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# SPACE SHUTTLE BASED MICROGRAVITY SMOLDERING COMBUSTION EXPERIMENTS

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**ABSTRACT**

Results from four microgravity smoldering combustion experiments conducted aboard the NASA Space Shuttle are presented in this work. The experiments are part of the NASA funded Microgravity Smoldering Combustion (MSC) research program, aimed to study the smolder characteristics of porous combustible materials in a microgravity environment. The objective of the study is to provide a better understanding of the controlling mechanisms of smolder for the purpose of control and prevention, both in normal- and microgravity. The microgravity smolder experiments reported here have been conducted to investigate the propagation of smolder through a polyurethane foam sample under both diffusion driven and opposed forced flow driven smoldering. The present experiments, although limited, are unique in that they provide the only available information about smolder combustion in microgravity in sample sizes large enough to allow the self-propagation of the smolder reaction throughout the sample length. Two quiescent tests at ambient oxygen concentrations of 35% and 40% and two opposed forced flow tests with air as oxidizer, were conducted aboard the NASA Space Shuttle (STS-69 and STS-77 missions).

The MSC data are compared with normal-gravity data to determine the effect of gravity on smolder, and are used to verify present theoretical models of smolder combustion. It is found that for the present test conditions, the microgravity opposed flow smolder reaction temperatures, propagation velocities, toxic compound production and reaction extent lie between those of normal-gravity upward and downward tests. Thermogravimetric analysis shows little effect of gravity on the kinetics of the smolder process in these cases. Neither of the two quiescent, microgravity cases resulted in self-sustained smolder propagation, while the normal-gravity downward cases propagated vigorously. The difference in these results shows that gravity has a significant effect on smolder combustion, at least for the sample size tested. Correlation of the forced flow smolder velocity data with a heat transfer based model, indicates that simplified heat transfer models of smolder propagation can effectively describe vigorous smolder, away from limiting conditions such as extinction and flaming.

## INTRODUCTION

Smoldering is defined as a non-flaming, self-sustaining, propagating, exothermic, surface reaction, deriving its principal heat from heterogeneous oxidation of the fuel[1,2]. If the material is sufficiently permeable, smoldering is not confined to its outer surface and can propagate as a reaction wave through the interior of the material. Smoldering may occur in a variety of processes ranging from smolder of porous insulating materials to underground coal combustion[3-6].

Smoldering is a basic combustion problem that encompasses a number of fundamental processes, including: heat and mass transfer in a porous media, endothermic pyrolysis of the combustible material, ignition, propagation and extinction of heterogeneous exothermic combustion reactions at the solid/gas pore interface[1,2]. Smoldering presents a serious fire risk because the reaction can propagate slowly in the material interior and go undetected for long periods of time. It typically yields a substantially higher conversion of fuel to toxic compounds than does flaming (albeit more slowly), and may undergo a sudden transition to flaming[7,8]. Smolder of cable insulation, another common fire hazard, is of particular concern in the space program; to date there have been a few minor incidents of overheated and charred cables and electrical components reported on Space Shuttle flights[9,10]. Recently, the planned establishment of the International Space Station and other space facilities has increased interest in the study of smoldering in microgravity because of the need to preempt the possibility, and/or to minimize the effect of a smolder initiated fire during the operation of these facilities[11].

There are two distinct classifications for one-dimensional propagation of a smolder reaction: opposed and forward[2,12]. These are defined according to the direction in which the fuel and oxidizer enter the reaction zone. In opposed (reverse) smolder, the configuration examined here and shown in Fig. 1, the reaction front propagates in a direction opposite to the oxidizer flow. This configuration is also referred to as co-current, or premixed-flame-like smolder, because with the coordinate system anchored at the reaction zone, fuel and oxidizer enter the reaction zone from the same direction, albeit with different velocities. The heat released by the heterogeneous oxidation (smolder) reaction is transferred ahead of the reaction by conduction and radiation, heating the unreacted fuel and the incoming oxidizer. The resulting increase of the virgin fuel temperature leads to the onset of the smolder reaction, and consequently gives way to its propagation through the fuel. The combustion process is generally oxygen deficient, and the propagating reaction leaves behind a char that contains a significant amount of unburned fuel[13].

The rate of one-dimensional opposed smolder propagation is dictated primarily by a balance between the rate of heat released by the reaction and the energy required to heat the solid fuel and gaseous oxidizer to the smolder reaction temperature. Increasing the oxidizer flow rate increases the rates of fuel oxidation and heat release, and consequently the rate of smolder propagation. However, the energy required to bring the incoming fuel and oxidizer to the reaction temperature also increases with flowrate, tending to decrease the smolder propagation rate. These two competing effects result in a smolder propagation rate that as the flow velocity is increased, first increases, reaches a maximum, and then decreases, until a point is reached, at which the heating of the reactants overwhelms the heat released by the smolder reaction and extinction occurs[14-17]. In the presence of gravity, the transport processes that control smoldering are affected by buoyancy. In the absence of gravity, these transport processes lead to a secondary classification of smoldering into forced convection-driven and diffusion-driven smolder. In reality, with multidimensional systems, smolder propagation is often a combination of mixed (forced and free) flow opposed and forward modes with one mode usually dominating.

The experiments presented here are part of the Microgravity Smoldering Combustion (MSC) project, a study of the smolder characteristics of porous combustible materials in a microgravity environment. The aim of the project is to provide a better fundamental understanding of the controlling mechanisms of smoldering combustion under normal- and microgravity conditions. This in turn will aid in the prevention and control of smolder-originated fires, both in normal-gravity and in a space-based environment. The project objectives are accomplished by conducting smolder experiments in normal-gravity and in a space-based laboratory (microgravity), and developing theoretical models of the process. Space-based experiments are necessary as smoldering is a very slow process and consequently its study in a microgravity environment requires extended periods of time that can only be achieved in space.

## FLIGHT HARDWARE

A sequence of photographs illustrating the flight hardware is shown in Fig. 2. The MSC tests are performed in a 21.7 liter, semi-cylindrical, hermetically sealed, aluminum combustion chamber. Two such combustion chambers are incorporated into the MSC flight assembly which contains the remainder of the hardware. The flight assembly integrates into the 0.14 $m^3$ NASA Get Away Special Canister (GAS-CAN), located in the cargo bay of the Space Shuttle.

The fuel sample consists of a flexible polyurethane foam cylinder, 132 mm diameter by 140 mm long, held in a clear quartz cylinder to permit imaging of the progress of the smolder process. The 10% diametric oversizing of the foam sample prevents preferential oxidizer flow between the walls and sample. The sample is loaded into the chamber with ~5 mm protruding from the igniter end of the chamber to insure good igniter contact.

The sample holder consists of a quartz cylinder, a cylindrical disc igniter, a cylindrical metal housing for a char cylinder (120 mm diameter by 52 mm long) placed at the other side of the igniter, and aluminum support brackets. For the opposed flow smolder test, a cap with the oxidizer flow inlet is fitted at the open end of the quartz cylinder, such that the oxidizer flows opposite to the direction of smolder propagation (opposed smolder). The oxidizer supply system provides a constant oxidizer mass flow through the foam sample via regulated pressure upstream of a choked flow orifice. The igniter consists of a 1.16 m 26AWG Nichrome wire (8.2 Ω) configured in parallel rows and sandwiched between two 5 mm thick, 130 mm diameter honeycomb (46 holes/$cm^2$) Cordierite ceramic disks that provide rigidity to the igniter as well as diffuse the heat flow. The igniter is placed at one end of the fuel surface in contact with the interior end of the foam cylinder. The igniter is electronically controlled using temperature at the igniter surface as the control parameter. The fuel sample is instrumented with an array of 10 type-K thermocouples which provide an axial and a radial temperature history of the smolder propagation. Figure 3 illustrates the thermocouple positions and sample holder assembly. Housed within the combustion chamber, the thermocouple compensation board provides electrical ice point compensation and amplification of the thermocouple voltage. The temperature data are later used to determine the rate of smolder propagation, and the characteristics of the reaction. A video camera viewing the side of the foam cylinder records the progress of the smolder reaction by monitoring the location of the brown front.

The MSC chambers are 21.7 liter 6061 T6 aluminum, O-ring sealed containers with top and bottom removable flanges. Two bulkhead electrical connectors are installed on each chamber to provide power and data access. One valve is present for charging and venting as well as one window for video camera view. The flow system is mounted to the combustion chamber top flange and flat internal wall of each chamber and consists of a 1.12 Liter supply bottle at 650 psig with regulator to maintain constant delivery pressure. The supply bottle and combustion chamber have identical oxygen concentrations. Two calibrated choked flow restrictors are incorporated in the flow system. For the ignition flow, a porous metal restrictor is used and for the test flow a pre-calibrated needle valve is used. The flow is switched from the ignition flow to the test flow via magnetically latching solenoid valves. The flow conditions are verified by pressure transducers at the supply bottle and upstream of the flow restrictors. The variation in flow throughout the test period is 5%.

Two combustion chambers are incorporated into the MSC flight assembly which can be seen in the upper portion of Fig. 2. The assembly is two shelves tied together by support stringers: one with the two combustion chambers and the other with the supporting electronics. The electronics shelf consists of an 800 W-hr capacity silver zinc battery, a power control unit (PCU), an ignition power unit (IPU), a data acquisition and control (DACS) assembly capable of 22.25 hours of data acquisition and storage at 0.2 Hz, two video camera controllers, and two 8 mm videotape recorders. The components of the electronics shelf provide the power, control, and data recording for the experiment. The total weight of the flight assembly is 85.5kg.

The MSC flight assembly integrates into the 0.14 $m^3$ Get Away Special Canister (GAS-CAN) and is housed within the Space Shuttle cargo area. The MSC experiment is initiated by a barometric switch that automatically initiates power at a specific altitude. The experiment operations are then started by the crew or by the MSC computer via a time default. The MSC experiment is deactivated 24 hours after activation The smolder process is initiated in one fuel sample at a time. For the flow test cases, the lower ignition oxidizer flow is initiated just prior to the igniter being switched on. The oxidizer flow is increased to the larger test velocity after the prescribed igniter time has been reached. Once the smolder front is established in the one fuel sample as determined by the temperature profile, ignition of the other fuel sample is started. Video images, pressure data and temperature data are recorded for each fuel sample once ignition is initiated. Data recording continues for 2 hours for each of the two fuel samples. Upon shuttle flight completion, the samples are removed from the combustion vessels, weighed, analyzed for geometric reaction extent (diameter of char region at 100 mm from the igniter and furthest extent from the igniter surface), and photographed. Post-flight gas and TGA analyses are conducted on the microgravity smolder products (gas and solid).

## EXPERIMENTAL MATRIX

Two sets of experiments have been conducted aboard the Space Shuttle Endeavor on missions STS-69 (Sept. 7-18, 1995) and STS-77 (May 19-29, 1996). The experiments investigate the propagation of smolder along a polyurethane foam sample under both diffusion-driven (quiescent) and forced-flow-driven opposed smoldering. Polyurethane foam was selected as fuel because it is representative of materials commonly used on both earth and space-based facilities, its material properties are well known, and it maintains its structural integrity upon smoldering. The physical properties of the foam are given in Table I.

The conditions for the first set of experiments (STS-69) are; 1A) quiescent 35% $O_2$/65% $N_2$ environment, and 1B) forced opposed air velocity of 1 mm/sec. The conditions for the second set of experiments (STS-77) are; 2A) quiescent 40% $O_2$/60% $N_2$ environment, and 2B) forced opposed air velocity of 2 mm/sec. The experiment conditions are part of a matrix of planned experiments that represent a non-convective environment of oxygen concentration ranging from 21% to 40%, and a convective environment with velocities similar to those that can be expected in space facilities, 0.3 to 10.0 mm/s. The ignition period of the forced flow cases has been standardized such that the ignition process is similar for each of the tests. The velocity chosen for this period is 0.1 mm/s, selected so as to minimize the effects of buoyancy on the ignition process[18]. Experiments under the same environmental conditions are conducted in normal gravity for comparative purposes.

## RESULTS

The primary results of the tests are the smolder ignition conditions, propagation velocity, smolder reaction temperature, and products of combustion (solid and gas). The characteristics of the smolder ignition are determined from the igniter power data and the temperature histories provided by the thermocouples on the igniter and in the foam near the igniter. The propagation velocity of the smolder reaction is determined from the temperature histories provided by the thermocouples placed along the foam sample centerline. In determining the smolder velocity, the arrival time of the smolder front at a thermocouple is determined by drawing a tangent line to the temperature curve (see Fig. 4a for example) at the first inflection point and cutting it by a line at a predetermined temperature ($400^{o}$C)[17]. The time at which these two lines intersect is considered the time of arrival at a particular thermocouple. Velocities are then calculated from the difference in time of arrival between adjacent thermocouples and their known spacing. This method is necessary as there is no well defined maximum temperature in the temperature profile. The smolder velocities reported here are an average of the three thermocouples not affected by the igniter nor the sample end. The standard deviation from the average spread rate in each fuel sample in the self-supported region is no larger than 12%. The reported normal-gravity smolder velocities are averages of five tests with a standard deviation of 10% The intensity of the smolder reaction is inferred from the peak temperatures and the temperature profiles provided by the thermocouples. The remainder of the smolder foam, char, and gases contained in the chamber are analyzed for weight and composition. The physical extent of the char produced by the smolder reaction is measured and referred to as reaction extent.

The results from the microgravity smolder experiment are summarized in Table II. Normal-gravity tests conducted in the same combustion chamber as the MSC tests with identical igniter power profiles are also presented in Table II for comparison.

<u>Forced Flow Tests</u>

Both forced flow tests showed strong smolder propagation along the entire sample length. Temperature profiles along the foam centerline for the 1 mm/sec forced air flow case are presented in Fig. 4a for the microgravity test, Fig. 4b for the normal-gravity (downward) simulation and Fig. 4c for the normal-gravity (upward) simulation. Temperature profiles along the foam centerline for the 2 mm/sec forced air flow case are presented in Fig. 5a-c. It is seen that the temperature profiles are similar in both the normal and microgravity cases although smolder temperatures are slightly larger in normal-gravity downward propagation test and slightly lower in the normal-gravity upward test. The temperature profiles from the last three thermocouples, at distances of 80, 100, and 120 mm from the igniter, are used to calculate the self-propagating smolder velocity, because the smolder in this region is not affected by the igniter. For these test conditions, it is found that the microgravity smolder average spread rate lies between the corresponding upward and downward normal-gravity smolder spread rates. This to be expected since, at these flow conditions, smolder propagation is strongly dependent on the availability of oxygen, and in normal-gravity, upward propagation, the buoyant flow opposes (and partially cancels) the forced flow; while in the downward case, the buoyant flow adds to the forced flow. In the case of the low air velocity (1 mm/sec) the smolder velocity in microgravity is approximately 20% lower than the corresponding normal-gravity downward smolder velocity (0.10 mm/sec vs. 0.12 mm/sec). In the upward propagation test, the smolder front actually extinguished as a result of the opposition of the forced flow and the buoyant flow. In the case of 2 mm/sec forced flow, the smolder propagation velocity in microgravity is approximately 12% smaller than in normal-gravity, downward smolder (0.16 mm/sec vs. 0.18 mm/sec) and 31% larger than normal-gravity, upward smolder (0.16 mm/sec vs. 0.11 mm/sec). The observation that microgravity smolder rates fall between normal-gravity upward and downward configurations is similar to observed lean premixed flame propagation rates in the standard flammability limit tube[19] and large combustion vessel[20,21]. The reaction front smolder temperature in microgravity is seen to also fall between those encountered in normal-gravity upward and downward tests. The difference between the normal- and microgravity reaction temperatures is on the order of $10^{o}$C.

The smolder characteristics in the igniter influenced region ($0<x<50$ mm) provide information about thermally assisted smolder. This type of smolder has a practical importance since it is common to have smolder initiated by an external heat source (overheated electrical wire or electronic board, burning object, etc.). As described before, the ignition process for all the forced flow tests is standardized by keeping a constant flow of air of 0.1 mm/sec throughout the ignition period, and electronically controlling the igniter power so that the igniter/fuel interface temperature (TC0,TC1) follows a prescribed temperature profile. This temperature profile was selected from experimentally observing what appeared to be the optimum conditions for smolder initiation[17]. The power to the igniter is turned off once the temperature of the foam at 25 mm from the igniter reaches 380 $^{o}$C, which is interpreted as an indication that the foam is self-smoldering. It should be pointed out that this criteria has been lately modified to the simpler procedure of applying a constant power to the igniter for a given period of time[22].

Inspection of the temperature profiles from the thermocouples in the igniter influenced region (TC2, 3 and 4, Fig. 4) shows a decaying smolder propagation velocity and foam peak temperature, as the distance from the igniter is increased. This is the result of the decreased heat flux from the igniter to the foam as the distance from the igniter increases. The average smolder velocity in this region for both of the forced flow microgravity tests is 0.03 mm/sec, while in normal gravity (upward and downward) it is 0.04 mm/s. The difference can be attributed to the larger heat released by the smolder reaction due to the buoyancy induced air flow. The lack of discernible difference between the upward and downward normal-gravity cases suggests that the buoyantly induced flow through the sample has a velocity somewhat larger than 0.1 mm/s. This is in disagreement with the results of Torero et al.[17] and Cantwell et al.[18] who estimated buoyant velocities in their experiments of the order of 0.1 mm/s. The difference is probably due to the differences in experimental apparatus and the type of experiment, since this velocity is deduced from direct experimental observations.

In normal-gravity, the smolder propagation rate is often observed to increase near the end of the fuel sample. This effect, however, is not observed in microgravity. This seems to confirm that transient smolder observed in normal-gravity[17] is due to increased buoyancy effects as the smolder front approaches the sample. Also, the characteristics of the secondary, forward propagating, char reactions that occur once the opposed smolder front has reached the sample end differ in normal- and microgravity due to the effect of buoyancy on the forced air flow[23].

A more detailed examination of these processes can be found in Torero et al.[17] and Walther[23].

*Analysis of Smolder Products*

Analysis of the MSC experiment gas and solid products are conducted post-flight. The remaining foam and char are inspected, weighed and analyzed by thermogravimetric means. The remaining char left behind by the passage of the smolder reaction has a geometric structure similar to that of the virgin polyurethane foam. The char, however, loses much of the original flexibility of the virgin foam and has a larger pore structure with higher permeability[24]. Figure 6a shows the structure of the char for the 1 mm/sec forced flow microgravity test. It can be seen that the char structure becomes more porous as the reaction proceeds away from the igniter toward the sample end. This seems to be due to the change in the rate of fuel conversion due to the change in oxidizer supply at the completion of the ignition period and possibly due to the different rates of smolder propagation. Figure 6b shows the char sample for the normal-gravity downward simulation. The effect of increasing oxidizer supply due to buoyant flows can be seen in the more open char structure. Torero et al.[17] has previously shown that increased oxidizer supply results in an increased permeability, therefore the more open char indicates a larger permeability in normal-gravity downward smolder than microgravity smolder due to the increased oxygen supply in normal-gravity. Visual inspection of the 1 mm/s char samples indicates that the normal-gravity downward smolder also propagated nearer to the quartz tube and closer to the sample end than the corresponding microgravity test. Normal-gravity upward tests showed the opposite effect. A similar, but less pronounced, trend was observed when the oxidizer velocity was increased to 2 mm/s. In microgravity the heat losses by natural convection are not present, this, coupled with the observation that in normal-gravity downward smolder the transport of oxygen to the reaction zone is larger than in upward smolder, indicates that the transport of oxygen is more important than heat losses in controlling the rate of propagation and intensity of the smolder process.

Thermogravimetric analyses (TGA) were conducted of the polyurethane foam and char samples in both air and nitrogen atmospheres. The decomposition of the samples in nitrogen shows no significant differences between normal- and microgravity smolder. The decomposition occurs in two distinct stages with maximum decomposition rate temperatures of 280$^{o}$C and 380$^{o}$C, similar to results obtained by other investigators[25,26], the plots are therefore not presented here. When the samples are decomposed in air, differences between the normal- and microgravity tests are observed, but the maximum decomposition rate temperatures are not significantly changed, 290$^{o}$C and 520$^{o}$C, Fig. 7. The first peak corresponds to the decomposition of remaining foam or condensed products while the 520$^{o}$C maxima can be attributed to oxidation of the char itself.

The characteristics of the thermal decomposition in air of char samples collected show significant variations along the foam centerline over the fuel length, Fig. 7. These findings are in agreement with the physical appearance of the char samples, Fig. 6. The positions at which TGA char samples were collected are identified on Figs. 6a and 6b as TGA-A through TGA-D. Samples collected at 10 mm from the igniter (Sample TGA-A) show the maximum decomposition rate temperature for the first stage to be lower (250$^{o}$C), while the temperature that corresponds to the second stage (510$^{o}$C) does not appear to be influenced by proximity to the igniter. At 50 mm from the igniter surface (TGA-B), the behavior of the decomposition is markedly different from samples taken at all other distances. A steady weight loss that occurs over a single broad temperature range is observed in both the normal- and microgravity samples.

The thermal decomposition behavior, weight (%) versus sample temperature ($^{o}$C), is shown in Fig. 7a for microgravity sample TGA-B (50 mm) and in Fig. 7b for the normal-gravity downward simulation. Further work is being conducted to examine the influence of the igniter and ignition conditions on the char characteristics at this location. At 100 mm from the igniter surface (TGA-C), the decomposition again occurs in two distinct stages with maximum decomposition rate temperatures of 290$^{o}$C and 510$^{o}$C. This can be seen in Fig. 7c (microgravity) and 7d (normal-gravity downward). These results indicate that the kinetics of smolder are more strongly influenced by proximity to the igniter than by gravity.

TGA in nitrogen to 450$^{o}$C were also conducted on partially degraded foam samples (TGA-D) collected near the sample end. The results for both the normal- and microgravity tests agreed well with a control sample of virgin polyurethane foam. The char generated during these TGA processes was further degraded in air to 900$^{o}$C. While the second stage behavior (520$^{o}$C) remains fairly unchanged, the initial stage of polyurethane decomposition, which has a maximum decomposition rate temperature of 280$^{o}$C to 290$^{o}$C, is no longer observed. Similar results have been observed by Bilbao et al.[25] and Takamoto et al.[26].

Major species gas concentration measurements from post-flight gas samples were made by gas chromatography / thermal conductivity detection (GC/TCD) and the light organic compounds were measured by gas chromatography / mass spectroscopy (GC/MS) according to test method EPA/TO-14[27]. Post-flight gas samples are drawn from the combustion chamber into evacuated stainless steel canisters, for analysis. Due to the gas collection method (post-flight), those gas products that will condense at lower temperatures are not measured. Table III shows the results of the post-flight gas analysis of the forced flow samples. The results show significant production of carbon monoxide and carbon dioxide in all tests, consistent with previous findings[28]. Given the oxygen limited characteristics of the smolder process and the low reaction temperatures, the conversion of fuel to CO and $CO_2$ can be attributed to pyrolysis and/or surface reactions of the fuel[29]. It can be seen that for both forced flow cases, the CO and $CO_2$ yield of the microgravity test falls between those of the corresponding upward and downward tests. This is in correspondence with the observed smolder temperatures and velocities. The 1.0 mm/s upward test was the only test condition that resulted in the smolder not propagating to the sample end, which is also reflected in the low product yield.

It can be seen that the overall concentration of several light organic compounds, is large, $O(10^3$ ppm), which can be attributed to the relatively low temperature thermal decomposition and smolder process[30]. It is interesting to note that these species were found to be in lower concentrations in microgravity than in the corresponding normal gravity tests. Since the oxygen concentration of the gas samples is lower for the microgravity tests, the reduced oxygen levels may be attributed to the oxidation of these light organic compounds. It should be pointed out that this oxidation may also be due to the differences in gas collection method. The microgravity samples are collected upon return to earth several days after the smolder test completion, whereas the normal-gravity counterparts are collected within a few hours of the test completion. Differences in the formation of oxygenated gas species by the smolder process may also lead to the differences in the overall oxygen concentration.

Previous tests conducted with smaller samples and different flow conditions (USML-1) have shown that microgravity smolder may produce more toxic compounds than normal-gravity smolder[31]. The present MSC tests seem to indicate that forced-flow microgravity smolder does not produce more toxic products than normal gravity smolder. The apparent contradiction may be due to the respective sample sizes and test methods. Due to their small size, the previous microgravity tests were heat loss limited and the extent of the reaction was dictated by the igniter conditions. Furthermore, the ambient gas was induced primarily around the sample, rather than through it, and recirculated through the reaction zone which resulted in a decreased chamber oxygen mass fraction and more oxygen limited test conditions. We believe that the present tests provide a better indication about the effect of gravity on smolder toxicity, since these tests were conducted with larger samples and under self-propagating smolder conditions.

Quiescent Tests

In the quiescent tests, the oxygen concentration is the variable experimental parameter. Two tests with oxygen concentrations of 35% and 40% by volume were conducted. It was found that while neither of the quiescent microgravity cases propagated without the influence of the igniter, both of the normal-gravity, downward cases (35 and 40%) propagated.

In the 35% $O_2$ microgravity test case, noise in the temperature readings apparently due to condensation of combustion products on the thermocouple compensation electronics caused the computer to shut down the igniter prematurely at 650 sec (compared to an expected time of 1000 sec). This malfunction can be seen in Fig. 8a and caused concern that lack of a self-propagating smolder may have been caused by the early shut down of the igniter. More aggressive ignition conditions were therefore tested in the 40% $O_2$ case (igniter time 1200 sec), to rule out the possibility of ignition under the previous criteria. In this case also, the smolder front did not propagate much beyond the influence of the igniter in microgravity. This is a dramatic difference from the normal-gravity smolder, where under these conditions the smolder reaction propagates vigorously along the whole sample length. For normal-gravity upward smolder, only the 40% $O_2$ case propagated. In 40% $O_2$ environments, the smolder propagation velocity in downward smolder was 60% larger than upward smolder (0.10 mm/sec vs.

0.04 mm/sec). These results are due to the different characteristics of the smolder process for downward (opposed) and upward (forward) propagation[32,33]. Temperature profiles along the foam centerline for the 40% $O_2$ case are presented in Fig. 9a for the microgravity test, Fig. 9b for the normal-gravity downward simulation, and Fig. 9c for the normal-gravity upward simulation.

It can be seen that in the igniter influenced (thermally assisted) region, the microgravity smolder rate for 40% $O_2$ (0.04 mm/s) is lower than either of the normal-gravity tests. Consistent with the findings of Torero et al.[32,33], thermally assisted opposed flow smolder (downward) has a larger spread rate (0.08 mm/s) than forward (upward) smolder (0.07 mm/s). This indicates that the major effect of buoyancy on quiescent thermally supported smolder is to introduce oxidizer, hence larger heat release, to the reaction zone. The effect of reduced oxygen concentration is also evident in the thermally assisted region as the smolder velocity for 35% O2 is reduced to 0.07 mm/s for the opposed (downward) test, Fig. 8b, and 0.05 mm/s for the forward (upward) case, Fig. 8c.

The effect of elevated oxygen concentration and large porosity is seen upon comparison of the smolder velocity in the thermally assisted region between the quiescent and forced flow tests. The quiescent tests have nearly twice the oxygen concentration as the forced flow cases (40% to 21%) and the smolder velocity is significantly larger than that of the forced flow thermally assisted region. Lack of an induced or forced flow shows that the large amount of oxidizer in the foam due to the large porosity may be more influential to the igniter influenced smolder at early times than buoyantly induced, forced, or diffusive oxidizer supply.

Post-flight gas analysis of the quiescent test samples was conducted and followed similar trends to the forced flow results. The amounts of CO and $CO_2$ correspond to the observed reaction extent and duration of the smolder event. CO levels again were quite high, 1.6% by vol.

for the 40% $O_2$ case and 0.8% by vol. for the 35% $O_2$ case. The light organic compounds detected were similar to those of the forced flow case. Comparison between the normal- and microgravity quiescent tests were not conducted as the microgravity experiments did not smolder in a self-sustaining condition. For the same reason, TGA analyses were not conducted on the quiescent samples.

## MODEL VERIFICATION AND DATA CORRELATION

Several models of pure forced flow opposed smolder combustion have been conducted to date[14-16,34,35]. The microgravity data set of this work is, in principle, the only one suited for their verification. Here, a simplified version of the opposed flow smolder model of Dosanjh et al.[14] has been used to derive an explicit expression for the smolder propagation velocity and to correlate the MSC microgravity smolder velocity data. In the model, smoldering is assumed to be one-dimensional and steady in a frame of reference anchored at the reaction zone, Fig. 1. Note that in this frame of reference the fuel and oxidizer enter the reaction in the same direction in opposed smolder (premixed-like reaction). The gas and solid are assumed to be in local thermal equilibrium, and the solid phase is considered continuous with a constant void fraction. Energy transport due to concentration gradients, dissipation by viscosity, work done by body forces, and kinetic-energy of the gas phase are neglected. Since smolder velocities are generally smaller than oxidizer flow velocities, gas velocities are taken as known quantities at each location in the sample. Furthermore, it is assumed that the smolder process occurs under oxygen limited conditions, consequently the heat released is given by the product of the oxidizer mass flux at the reaction zone, and smolder heat of combustion (energy per unit mass of oxidizer), which is assumed constant and known. Radiation is incorporated in the analysis using a diffusion approximation[36]. With these assumptions, and neglecting heat losses to the surrounding environment, the smolder propagation problem is simply described by the following form of the energy equation:

$$\left[\dot{m}_F'' C_{PF} + \dot{m}_A'' C_{PA}\right]\frac{dT}{dx} = \left[l_{eff} + l_{rad}\right]\frac{d^2T}{dx^2} + Q\frac{d\dot{m}_O''}{dx} \tag{1}$$

where $C_{P\,A}$ and $C_{P\,F}$ are the specific heats of the air and foam, $l_{rad}$ is the linearized radiation coefficient, and $Q$ is the smolder heat of combustion. The mass fluxes of fuel, air, and oxygen entering the reaction zone are given by:

$$\dot{m}_F'' = \left(1-f\right) r_F U_S \tag{2}$$

$$\dot{m}_A'' = f\, r_A U_g \tag{3}$$

$$\dot{m}_O'' = Y_O \dot{m}_A'' - f\, r_A D \frac{dY_O}{dx} \tag{4}$$

where $D$ is the diffusivity. $l_{eff}$ is an effective thermal conductivity of the foam described by:

$$l_{eff} = f\, l_A + \left(1-f\right) l_F \tag{5}$$

The boundary conditions that complete the problem are, at the smolder reaction front; $x = x_S$, $T = T_{S,}$, $\dot{m}_O'' = 0$, $\frac{dT}{dx} = 0$. At the virgin material; $x$ ® ¥, $T = T_i$, $\dot{m}_O'' = \dot{m}_{O,i}''$, $\frac{dT}{dx} = 0$. Integrating Eq. 1 with respect to $x$ from $x_S$ to ¥ and rearranging, the following expression is obtained for the opposed flow smolder propagation velocity:

$$U_S = \frac{r_A\left[QY_{O,i} - C_{PA}\left(T_S - T_i\right)\right]}{r_F C_{PF}\left(1-f\right)\left(T_S - T_i\right)} U_g \tag{6}$$

where $U_S$ is the smolder velocity, $r_A$ and $r_F$ are the densities of the air and foam, $f$ is the porosity, $Y_{O,i}$ is the inlet oxygen mass fraction, $U_g$ is the inlet gas (Darcy) velocity, and $T_S$ and $T_i$ are the smolder and inlet air temperatures.

Equation 6 is used to correlate the MSC data. The smolder reaction temperature is an unknown in the equation, and although the analysis of Dosanjh et al.[14] predicts this temperature through an asymptotic analysis where the smolder reaction is assumed to be a one step, Arrhenius type reaction, it also includes a number of assumptions that often are not applicable to the experiments. For this reason, the experimentally measured smolder reaction temperature is used in Eq. (6) to correlate the experimental data. The smolder heat of combustion is not well determined for smolder combustion and depends strongly on the thermo-chemistry of the smolder process[2]. In this work, the optimization of the data correlation is actually used to empirically deduce its value.

The correlation with Eq. (6) of the MSC smolder propagation velocity data obtained to date, in normal-and microgravity, is presented in Fig. 10 using the optimized value of Q=4,550 kJ/kg-$O_2$ for the smolder heat of combustion. Although two data points are insufficient to reach conclusions, it appears that the model of Dosanjh et al.[14] is capable of predicting the smolder velocity at least for vigorous smolder conditions such as the MSC microgravity tests. It is seen that the normal-gravity data does not correlate well because the buoyant flow induced inside the foam affects the actual value of the gas velocity, and consequently the oxygen mass flux to the reaction zone. It should be noted that in the work of Torero et al.[17], an empirically calculated buoyant flow was combined with the forced flow to improve the correlation of the data with the Dosanjh et al.[14] model. This is also a possible reason for the discrepancy in the smolder heat of combustion calculated from the correlation of the MSC microgravity data

(4,550 kJ/kg-$O_2$), and that calculated by Torero et al.[17] by correlating normal-gravity data (3,900 kJ/kg-$O_2$). We feel that the smolder heat of combustion calculated here, 4,550 kJ/kg-$O_2$, is more accurate due to the more well defined flow within the medium, leading to fewer assumptions in the model.

It should be noted that a simple heat transfer based model of smolder combustion that is able to predict well the smolder propagation, does not imply that chemical kinetics are not important, but only that the problem is controlled by the rate of heat released by, and transported from, the reaction. The heat released is the result of complex thermochemical reactions, not calculated here, but chosen to optimize the correlation of the experimental data. A complete smolder model should incorporate the appropriate smolder chemical kinetics, such that the heat release rate could be calculated upon solution of the corresponding governing equations. Furthermore, the model presented here has the underlying assumption that all of the oxidizer is consumed by the smolder reaction. Thus, it is not applicable to predict smolder conditions where the reaction is weak, because leakage of oxidizer through the reaction may take place and chemical kinetics may dominate the smolder process.

## CONCLUSIONS

The present experiments, although limited, are unique in that they provide the only available data about smolder combustion in microgravity in sample sizes large enough to allow the self-propagation of the smolder reaction throughout the sample length. The experimental results provide further verification about the smolder controlling mechanisms, and data for model verification.

Particularly important is the role of gravity in smoldering, especially in natural convective smolder. In a quiescent, microgravity environment, smolder is a very weak combustion process due to the limited transport of oxidizer to the reaction zone. As a result, heat losses from the reaction to the unburned fuel and surrounding environment play a critical role in determining whether smolder will self-propagate. As expected, in forced flow smolder the role of gravity as an oxygen transport mechanism is less important. However, because gravity also affects opposed forced flow smolder under conditions of vigorous smolder, the effect of gravity is expected to be more pronounced in smolder under limiting flow conditions (low flow velocities and oxygen concentrations) and in transition processes such as ignition, extinction and flaming combustion.

The present tests indicate that, at least in opposed forced flow smolder, the microgravity smolder products are not more toxic than those from normal-gravity smolder. This is in apparent contradiction with the results of previous tests conducted in the USML-1, which produced larger CO and light hydrocarbon concentrations in microgravity than in normal-gravity[31]. The difference is probably due to the respective sample sizes and smolder configuration. The USML-1 tests were conducted with small samples, and consequently smolder was heat loss limited and the extent of the reaction was dictated by the igniter conditions. Furthermore, the air was induced primarily around the sample periphery, rather than through the sample. Thus, since the present tests are conducted with larger sample sizes and result in self-propagating smolder, they should provide a better indication of the effect of gravity on smolder toxicity.

The MSC experiments show that forced flow smolder combustion in the absence of gravity is weaker than in normal-gravity downward smolder and more vigorous than upward smolder. The microgravity quiescent environment tests do not propagate beyond the influence of the igniter. In contrast, normal-gravity upward smolder tests show propagation throughout the entire sample. This illustrates the effect of reduced oxidizer supply to the reaction zone. The flows induced by buoyancy in normal-gravity enhance oxidizer supply to the reaction zone in downward smolder, while in upward smolder the buoyant flow and the downward forced flow (1 mm/sec and 2 mm/sec) are in opposition and partially cancel one another. This results in a reduced oxidizer supply, thereby weakening the reaction. The coupled effect of reduced oxygen supply and enhanced heat losses also affects the relative concentrations of the combustion products. In the region influenced by the igniter smolder occurred under all test conditions. The resulting thermally assisted smolder showed the same effects of gravity on the smolder process and produced heat and products very similar to those produced under conditions that lead to self-supported smolder.

The microgravity tests provide the only available smolder velocity data for forced flow smolder model verification. The good correlation of the forced flow data with the model of Dosanjh et al.[14], indicates that, at least for the present experimental conditions, the smolder propagation process is oxygen limited and controlled by heat transfer from the smolder reaction to the virgin fuel upstream. Theoretical models of vigorous smolder based on these criteria, therefore, may successfully describe the smolder process. The observed lack of self-sustained smolder propagation in a quiescent environment, even for elevated oxygen concentrations, seems to confirm the conclusions derived by Dosanjh et al.[37] and the model predictions of Aldushin et al.[34], which conclude that smoldering cannot self-propagate in the absence of gravity without a forced oxidizer flow. One should be cautious, however, when extending the present results to other geometries (different width and length samples), void fractions and fuels.

Finally, it should be emphasized that the conclusions presented in this work are based on only four microgravity tests: two of opposed flow smolder under optimum propagation conditions, and two of quiescent smolder under conditions of limited oxygen transport to the reaction (encased foam) and intermediate oxygen concentrations. Thus, these results cannot be generalized until further tests are conducted.


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