AIAA JOURNAL
Vol. 32, No. 5, May 1994

Experimental Observations of the Effect of Gravity Changes on Smoldering Combustion

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An experimental study is conducted to determine the effect of gravity changes on the natural convection smolder characteristics of flexible polyurethane foam. Gravity, and consequently buoyancy, is expected to affect smoldering because it induces convective transport of mass and heat to and from the reaction zone. The overall objective of the work is to provide information about the potential onset of a smolder-initiated fire in a space-based facility. Experiments are conducted in an aircraft following parabolic trajectories that provide up to 25 s of low gravity (KC-135A) and up to 20 s (Learjet Model 25), with a pull-up and pull-out of approximately 2 *g* per parabola. Measurements are performed, during a series of parabolas, of the temperature histories of the polyurethane foam at several locations along the fuel sample interior, both for upward and downward propagation. The measurements show that gravity plays a significant role in the competition between the supply of oxidizer to, and the transfer of heat to and from, the reaction zone. It is found that within the reaction zone, the supply of oxidizer is dominant in downward smolder, and that the smolder temperature decreases at low gravity for lack of oxidizer. Away from the reaction zone there is a temperature increase at low gravity because of the reduction in buoyantly induced convective cooling. The opposite is observed at high gravity. Similar mechanisms are observed in upward smoldering, although here high gravity results not only in an increase in the smoldering temperature but also in an increase in the temperature of the fuel ahead of the reaction. This increase is either because of the increase in the flow of hot postcombustion gases ahead of the reaction zone or the extra heat generated by oxidative reactions occurring in the char. Although the variable gravity periods are too short to study smolder propagation, they allow the observation of trends in the smolder reaction temperature, aiding understanding of how gravity affects smoldering.

Introduction

SMOLDERING is a nonflaming, surface combustion reaction that takes place in the interior of porous combustible materials. The exothermic smolder reaction can propagate through the material, in a creeping fashion, by transferring enough heat to the virgin fuel ahead to initiate a surface combustion reaction. For the smolder reaction to be sustained, enough oxygen must be transported to the reaction zone to support the reaction. 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 transition to flaming. Recently, with the planned establishment of long-life space facilities, there is increased interest in the study of the effect of gravity (buoyancy) on smoldering because of the potential danger of a smolder-initiated fire in the facility. Buoyancy is expected to influence smoldering through its effect on the convective mass and heat transport within the smoldering material.

Considerable work has been conducted to date on smoldering; reviews on the subject can be found in the works of Ohlemiller[1] and Drysdale.[2] Limited attention has been given, however, to the effect of buoyancy on the process. Dosanjh et al.[3] and Newhall et al.[4] studied the effect of buoyancy on downward smoldering of cellulose by varying the ambient pressure. The former found that the smolder reaction propagation velocity and temperature increase with the airflow rate, thus confirming that smoldering is an oxygen limited process.[1] Newhall et al.[4] confirmed the dependence of the smolder velocity on the oxidizer flow rate and showed that buoyancy plays a role in cellulose smolder particularly at low flow velocities. Torero et al.,[5,6] using polyurethane foam, studied the effect of buoyancy on opposed and forward forced flow smoldering by conducting a series of experiments in normal gravity and comparing upward and downward smolder propagation. Cantwell and Fernandez-Pello[7,8] conducted preliminary studies of the effect of gravity changes on the forced flow smolder characteristics of polyurethane foam, near the ignition source, and close to the ambient air-fuel interface. Their experiments were conducted in a 2.2 s drop tower and in a KC-135 aircraft following a parabolic trajectory. The present work extends the studies mentioned earlier by investigating the effect of gravity changes on the natural convection smoldering of polyurethane foam as the smolder front propagates in a quasi-one-dimensional fashion, downward and upward through the sample. By conducting the experiments for a better characterized smolder process and analyzing the effects at different depths within the fuel sample, more conclusive results are obtained concerning the role of gravity on smolder combustion.

Experiment

A schematic diagram of the experimental package flown on the KC-135 and Learjet aircraft is shown in Fig. 1. The combustion chamber is made of steel, with a 300 mm side square cross section and 435 mm high. One of the side walls is fitted with a Lexan window for optical access. The porous fuel is tightly fitted in an open-ended 300 mm long vertical duct with a 150 mm side square cross section. The duct walls are made of insulating 10 mm thick Fiberfax sheet covered with aluminum tape to prevent species diffusion through the walls. The fuel sample is 150 mm long and occupies one-half of the duct. An igniter and a 150 mm insulating char section occupies the other half of the duct. The char is the residue from a previous smoldering experiment and is used to insulate the

Received April 29, 1993; revision received Aug. 12, 1993; accepted for publication Aug. 19, 1993.

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back side of the igniter and partially simulate a smolder front that had passed through a deeper bed of material. The igniter consists of a Nichrome wire sandwiched between two, 5 mm thick, porous ceramic honeycomb plates that provide rigidity to the igniter and heating uniformity. The foam sample width is selected to ensure a region of one-dimensional smolder propagation at least 5 cm in diameter along the centerline, and its length is selected to ensure a region free of end effects at least 50 mm long. The radial extent of the smolder reaction and its characteristics are determined by cutting the sample at the end of the experiments and observing the char structure. A more detailed description of the apparatus is given by Torero.[9]

All the tests in this work are conducted with open cell, unretarded, white polyurethane foam, with a 26.5 kg/m^3 density and 0.975 void fraction. A first group of experiments was conducted aboard a KC-135A, NASA 930 aircraft, which flies a parabolic trajectory to produce periods of low gravity lasting about 25 s, with typical accelerations of approximately $\pm$ 0.2 m/s^2. Each parabolic trajectory is initiated and terminated with a pull-up and pull-out of 1.8 to 2.0 g. These trajectories are flown consecutively, typically in groups of 10, with a total of 30 to 40 parabolas per flight. The acceleration is measured by an accelerometer attached to the airframe. A second group of experiments was conducted aboard a Learjet Model 25, which produces periods of low gravity lasting about 20 s, with typical accelerations of approximately $\pm$ 0.04 m/s^2. The pull-up and pull-out were requested to match the acceleration characteristics of the KC-135A parabolas. Although the Learjet performs a maximum of 6 parabolas per flight only, the maneuvers can be requested at specified times during the flight, thus enabling the observation of the smoldering behavior at specific regions as it propagates through the sample.

Experiments are started approximately 15 min before the onset of the variable gravity cycles to avoid the effects of the gravity variation on ignition, and the igniter power is left on during the whole experiment to ensure the onset of smoldering. The igniter temperature becomes stable at around 400°C, which may enhance the oxidation of the char in the sample vicinity. This effect, however, is local and does not significantly affect the smolder away from the igniter. Only one sample is ignited per flight and generally smolders during the whole flight. The chamber pressure is maintained constant by manually venting the combustion gases through an exhaust valve. Temperature histories along the foam sample are measured with six Chromel-Alumel thermocouples 0.8 mm in diameter embedded at fixed locations in the foam. These temperature histories are used to analyze the effect of gravity changes on the smolder reaction. Although the rate of smolder propagation usually can be obtained from the temperature histories of consecutive thermocouples,[5] this approach is not applicable here because the smolder velocities are too small to be measured during the time of each parabola.

Measurement of the oxygen concentration inside the foam pores was attempted in the laboratory. Unfortunately complications due to the large quantity of condensable material produced by the smolder reaction rendered these measurements infeasible.

Results and Discussion

All of the experiments are conducted under natural convection conditions for downward and upward smoldering propagation. In the downward smoldering experiments, the foam is ignited at the top of the sample and the smolder reaction propagates downward through the sample. In the presence of gravity the smolder propagation is expected to be of the opposed type[5] with the air being naturally induced upward through the virgin foam toward the reaction zone and the products flowing through the char toward the top. In the upward smoldering experiments, the apparatus is rotated 180 deg such that the foam is ignited at the bottom and the reaction propagates upward. Thus, under gravity, the smolder propagation is expected to be, in this case, of the forward type,[6] with air flow induced upward through the char toward the reaction zone, and the products flowing through the virgin foam toward the top. Comparison and individual study of both smolder configurations provides information on the effects of buoyancy on smolder.

Downward Smoldering

Characteristic temperature histories at three locations along the foam sample for downward smolder at normal gravity and during a parabolic flight are presented in Fig. 2 as a function of the time from ignition. The gravity variation is superimposed in the figure to facilitate the data interpretation. As the smolder reaction approaches the thermocouple location, the temperature increases due to the streamwise heat transfer from the reaction zone to the fuel ahead. Heat transfer occurs by conduction and radiation[10] as well as convection.[5,9] In downward smolder convection has a cooling effect as the buoyantly induced flow moves in the opposite direction to that of smolder propagation. Once the smolder reaction reaches the thermocouple location, the temperature levels off and becomes relatively constant due to a balance between the exothermic surface smolder reaction, the endothermic decomposition of the fuel, and heat losses to the flow. After the reaction has passed the thermocouple location, the temperature recorded is that of the char, which decays due to heat losses to the wall and the environment. Some of these heat losses are due to convective recirculating currents that are generated in the char.[5]

The three thermocouples whose temperatures are presented in Fig. 2 are respectively located at 15, 70, and 105 mm from the igniter, and their temperature profiles are representative of three regions within the sample that have specific smolder characteristics. The zones are: an initial zone, zone I, near the igniter, approximately 50 mm long, where the smolder reaction is strongly influenced by the heat transferred from the igniter; a second zone, zone II, 50 mm long in the middle of the sample where the smolder process is relatively free of end effects; and an end zone, zone III, 50 mm long, where there is a significant influence from the external environment on the smolder process. A more detailed description of these three zones is given by Torero et al.[5] Analysis of the measured temperature histories indicates that the effect on the temper-

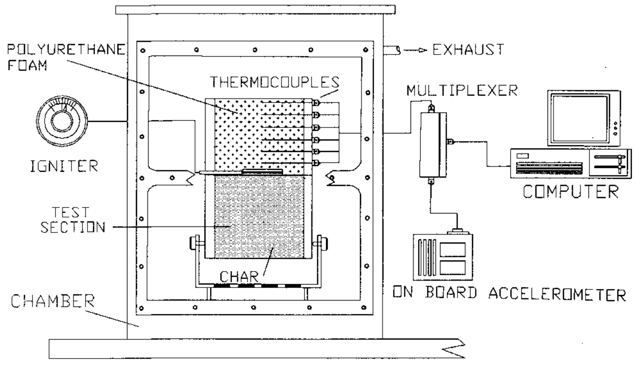

Fig. 1 Schematic of experimental apparatus.

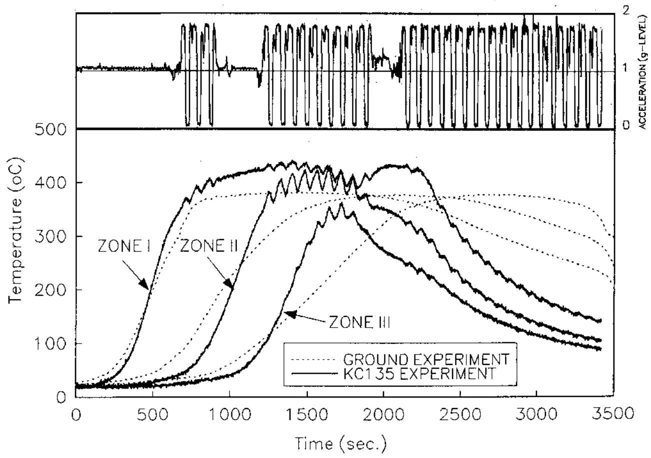

Fig. 2 Downward smolder temperature histories at three sample locations during a parabolic flight and at normal gravity.

ature profile of the gravity changes occurring during the parabolic flight depends on the location of the thermocouple in relation to these three zones and to the reaction zone. Thus, results will be presented separately according to zone and location relative to the reaction front.

Presentation of the results begins with zone II, since the smolder in this zone is the most representative of a self-propagating smolder. Representative periods of the temperature history measured by a thermocouple located 70 mm from the igniter, covering at least two parabolas, are presented in Figs. 3–5. They show the virgin

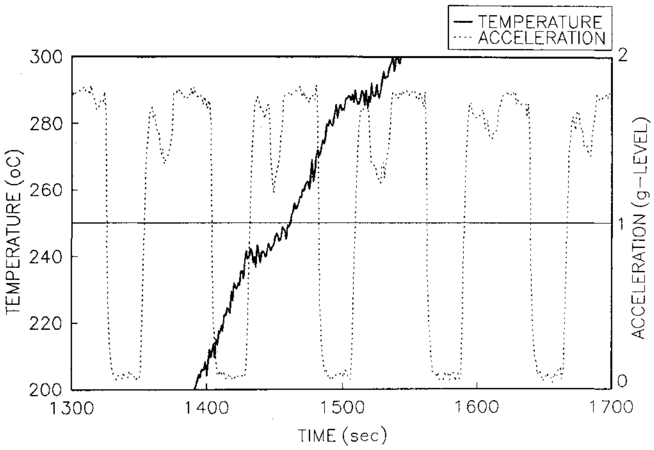

Fig. 3 Downward smolder temperature history detail in zone II (unburnt foam).

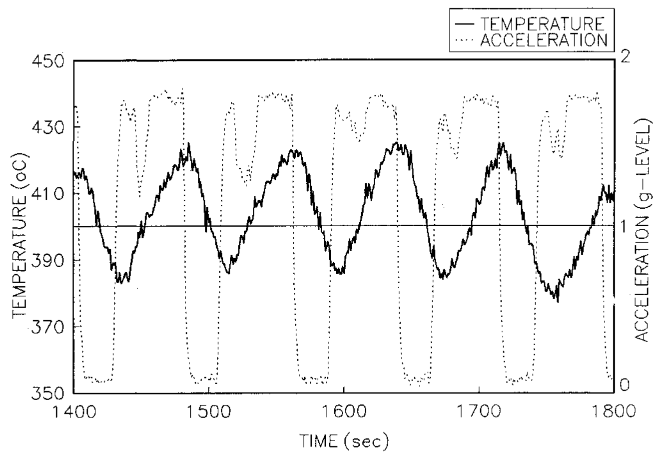

Fig. 4 Downward smolder temperature history detail in zone II (reaction zone).

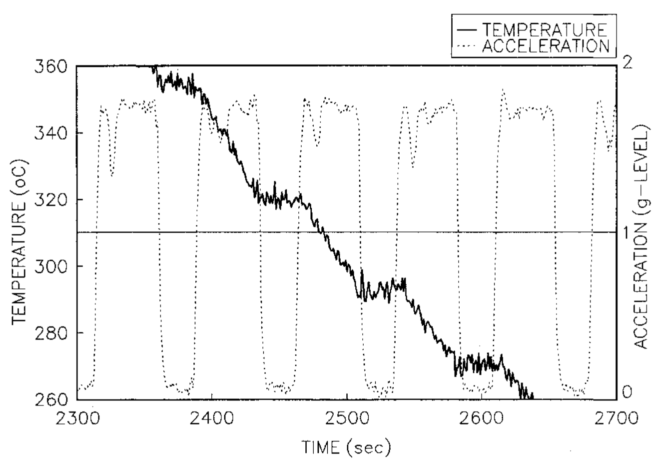

Fig. 5 Downward smolder temperature history detail in zone II (char).

foam ahead of the smolder reaction, in the reaction zone, and in the char behind the reaction, respectively. An acceleration trace for the same period is overlaid in the figures to facilitate the interpretation of the results. The noise in the data is believed due to radio frequency interference from the aircraft. From the temperature profiles of Fig. 3, it is observed that in the virgin foam ahead of the reaction, where the temperature gradient is positive due to heating from the reaction, the temperature gradients are larger during low gravity than during high gravity. In the reaction zone (Fig.4), where the temperature is fairly uniform, the temperature decreases sharply during low gravity and increases during high gravity. Finally, from the temperature profile of Fig. 5, corresponding to the char region, which has an overall negative gradient due to heat losses to the environment, a gradient reversal can be seen in low gravity and a steepening of the negative gradient in high gravity. These results are in qualitative agreement with those of Cantwell and Fernandez-Pello.[7,8]

Further information about the effect of gravity on the downward smoldering controlling mechanisms can be obtained from the temperature histories in zones I and III. These are presented in Figs. 6 and 7, respectively. The temperature history of Fig. 6 is obtained from a thermocouple located 15 mm from the igniter while the reaction is passing. The effect of the gravity change on the reaction temperature in this zone follows the same trend as observed in zone II. However, the quantitative effect is weaker, with a temperature drop in the low gravity period of approximately 15°C vs the 40°C to 45°C observed in zone II. The temperature history of the smolder reaction as it passes by a zone III thermocouple is given in Fig. 7. Here the proximity to the end of the sample results in the weakening of the reaction. The characteristics of the temperature histories in the virgin material and char in zones I and III are simi-

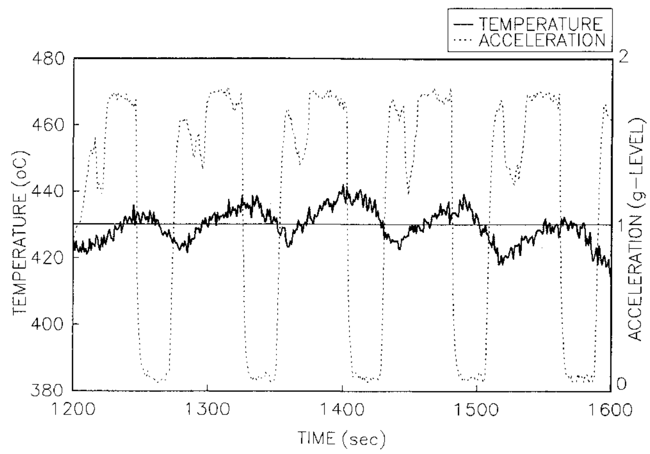

Fig. 6 Downward smolder temperature history detail in zone I (reaction zone).

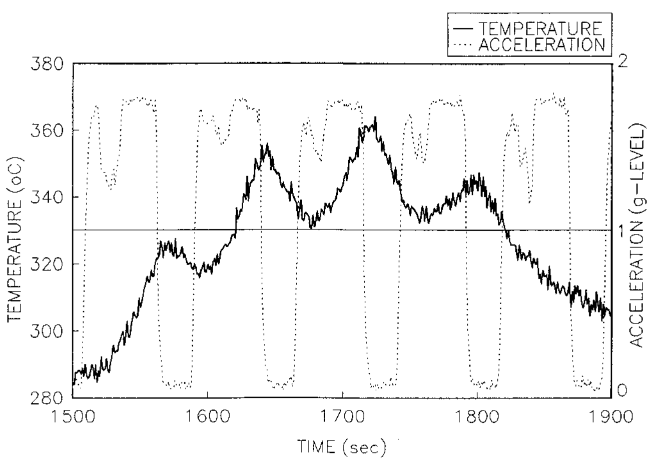

Fig. 7 Downward smolder temperature history detail in zone III (reaction zone).

lar to those in zone II, except for quantitative differences as those indicated earlier. Thus, they will not be presented here for brevity of presentation.

In the KC-135 experiments, the continuous variable gravity cycles resulted in an overall weakening of the reaction in zone III, which led to extinction (Figs. 2 and 7). In the Learjet experiments, however, it was possible to time the parabolas so that the reaction would recover, thus preventing extinction. This allowed us to obtain additional information about the smolder reaction temperature in zone III. In general, the Learjet experiments showed similar trends to those observed in the KC-135A experiments. Specifically, in the reaction zone the temperatures decrease in the low gravity periods and increase in the high gravity ones. The difference between the maximum and minimum smolder reaction temperatures measured for each cycle is plotted as a function of distance from ignition in Fig. 8. The maximum corresponds to high gravity periods and the minimum to low gravity ones. The temperature difference increases as the reaction progresses through the fuel sample, from 15°C near the igniter, to approximately 40°C in zone II, and to values over 100°C near the end of the sample. As is explained later, this variation in the temperature difference is the result of an increase in the buoyant flow rate that occurs as the smolder front propagates through the sample. In those conditions where the gravity changes lead to extinction, the temperature difference decreases toward the sample end, as observed in Fig. 7.

The previous results suggest a smolder process that is controlled by the competition between the supply of oxidizer to the reaction zone and the transfer of heat from the reaction zone to the surroundings. The existence of two competing mechanisms, chemical kinetics and heat losses, was previously pointed out by Ohlemiller[1] and Torero et al.[5] In the latter work it is shown that in forced flow smoldering, at low flow velocities, oxygen depletion is the dominant controlling factor, which results in low smolder propagation velocities and temperatures. Increasing the flow velocity strengthens the smolder reaction due to the oxygen addition, which results in larger smolder velocities and temperatures. However, as the flow velocity is increased further, the smolder reaction becomes weaker and eventually extinguishes due to convective cooling of the reaction. Similar smolder trends are deduced from the present experiments, although the transport mechanisms are in this case somewhat different.

In natural convection smolder, the transport of species to and from the reaction zone takes place by diffusion and by natural convection. Heat is transferred from the reaction zone by conduction and radiation, and also by natural convection generated locally or throughout the test section by the density difference between the hot postcombustion gases and the ambient air. Two main types of flows are identified; a natural draft that is induced vertically upward through the foam due to the presence of hot postcombustion gases in the char region, and a local recirculating flow that is caused by the interaction in the char region between the cold gases near the test section walls and the hot postcombustion gases.[9] The natural draft flow opposes the direction of smolder propagation, and thus the smolder is basically of the opposed flow type.[5] The flow rate is determined by a balance between the hydrostatic pressure, which depends on the temperature and length of the char region, and the pressure loss, which depends on the permeability and length of the foam and char. The permeability of the char, although much larger than that of the foam, depends on the smolder reaction characteristics, increasing with the strength of the reaction.[5,9] Since the high permeability char region expands as the front propagates, the flow through the system increases as the front propagates through the sample. The recirculating flows are produced by a boundary-layer flow that is formed at the cold duct walls, and moves downward toward the reaction zone, eventually turning around and joining the upwardly moving postcombustion gases. The penetration of these boundary-layer flows depends strongly on the permeability of the char. The net result of these buoyantly generated flows is a mass flux of air at the reaction zone that increases in an almost exponential fashion as the smolder reaction progresses through the foam. A detailed quantitative analysis of these flows can be found in Torero.[9]

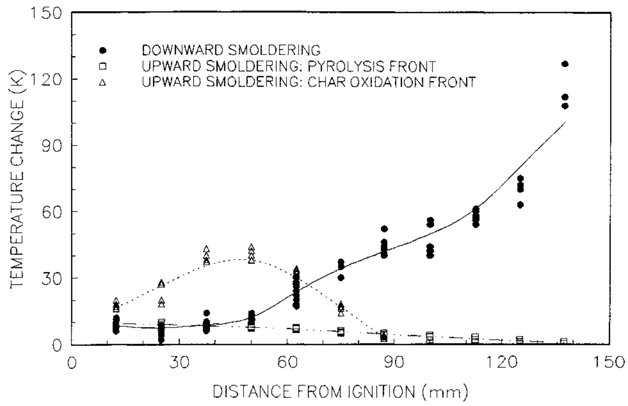

Fig. 8 Variation along the foam sample of the reaction temperature difference between a high and a low gravity period, for upward and downward smoldering.

The presence in the foam of the previously described buoyantly generated flows helps explain the nature of the temperature measurements presented above. In the virgin material the temperature is determined by a balance between the heat transferred ahead of the reaction by conduction and radiation and the cooling by the incoming buoyant flow. In low gravity the buoyant flow is largely suppressed, and consequently the foam temperature increases more rapidly, as observed in Fig. 3. This effect is more pronounced as the smolder reaction progresses through the sample. The temperature in the char region follows a similar trend, although the mechanism is somewhat different. The temperature is determined by a balance between heat transferred from the reaction by conduction, radiation and convection, and heat lost to the environment by convection and radiation, together with cooling from the recirculating flow. The reduction (increase) in low (high) gravity of the buoyant cooling results in char temperatures that increase (decrease) in low (high) gravity, as observed in Fig. 5.

In the reaction zone, the smolder temperature is determined primarily by the balance between the heat generated by the exothermic smolder reaction, and the heat transported away from the reaction.[1,3,5] For opposed flow smoldering the heat generated by the reaction is directly proportional to the oxidizer mass flux reaching the reaction.[3,5] If smoldering is taking place under conditions that result in vigorous smolder, the increase in heat generation dominates over the cooling by the incoming air flow, and as a result the smolder temperature increases as the incoming oxidizer flow rate is increased.[5] Thus, at low gravity the reduction of the buoyant flows should cause a decrease in the smolder reaction temperatures, and the opposite should occur at high gravity, in agreement with the results of Fig. 4. Furthermore, since as explained earlier, the buoyant flow rate increases as the amount of char increases, the difference in smolder reaction temperatures between the high and low gravity periods should also increase as the smolder front propagates through the sample, also in agreement with the results of Fig. 8. If the conditions at which the smolder reaction is taking place are such that the reaction is weak, then the cooling effect of the opposed flow is dominant and the smolder temperature and velocity decrease with the increase in the oxidizer flow rate.[5] This situation is the case observed in some of the experiments conducted in the KC-135, where, as explained before, the consecutive periods of low gravity caused the reaction to weaken to a point were the combination of the cooling from the high flow rates in the high gravity periods, and the reduced heat released from the low gravity periods, caused the eventual extinction of the reaction.

Upward Smoldering

A characteristic example of the temperature histories for upward smoldering at different locations along the foam sample, during a KC-135 parabolic flight, is presented in Fig. 9. Normal gravity data are also presented for comparison purposes. The temperatures correspond to locations along the sample 15, 70, and 105 mm from the igniter, and thus are representative of the temperatures in the three zones mentioned previously. From Fig. 9 it is seen that the smolder reaction temperature decreases significantly as the reaction propagates upward through the sample. Char temperatures in zone I are higher (approximately 450°C) than those characteristic for smolder (of the order of 380°C), and remain high during most of the experiment. This result is an indication that there is probably char oxidation in this zone of the sample. On the other hand, the temperatures in zones II and III are lower than those expected in a smolder oxidation reaction, which suggests that a pyrolysis reaction rather than a smolder one is propagating in those zones. These smolder characteristics are often encountered in forced flow forward smoldering at intermediate air flow rates.[6,9] To verify if these results were related to the periodic gravity changes in the KC-135 flight, experiments were also conducted in the Learjet with fewer but more timely gravity cycles. The reaction temperature also decayed in these experiments as the reaction progressed through the foam, thus verifying that this behavior is more related to the upward form of smolder than to the actual gravity changes. Detailed temperature histories of the smolder reaction at different locations in the sample are presented in Fig. 10. It is seen that the effect of gravity on the smolder reaction temperature is similar to that observed in downward smolder, with the temperature increasing in the high gravity periods and decreasing in the low gravity ones. The temperature recorded by the thermocouple at 70 mm from the igniter corresponds to a very weak pyrolysis reaction and appears

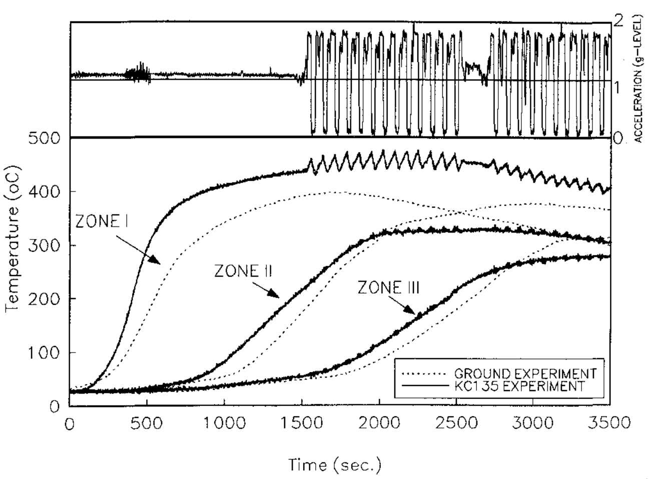

Fig. 9 Upward smolder temperature histories at three sample locations during a parabolic flight and at normal gravity.

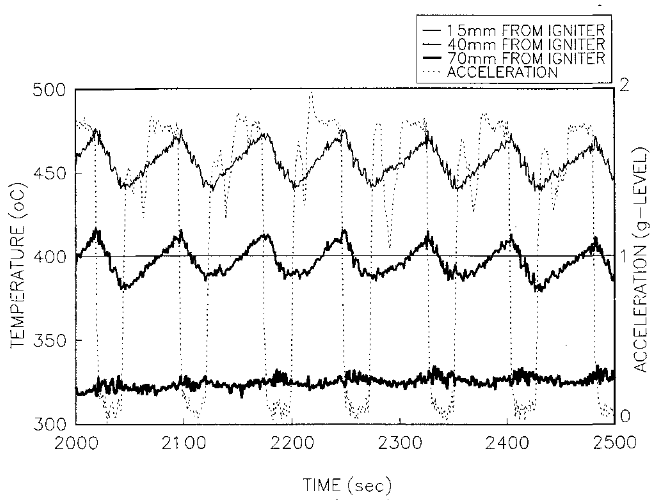

Fig. 10 Upward smolder temperature history detail at different sample locations (reaction zone).

Fig. 11 Photograph showing a cut sample of burnt foam from a downward smoldering experiment.

to have an opposite trend than that of the oxidation reactions. The magnitude of the temperature fluctuations in the oxidation and pyrolysis fronts are presented in Fig. 8. They show the weakening of the reaction as it propagates deep into the sample.

The nature of these results, and the differences with those observed for downward smoldering, are explained by the gas flow characteristics of upward smoldering. In upward smoldering, buoyancy induces gas flow that moves upward through the char toward the reaction zone, and then through the virgin foam to the top of the test section. Thus, the resulting smolder process is similar to that encountered in forward smoldering.[6] The gas flow has two opposing effects on the mechanisms controlling the smolder reaction. The upward flow of hot postcombustion gases preheats the virgin foam and consequently enhances the smolder reaction. However, as incoming oxidizer flows through the hot char, the char undergoes an oxidation reaction that partially depletes the oxygen prior to it reaching the actual smolder front. The reduced oxygen concentration deters the onset of the smolder reaction and may instead favor the onset of a pyrolysis reaction that has a lower temperature and that is sustained by the heat generated by the char oxidation.[6,9] The potential competition between an oxidative smolder reaction and a pyrolysis reaction has been discussed before in the works of Ohlemiller,[1] Tong and Tien,[11] and Ohlemiller and Lucca[12] in relation to forward smolder. The amount of oxygen removed from the air depends on the amount of fuel contained in the char and the length of the char region. The end result is that as the smolder propagates upward through the sample, the foam undergoes initially a smolder oxidation reaction that has high temperatures due to the preheating of the foam and the oxidation of the char. As the smolder front progresses through the foam and a larger amount of oxygen is depleted from the air, the reaction changes from an exothermic-oxidation reaction to an endothermic pyrolysis reaction, which is increasingly weaker as it propagates through the sample. Decreasing gravity reduces the airflow rate and consequently the char and foam oxidation, which results in lower reaction temperatures, as observed in Fig. 10. It also decreases the temperature in the pyrolysis reaction and in the virgin foam due to the reduced flow of hot postcombustion gases downstream and the lower heat generated by the char oxidation. The changes in temperature, however, are not very significant because the gas heat capacity is very small compared with that of the solid. Multiple-variable gravity cycles tend to weaken the overall reaction, and the temperature dif-

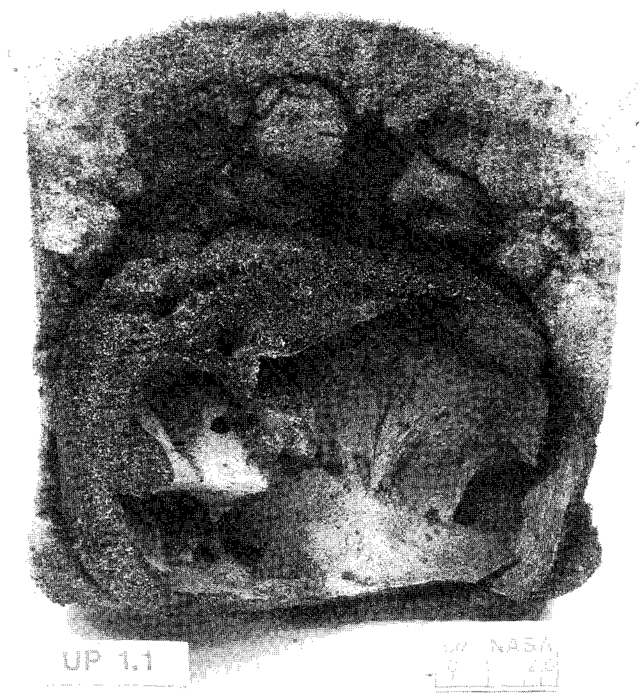

Fig. 11 Photograph showing a cut sample of burnt foam from a downward smoldering experiment.

ference during each variable gravity cycle becomes less noticeable, as it is seen in Figs. 8–10. This result was more evident in experiments performed on board the KC-135, where the large number of parabolas lead to an earlier extinction of the reaction.

The previously described smolder characteristics and the differences between the downward and upward smolder are clearly reflected in the physical structure of the foam left after the experiments. Figures 11 and 12 show photographs of the cross section of a foam sample after undergoing downward and upward smolder, respectively. In downward smolder, the smolder reaction propagates almost to the end of the sample, the char left behind has a uniform structure, and there is no evidence of pyrolyzed foam. In upward smoldering, char is formed in the initial 100 mm of the sample, and the rest of the foam shows strong evidence of pyrolysis, with the foam discolorization and structure changes.

Concluding Remarks

The present study has helped to identify the controlling mechanisms of free convection smolder and to determine the influence of gravity on the process. It was found that the competition between oxygen supply and heat transfer that determines the characteristics of the smolder reaction is altered by the changes in gravity levels. Within the reaction zone, the reduction in oxygen supply in low gravity is dominant, and the reaction weakens. Away from the reaction zone, the reduction in convective cooling at low gravity tends to increase the material temperature.

The experiments, although providing a phenomenological view of the smolder characteristics in a variable gravity environment, cannot determine the final fate of the reaction in a microgravity environment. However it is possible to infer some of the events that may occur in microgravity smolder. Under quiescent self-smolder conditions, smolder may propagate because the oxygen contained in the foam pores appears to be sufficient to sustain smolder,[5] although at significantly low smolder propagation velocity and temperature. It also could extinguish as a result of oxygen dilution by the combustion products. In the presence of low velocity flow of oxidizer, or under external heating, the insulating conditions that microgravity provides may result in an enhancement of the smolder reaction and its possible transition to flaming.

Acknowledgments

This work was supported by NASA under Grant NASA-NAG 3-443. The authors would like to acknowledge the valuable help of Jeffrey Mullins of NASA Marshall Space Flight Center and Eric Newman of NASA Lewis Research Center while performing the experiments.

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