composition of the post-combustion gases. Since the temperature data for the plate igniter tests (3.0 and 4.0) is not yet available, the results and conclusions will primarily deal with the axial-igniter tests (1.x and 2.x). The results from the plate-igniter tests are only briefly reported.

A. Temperature Histories

The temperature histories provided by thermocouples 1 to 4 in the microgravity and normal-gravity experiments for test 1 (axial igniter/fan off) and test 2 (axial igniter/fan on) are presented in Figures 2 and 3, respectively. The temperature histories for the other thermocouples will not be presented here. They were positioned near the surface of the foam to detect flaming, which did not occur in any of the tests. Note that the thermocouple temperatures have not been corrected for heat loss. Given the relative mass of the thermocouples as compared to that of the foam, it is possible that the measured temperatures were significantly affected by conductive losses. Normal-gravity tests also suggest that the temperatures may have been depressed due to the thermocouple's compression of the foam, which may have locally inhibited smolder.

The result of the irregular ignition profile in test 1.x, as previously described, can be seen in Figure 2 for both microgravity and normal-gravity runs. It is evident from the temperature histories that the smolder self-extinguished at both gravity conditions. All four thermocouples reached peak temperatures at about the same time. If the smolder was self-propagating, the temperature histories would indicate the radial propagation of the smolder wave, with peaks of about 400°C displaced in time. All four temperatures dropped after the peak temperature was reached, even though the igniter was still energized. The temperatures dropped rapidly after the igniter was turned off at 9.5 minutes, which demonstrates the large conductive losses for these small samples. The igniter current was held steady at 3.9 amps from 4.0 to 9.5 minutes, so the initial drop in temperature must be due to a decrease in the heat of the reaction, as will be discussed later.

From a comparison of the microgravity and normal-gravity temperature profiles, it appears that gravity had a limited effect on the temperature histories. The peak temperatures were greater in microgravity than normal gravity for all four thermocouples, with the difference increasing with distance from the igniter. Whereas the peak temperature difference was about 16°C at the igniter, it was 50°C at thermocouple 4, which is 5 mm from the foam surface. The temperature difference is presumably due to buoyant cooling in normal gravity, which would be most strongly felt near the surface of the foam.

The temperature histories for test 2.x, shown in Figure 3, can be more easily interpreted, as the igniter was held at a constant power. In general, the temperature profiles are similar to those for test 1, except for the irregular heating profile in test 1. Extinction is again indicated by the temperature profiles; the temperatures drop slightly while the igniter is energized, and rapidly when the igniter is turned off. However, test 2.x has the unusual feature that the fan was initially on, and then turned off at approximately 8 minutes. Deactivating the fan caused the igniter temperature to gradually increase about 23°C in microgravity, until the igniter was turned off. Meanwhile, at thermocouples 2 to 4, the temperature rose 35 to 43°C in microgravity. In normal-gravity, the deactivation of the fan caused a minor temperature increase of 6 to 11°C. After the fan was shut off, the temperatures were found to increase the most at the thermocouples nearest the foam surface, in both microgravity and normal gravity. This observation is not surprising, since the convective heat loss is the strongest near the foam surface. The temperature increase associated with the fan deactivation was presumably smaller in normal gravity due to the continued presence of the buoyant cooling.

The contribution from the igniter was measured in normal gravity by insulating the igniter with fiberglass insulation and recording the temperature history in the absence of smolder. This data is plotted in Figure 4 along with the igniter temperatures from runs 2.0 and 2.1. The resulting difference in temperatures is approximately the contribution from the exothermic smolder reaction. In both tests, it can be deduced that the reaction started at approximately 1.5 minutes and increased until 4 minutes, at which time the reaction decayed to extinction. Extinction appears to have occurred at some point between 4 and 7 minutes. The differences in the two tests is not believed to be significant. In test 2.x, it is also notable that the peak temperatures (prior to the fan deactivation) for the two gravity conditions are within 15°C of each other, for all four thermocouples. This suggests that the low forced flow may have been comparable to any buoyant effects during the smolder. The temperature histories of Figures 2 and 3 can be used to roughly calculate smolder propagation velocities using the method previously developed for ground-based experiments (Torero, et al.[4]). The smolder velocity is calculated from the known distance between two consecutive thermocouples and the time lapse for a given temperature to be attained by the thermocouple. That time is determined by the intersection of the tangent to the temperature curve at the inflection point and a horizontal line at the pre-established temperature (350°C). This technique is not truly applicable for this experiment since the measured temperatures did not reach 350°C, except at the igniter. However, approximate information about the smolder propagation velocity can be obtained by extrapolating the tangent of the temperature curve (at the inflection point) until it reaches the 350°C. From the temperature histories of run 2.0, using this technique, it is found that the resulting smolder velocity decays from approximately 0.08 mm/s between thermocouples 1 and 2, to 0.04 between thermocouples 2 and 3, and to 0.02 mm/s between thermocouples 3 and 4. Thus, the smolder was not steady but decayed to extinction. Similar trends are obtained from the temperature histories of test 1. For an average smolder velocity of 0.04 mm/s, and a smolder wave propagating for approximately 18 mm (from thermocouple 1 to 4), the smolder time was estimated to be 7.5 minutes, which is roughly consistent with the temperature profiles of Figure 3. The smolder propagation velocities obtained for the normal-gravity tests experiments are similar. The calculated smolder velocities are of the same order of magnitude as those measured in larger experiments of opposed-flow smolder at low flow velocities (0.5 mm/sec) and natural convection smolder (Torero[4]). They correspond to the "weak" smolder cases tested. The maximum smolder velocities measured in those experiments were obtained for flow velocities of 3 mm/sec and were of the order of 0.15 mm/sec.

B. Char Patterns

During the testing, the smoldering foam was observed to expand and smoke, much of which later condensed as a yellow residue on the module interior. Upon removal after testing, the samples were cut open to reveal the extent of the smolder propagation. Photographs of the smoldered samples from tests 1.x and 2.x are shown with microgravity samples in Figures 5 and normal gravity samples in Figure 6, respectively. Each sample was cut in half on its axis; the interior view of a single half is shown. The normal-gravity tests were conducted with the sample in a horizontal orientation; with the gravity vector oriented down.

The plane of the cut for each sample was selected to include the igniter thermocouple. In most of the samples, the position of the igniter thermocouple can be seen as a narrow dark line. The dark line results from charring from the hot thermocouple, suggesting that thermocouple measurements could have been significantly affected due to conductive heat loss along the thermocouple. The narrow width of the charred line implies that the conduction along the thermocouple had a localized effect and probably did not effect the smolder propagation in general. This is not surprising, given the foam's low thermal diffusivity compared to that of the thermocouple sheath.

In the char pattern for test 1.0, it can be seen that smolder propagated symmetrically outward from the igniter, in an oval shape. The dark charred region extends to within about 1 cm of the sample edge, except at the ends of the sample. A pyrolysis zone, typical of foam exposed to low temperatures, is visible as a light brown discoloration. This zone is roughly 5 mm thick, indicating that the smolder reactions reached within about 5 mm of the surface. Accounting for the limited propagation at the ends, it is estimated that the char and pyrolysis regions include about 50% of the sample volume. Based on previous studies (Ohlemiller[1]; Torero[3]), the extent of the propagation was somewhat surprising for the low temperatures measured. However, it is in approximate agreement with the propagation velocities estimated from the temperature histories.

The char pattern from normal-gravity test 1.1 was found to be similar to the pattern from test 1.0. The visible extent of propagation was similar in both tests, but there were two notable differences.

First, large voids, on the order of 1 cm long, were created in the normal-gravity char region, whereas there were none apparent in the microgravity char. The voids were found in other, but not all, of the normal-gravity tests and none of the microgravity tests. It is speculated that the voids result from gravitational forces on the weakened polymeric structure, but it is not clear what controls their occurrence. A close comparison of the char structure of the microgravity and normal-gravity tests also shows significant differences. The normal-gravity voids had a crust of melted material which appeared to clog the foam pores. Microscopic observation of the normal-gravity char showed that discolored filaments in some cases had melted into spheres. Furthermore, strong signs of fuel pyrolysis could also be observed at the edges of the char region. These observations are typical of a low temperature smolder process (Dosanjh[5], Torero[3]). In contrast, the char in the microgravity samples was more typical of high temperature smolder with a fibrous, relatively dense structure, despite the similar temperature profiles.

Second, the effect of gravity is also evident even in the presence of forced convection in that the normal-gravity smolder did not propagate as far in the downward direction. In normal-gravity, natural convection induces an upward air flow, inhibiting the downward (opposed) propagation of the smolder, as seen in Figure 6.

With the fan-induced concurrent flow in test 2.x, the smolder also propagated substantially farther toward the fan, particularly in microgravity. The dark char, with forced flow in microgravity (test 2.0), reached within about 5 mm of the fan end of the sample, whereas the char was roughly 1 cm from the end without flow (tests 1.0 and 1.1). The char, with forced flow in normal-gravity (test 2.1), was also about 1 cm from the end. The pyrolysis zone, with forced flow at either gravity level, reached to (or nearly to) the end of the foam, unlike the quiescent tests. A close inspection of the samples from test 2.x has also revealed significant concentrations of tar at the fan end of the sample, again particularly in microgravity.

In the upstream end of the foam, the forced flow had a minimal effect in microgravity. The shape of the dark char region appears to be slightly more streamlined (≈1 mm) with flow (test 2.0), than without (test 1.0). The char region with flow is slightly wider within 0 to 2 cm of the upstream end. Convective effects noted at both ends of the fan thus suggest that the smolder and pyrolysis were enhanced by convective mass transport in this region.

Except for the fan end, normal-gravity tests with the foam oriented vertically so that the forced flow opposed the buoyant flow show smolder patterns that are similar to the microgravity ones. This suggests that the two convective effects counteract one another in this region. At the fan end, however, the char patterns indicate that in this region, the fan-induced flow enhances smolder, especially in microgravity. Whether the fan-induced flow is stronger or weaker than that induced by natural convection is difficult to determine, since we do not have direct measurements of the flow velocity inside the foam, we can only use this type of indirect observation to infer the flow pattern in the sample interior.

The tests with the plate igniter show similar results to those for the axial igniter. The char region forms a hemisphere with the center plane at the igniter, except downstream from the igniter in the microgravity experiment when the fan is on, where the smolder is enhanced, as in the test 2.0. The dark char region extends about as far from the igniter as with the axial igniter. However, it appears that the light-colored pyrolysis zone extends somewhat further along the axis, away from the fan, presumably due to the distance from the foam surface and the subsequent insulation from heat losses.

C. Gas Analyses

The results of the analyses of the post-combustion gases are presented in Table III, for the microgravity and normal-gravity tests. Only the major components have been included in this report. The results are based on analyses, performed at the Toxicology Laboratory at NASA Johnson, with both Gas Chromatography (GC) and Gas Chromatography/Mass Spectrometry (GC/MS).

Oxygen depletion and the production of carbon dioxide, carbon monoxide, and hydrocarbon species are good indicators of the combustion reaction characteristics. However, in interpreting the data, it should be kept in mind that smoldering is a low-temperature surface reaction that is generally oxygen limited. It is seen that the microgravity smolder tests produced significant amounts of carbon monoxide and carbon dioxide, as well as a number of light organic compounds. These species are characteristic of pyrolysis and oxygen-limited combustion. It is believed that the chlorinated compounds are contaminants resulting from the methylene chloride that was used to solvent bond the joints in the polycarbonate modules.

Comparison of the species concentrations reveals that the amounts of the gaseous products roughly corresponds to the time that the igniter was on, for a specific gravity level. This observation suggests that fuel pyrolysis may have contributed significantly to the production of gaseous components.

Microgravity test 2.0 (axial igniter, fan on) produced the largest concentrations of combustion products. This test did have the greatest smolder propagation, particularly toward the fan. However, the difference between the products of tests 1.0 and 2.0 is far too great to only result from this difference in the smolder propagation. This implies that the smolder consumed a larger amount of fuel per unit volume in microgravity than normal gravity.

The normal-gravity tests produced these species in substantially smaller amounts than the microgravity tests. This is somewhat surprising, since the extent of smolder propagation as apparent in the char patterns was not strongly effected by gravity for any of the tests. Yet in all cases, the amount of carbon monoxide was much greater (89 to 3900 ppm) than that produced in normal gravity (<3 to 6 ppm). This suggests that the reaction may have been oxygen limited. In most cases, the microgravity tests produced twice as much carbon dioxide as the normal-gravity tests. It must be kept in mind that the measured temperatures were too low for the gas-phase oxidation of carbon monoxide (Glassman[9]).

Methane is evident in the microgravity cases at 17 to 570 ppm, whereas no methane above 5 ppm is detected in the normal gravity samples. Also, propene is present in the microgravity samples at 12 to 107 ppm, and it is not detected (limit = 0.2 ppm) in the normal gravity ones. Other products (e.g., 2-propanol) are detected in the microgravity samples and are undetected, or weakly detected, in the normal-gravity samples.

III. DISCUSSION

A. Heat Losses

That heat losses are an important factor in the smolder propagation for the present experimental conditions in microgravity as well as normal gravity is somewhat unexpected and specific to the smolder (not flaming) combustion process. Since air has such a low thermal conductivity and mass diffusivity, one would expect that with the absence of natural convection in microgravity, the heat losses to the environment would be small and that the deterrent to the progress of the reaction would be a small supply of oxidizer to the reaction zone.

However, these concepts are somewhat modified by the fact that the smolder process is very slow, and consequently, the characteristic time for smolder propagation can be significantly smaller than that for diffusion of heat and mass. With a thermal diffusivity for air of $5x10^{-5}$ m^2/s and a characteristic length of 25 mm (based on the foam radius), the characteristic times for heat and mass diffusion are of the order of 12.5 seconds (Lewis number assumed unity), which is relatively small compared with the characteristic time of smolder propagation, which with a smolder velocity of 0.05 mm/s and a characteristic sample length of 25 mm is of the order of 500 seconds. The diffusive time scale agrees well with the experimental time scales for cooling after the igniter is deactivated. Thus, from the point of view of transport of mass and heat, the smolder reaction is basically stationary and there is ample time for the heat and mass to diffuse to and from the reaction zone.

If the sample size is small, as it is in this case, the percentage of the heat generated by the smolder reaction that is transferred by conduction to the surroundings becomes increasingly significant as the smolder propagates away from the igniter and the contribution of the external heat source (igniter) is diminished. When the percentage of heat generated by smolder becomes insufficient to overcome the heat losses due to conduction, the smolder reaction weakens and extinguishes. Under these conditions, the smolder process is very sensitive to heat losses, and consequently controlled by heat transfer processes (Torero, et al.[4]). The oxidizer and combustion products have enough time to be transported in and out of the reaction zone at their corresponding diffusion rates which, although small, should be sufficient to support at least a weak smolder reaction. If the sample size were increased, however, and the ratio of heat losses to heat generation decreases, the smolder process would becomes increasingly controlled by the supply of oxidizer, and it may reach the point that diffusion of oxidizer may not be sufficient to sustain the reaction.

B. Mass Transfer

Because of the similarity in the temperature fields and the extent of the char patterns, it is surprising that such dramatic differences in the combustion products are noted. The key to understanding this may be in the flow fields in microgravity as compared to normal gravity. In the absence of buoyant convection, the flow is strictly due to the fan, when it is activated. Due to the relative pressure drops in the annulus around the foam and through the foam, most of the air flow is believed to travel around the perimeter of the foam except near the ends of the foam when the two pressure drops become comparable. Significant flow through the foam end in microgravity is observed via the tarring in microgravity Run 2, which supports this flow analysis.

If the flow in microgravity is primarily annular except as noted above, then the primary source of mass transport within the central region of the foam is diffusion. This would provide longer residence times in the reaction zone for the heavy fuel fractions, and may result in a higher degree of fuel cracking. In normal gravity, the local buoyant flows generated within the foam results in shorter residence times in the reaction zone, and thus in fewer cracked fuel components and a greater degree of recondensation of heavy fuels on the pyrolyzing fuel.

CONCLUSIONS

The present experiments, although limited in fuel sample size and igniter power, provided valuable information about the smolder characteristics of a porous polymeric fuel in microgravity. The following conclusions can be drawn from these preliminary tests.

(1) Temperatures in microgravity were in general similar to those measured in normal gravity, with only a slight increase in microgravity temperatures noted in the quiescent test, where convective losses are effectively eliminated. The effect of the fan as a source of convective cooling is clearly noted in microgravity, and provides cooling of similar magnitude as normal gravity natural convection.

(2) Char patterns were also similar between normal and microgravity samples, with the effect of gravitational orientation having a minor effect on the char patterns. The major differences note were 1) the char was more uniform and fibrous in microgravity as compared with the irregular voids found in the char from normal gravity; and 2) significant deposits of tar were discovered at the fan end of the sample from run 2.0. This indicates the presence of the flow through the foam end, which presumably enhanced the deposition of the tars in this region.

(3) Under the present conditions of fuel size and external heating, the smolder process was in a "weak" regime because the heat losses from the reaction zone were significant in comparison to the heat generated by the reaction. Under these conditions, smolder was primarily limited by heat losses from the reaction to the surrounding environment. This is in contrast to the short-duration aircraft tests which indicated that the oxygen supply was the controlling mechanism for larger samples. It remains to be demonstrated which mechanism is truly controlling when both extended microgravity periods and large sample sizes are available.

(4) Despite similar temperatures and visible extent of smolder, significant production of light combustion gases was found to have occurred in microgravity, possibly due to the longer residence times in microgravity due to the absence of natural convection. Of particular note, the microgravity levels of carbon monoxide were orders of magnitude higher than that observed in the normal-gravity tests. This may be a specific result of smoldering in a microgravity environment, which would imply that microgravity smolder products may be more toxic than smolder products produced on Earth.

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TABLE I: TEST CONDITIONS

Run	Gravity	Igniter Shape	Ignition Current (amps)	Ignition Time (min)	Air flow	Notes
1.0 1.1	μG 1G	Axial	4.2 to 2.5 to 3.9	9.5 9.5	No	Irregular ignition profile, due to data display malfunction
2.0 2.1	μG 1G	Axial	4.2	15.5 15.5	Yes	Fan turned off at approximately 8 minutes
3.0 3.1	μG 1G	Plate	4.2	_22 15.0	No	Igniter turned off for brief time at approximately 18 minutes
4.0 4.1	μG 1G	Plate	4.2	24.3 15.0	Yes	Fan kept on, contrary to nominal procedure (at the authors' direction)

TABLE II: THERMOCOUPLE POSITIONS AXIAL IGNITER (1.x AND 2.x)

TC	Position (mm)	
	Radial (from axis)	Axial (from fan end)
1	2 (at igniter)	50
2	10	45
3	15	40
4	20	35
5	5	2
6	10	7

TABLE III: ANALYSIS OF THE POST-COMBUSTION GAS SAMPLES

Compound	Microgravity				Normal-Gravity			
	1.0	2.0	3.0	4.0	1.1	2.1	3.1	4.1
Oxygen	21%	19%	21%	20%	20%	20%	20%	20%
Nitrogen	78%	79%	78%	78%	79%	79%	79%	79%
Hydrogen	ND	40	ND	ND	ND	ND	ND	ND
Methane	17	570	96	180	ND	ND	ND	ND
Carbon Monoxide	89	3900	150	610	4.0	Trace	Trace	5.5
Carbon Dioxide	2300	7400	7600	10700	2100	3000	3300	3800
Propene	15.2	107	12.1	43.8	—	—	—	—
Acetaldehyde	6.33	117	36.4	85.1	120	66	66	150
Propanone	25.8	47.7	4.89	40.9	41	18	13	26
Propanal	ND	7.91	ND	ND	13	4.4	ND	9.1
2-Propanol	6.08	19.0	0.18	13.2	3.7	1.0	0.83	3.7
Dichloromethane	63.5	70.7	70.3	49.7	46	26	44	46

ND: Not detected; limit is 3 ppm for carbon monoxide, and 5 ppm for hydrogen and methane.
Trace: Amount detected is sufficient for compound identification only.
— : Not reported in analysis.

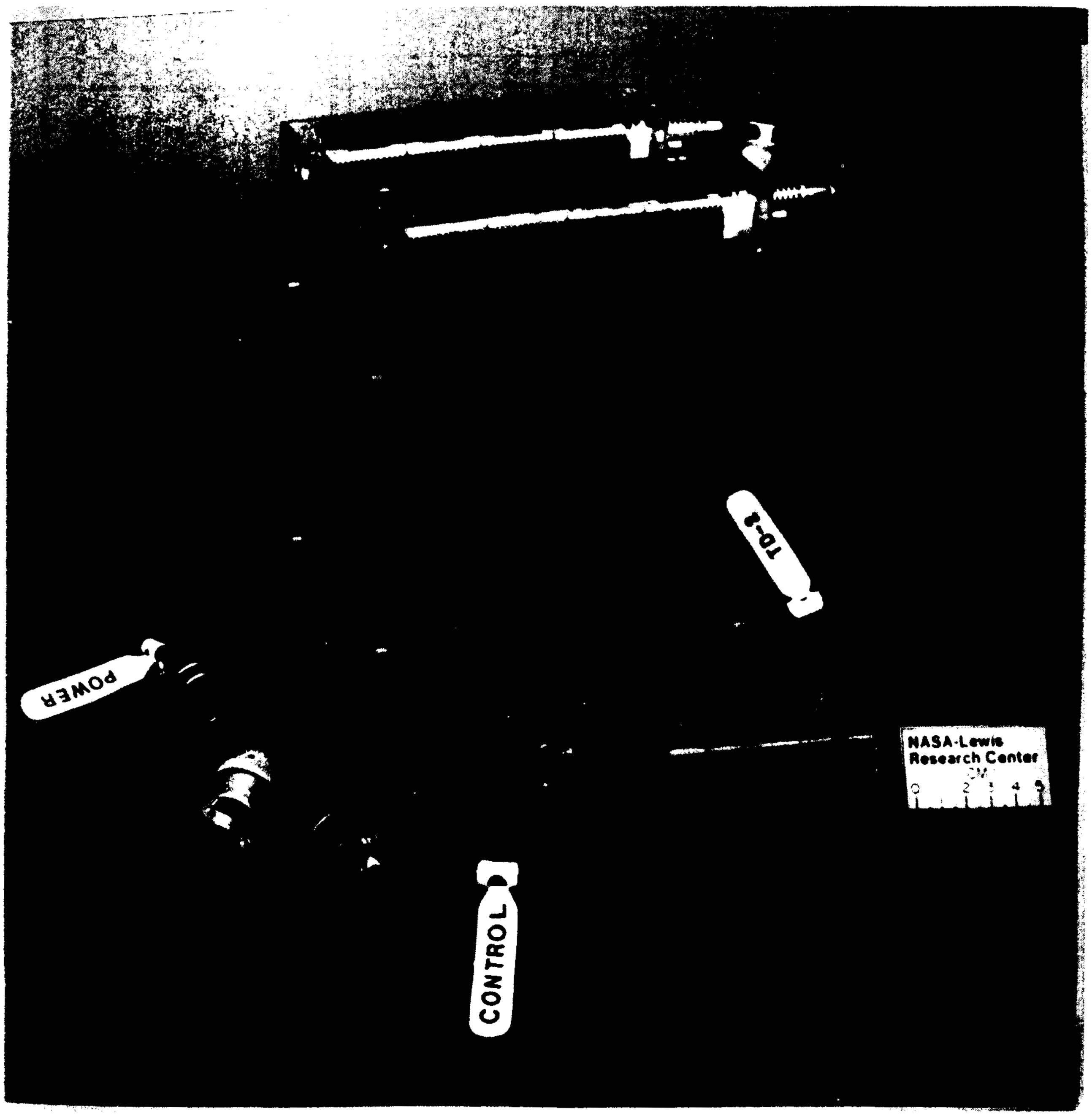

Figure 1 Flight Hardware assembled for a test with an axial igniter.

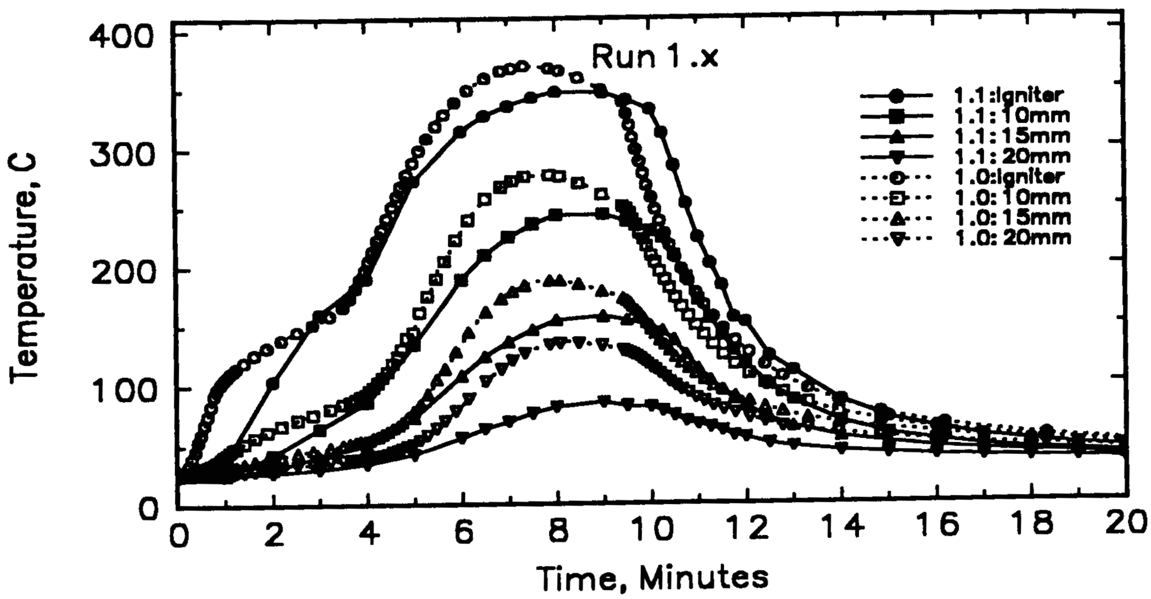

Figure 2 Temperature data from Runs 1.0 and 1.1; (Fan off); Thermocouples 1 to 4.

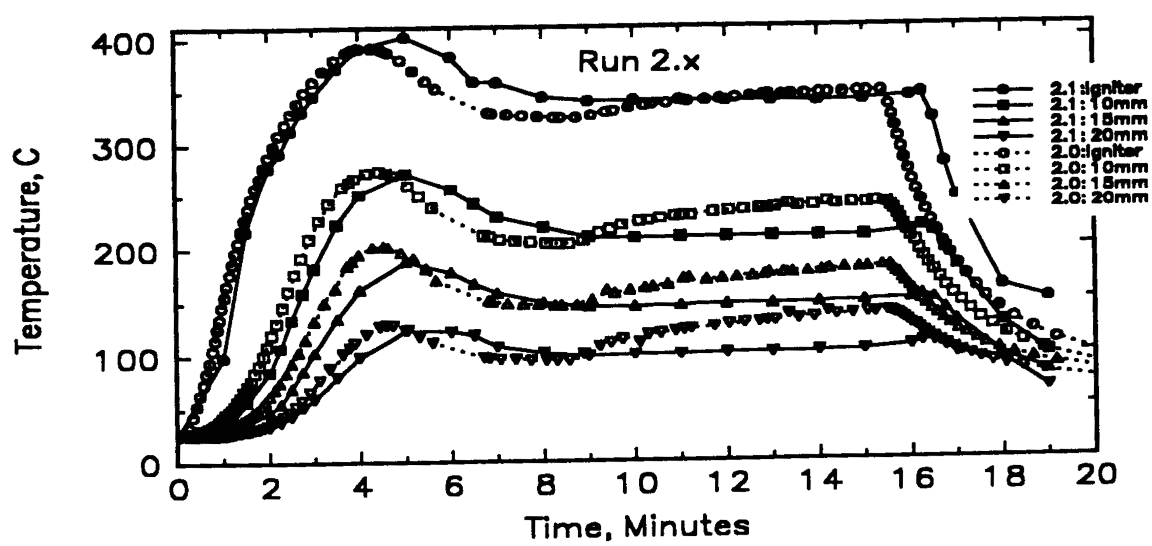

Figure 3 Temperature data from Runs 2.0 and 2.1 (Fan on); Thermocouples 1 to 4.

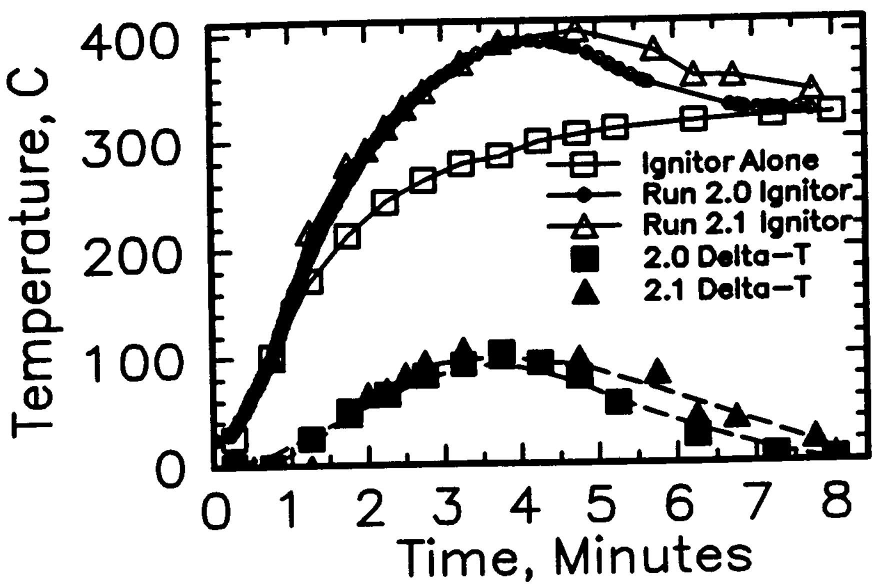

Figure 4 Igniter Temperature Comparison.

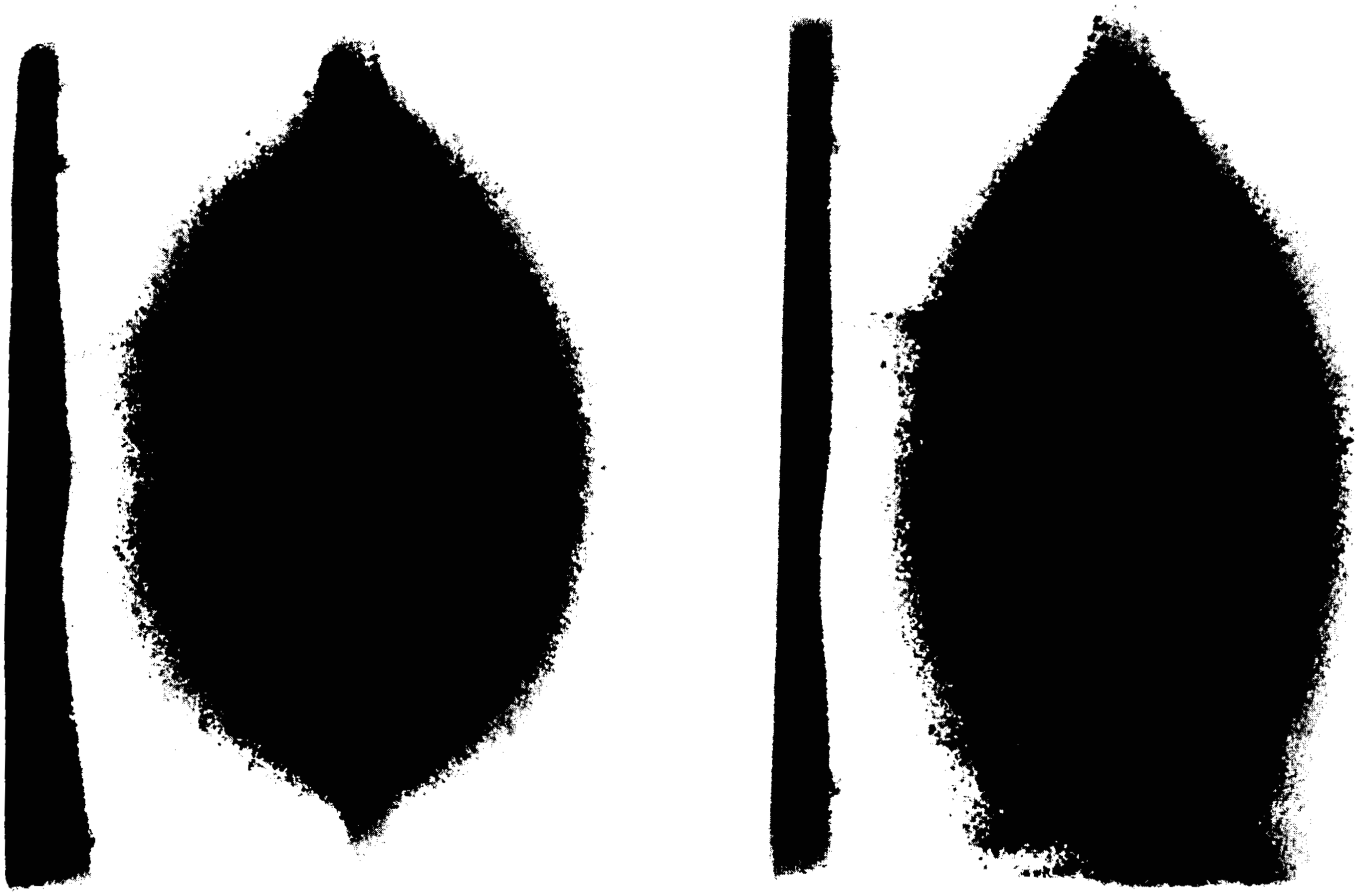

Figure 5 Foam Samples, from Runs 1.0 (Left) and 2.0 (Right), Fan end at base of figure. Samples are 8 cm long.

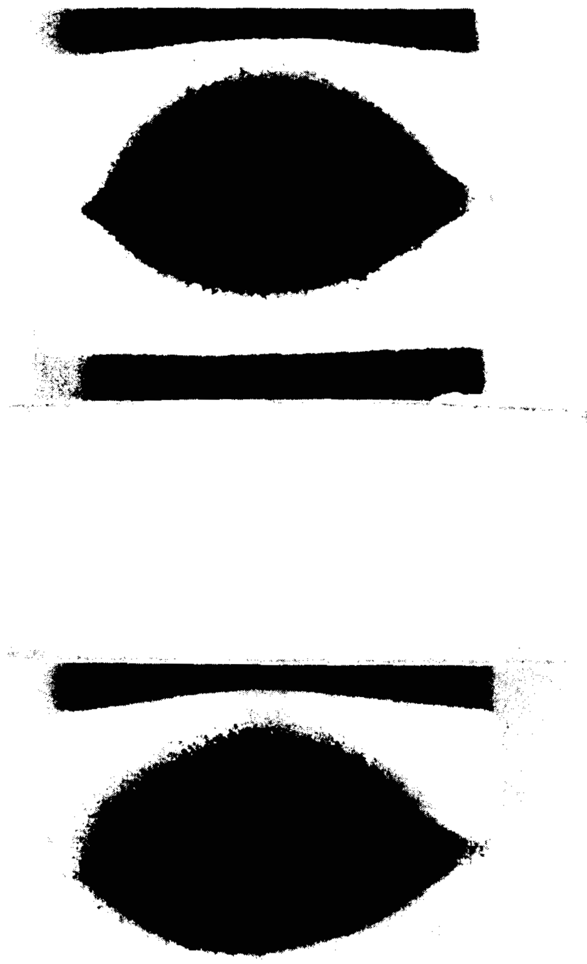

Figure 6 Foam Samples, from Runs 1.1 (Top) and 2.1 (Bottom), Fan end at left, Gravity Vector down. Samples are 8 cm long.

Discussion

(Speaker: Carlos Fernandez-Pello, University of California, Berkeley, California)

Question: *When you see a lot of CO produced in a reaction that under other conditions does not produce a lot of CO, my naive view is that somehow I have limited the amount of oxygen getting to this combustion process, and that is why I don't go to completion in that reaction. Is that consistent with your interpretation of these results?*

Answer: Yes. Basically I think what happens is the supply of oxidizer is by diffusion and what we have in microgravity is we have a higher temperature, with higher pyrolysis of the fuel, and an attempt to react more than in normal gravity. We are comparing normal and microgravity. In normal gravity the convective flow cools the reaction and prevents this from occurring, but in microgravity there is not enough oxidizer to oxidize the CO to CO_2. One thing that is a bit deceiving, also, is that this is a surface reaction, so when we think of the oxidation process in the gas phase, that occurs at above 1000°C. Here, in the experiment, the temperatures are of the order of 400°C, so the concepts that apply to the oxidation process in flames do not apply here. But basically you are right.