N96- 15554

MICROGRAVITY SMOLDERING COMBUSTION ON THE USML-1 SPACE SHUTTLE MISSION

Dennis P. Stocker and Sandra L. Olson
NASA Lewis Research Center
Cleveland, Ohio

Jose L. Torero and A. Carlos Fernandez-Pello
Department of Mechanical Engineering
University of California at Berkeley
Berkeley, California

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. The characteristics of the smolder reaction and its rate of propagation are determined by the balance between the transport of oxidizer to the reaction zone and the transport of energy to and from the reaction zone [1,2]. 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 [1,3,4].

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.

Considerable work has been conducted to date on smoldering at normal gravity [1,2], but very limited information is available on smolder in low gravity [5-7]. This is in part because of the long periods of microgravity needed to conduct smolder experiments. 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. 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.

EXPERIMENT

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 (Fig. 1). The test variables during the experiment were the igniter geometry and the convective environment. Through the use of an axial igniter 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. 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 air flow past the sample with a velocity of the order of 100 mm/sec. For the quiescent tests, large sections of the tube were removed to provide free exchange of air throughout the module. The plate and axial igniters were resistively-heated elements, consisting of nickel-chromium wire sheathed in ceramic.

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 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.

RESULTS

<u>Temperature Histories</u>: A representative example of the temperature histories obtained in these experiments is shown in Fig. 2. It presents the temperature histories provided by thermocouples 1 to 4 in the microgravity and normal-gravity experiments for test 2 (axial igniter/fan on). 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. 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.

From a comparison of the microgravity and normal-gravity temperature profiles, it appears that gravity had a limited effect on the temperature histories. In most cases, the peak temperatures were greater in microgravity than normal gravity for all four thermocouples, with the difference increasing with distance from the igniter. The temperature difference is presumably due to buoyant cooling in normal gravity, which would be most strongly felt near the surface of the foam.These temperature histories can be used to roughly calculate smolder propagation velocities using the method previously developed for ground-based experiments [4]. Using that technique, it is found that for all tests, the smolder was not steady but decayed from approximately 0.08 mm/s to 0.02 mm/s, and finally extinguished. The smolder propagation velocities obtained for the normal-gravity tests experiments are also 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 [8]. 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.

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.The char pattern from normal-gravity tests were found to be similar to the pattern from the microgravity test. 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 [3,4]. 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.

Gas Analyses: The results of the analyses of the post-combustion gases are presented in Table I, for the microgravity and normal-gravity tests. Only the major components have been included in the table. 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. 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). In most cases, the microgravity tests produced twice as much carbon dioxide as the normal-gravity tests. Methane and propene are evident in the microgravity cases, whereas they are hardly detected in the normal gravity samples. Other products (e.g., 2-propanol) are detected in the microgravity samples and are undetected, or weakly detected, in the normal-gravity samples.

Heat Losses: The present results indicate that heat losses were an important factor in the smolder propagation for the present experimental conditions in microgravity as well as normal gravity. This 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. 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.

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.

(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.

(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.

(4) Despite similar temperatures and visible extent of smolder, significant production of light combustion gases was found to have occurred in microgravity. 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.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the many NASA personnel that made this space experiment possible. In particular, we would like to thank the Toxicology Branch of NASA Johnson, who conducted the gas analyses. We would like to thank the USML-1 crew for their design suggestions and for their hard work during experiment training and simulations. Special thanks go to Col. Carl J. Meade and Dr. Lawrence J. DeLucas for their interest and dedication while conducting the experiments during the USML-1 mission.

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TABLE I: 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.

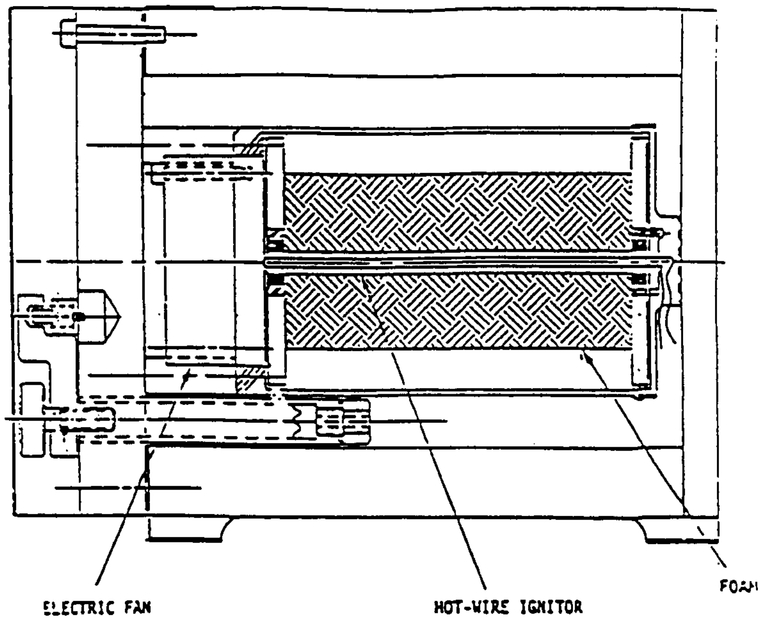

Figure 1. Schematic of experimental module, axial ignitor.

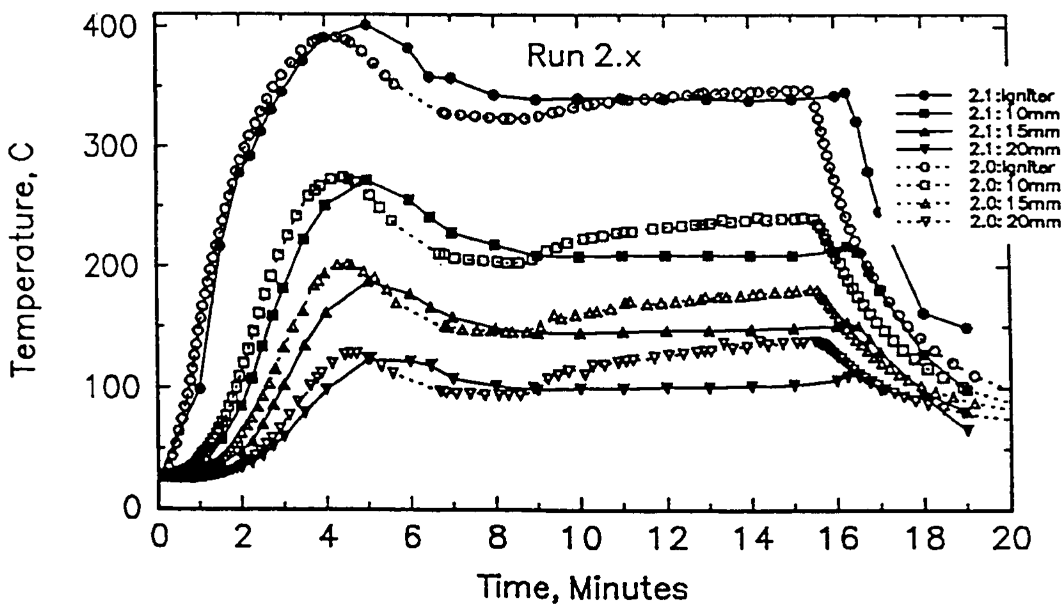

Figure 2. Temperature data from runs 2.0 and 2.1 (axial ignitor, fan on); thermocouples 1 to 4.