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# A METHOD FOR ASSESSING MATERIAL FLAMMABILITY FOR MICRO-GRAVITY ENVIRONMENTS

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## Introduction

On a spacecraft, one of the greatest fears during a mission is the outbreak of a fire. Since spacecraft are enclosed spaces and depend highly on technical electronics, a small fire could cause a large amount of damage. NASA uses upward flame spread as a "worst case scenario" evaluation for materials and the Heat and Visible Smoke Release Rates Test to assess the damage potential of a fire. Details of these tests and the protocols followed are provided by the "Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion" document [1]. As pointed by Ohlemiller and Villa [2], the upward flame spread test does not address the effect of external radiation on ignition and spread. External radiation, as that coming from an overheated electrical component, is a plausible fire scenario in a space facility and could result in a reversal of the flammability rankings derived from the upward flame spread test [2]. The "Upward Flame Propagation Test" has been the subject of strong criticism in the last few years. In many cases, theoretical exercises [3] and experimental results [4-7] have demonstrated the possibility of a reversal in the material flammability rankings from normal to micro-gravity. Furthermore, the need to incorporate information on the effects of external radiation and opposed flame spread when ranking materials based on their potential to burn in micro-gravity has been emphasized.

Experiments conducted in a 2.2 second drop tower with an ethane burner in an air cross flow have emphasized that burning at the trailing edge is deterred in micro-gravity due to the decreased oxygen transport [8]. For very low air flow velocities ($U<0.005$ m/s) the flame envelopes the burner and a slight increase in velocity results in extinction of the trailing edge ($U>0.01$ m/s). Only for $U>0.1$ m/s extinction is observed at the leading edge (blow-off). Three dimensional numerical calculations [9] performed for thin cellulose centrally ignited with an axisymetric source have shown that under the presence of a forced flow slower than 0.035 m/s flames spreads only opposing the flow. Extinction is observed at the trailing edge with no concurrent propagation. Experiments conducted by the same authors at the JAMIC 10 second drop tower verified these calculations. Reducing the oxygen supply to the flame also results in a decrease of the Damköhler number which might lead to extinction. Greyson et al. [6] and Ferkul [7] conducted experiments in micro-gravity (5 second drop tower) with thin paper and observed that at very low flow velocities concurrent flame spread will stop propagating and the flame will reduce in size and extinguish. They noted that quenching differs significantly from blow-off in that the upstream leading edge will remain anchored to the burn out edge.

Based on this information a new test method, the Forced Ignition and Spread Test (FIST), which is based on the Lateral Ignition and Flame spread Test (LIFT) [10,11] has been developed to determine material flammability criteria that will address external radiation and opposed flame spread. The cost of the materials to be used in space facilities and the laminar nature of the flow in spacecraft (HVAC systems provide velocities of the order of 0.1 m/s) required the scaling down of the LIFT. The present work provides a systematic determination of the effects of scale reduction on ignition and flame spread and provides preliminary ignition data obtained using the FIST. The material used is commercial grade PMMA.

## Scaling Down Experiments

The LIFT as described by the ASTM Standard [11] was used to systematically scale down the size of the ignition and flame spread samples of PMMA. The sample thickness remained the same for all tests, 12.5 mm, to guarantee that the fuel will remain thermally thick. The standard prescribes an ignition specimen (155 mm x 155 mm) to be placed in the region of constant heat flux and the full sample (155 mm x 806 mm) to study the effect of external radiation on lateral flame spread. Throughout this work the size of both samples was varied systematically and the results are presented in Figure 1.

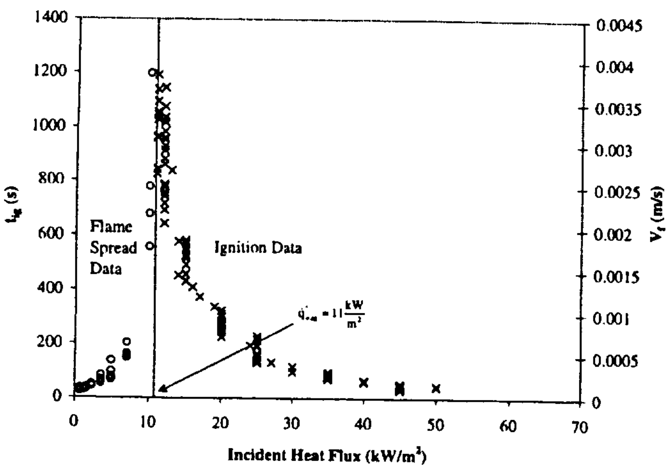


**Figure 1** – Flammability diagram for different sample sizes. The experimental data presented by Quintiere [10] is included.

The samples size was reduced down to a characteristic length of 25 mm showing no significant changes in the ignition delay time or the spread rate. Figure 1 shows a "flammability diagram" where each data point presented corresponds to an average of at least 8 tests conducted under identical conditions. For clarity, the different sample sizes are not indicated but correspond to 12 different characteristic lengths.

Natural convection does have a scale dependent influence on ignition and spread. The buoyantly induced flow enhances mass transfer at the surface but deters the heating process. The opposite effects have the same dependency on the length scale therefore cancel out. In the absence of buoyancy (μg) a forced flow needs to be induced. The effect of a forced flow on the ignition and spread characteristics is being evaluated and preliminary results have been reported by Cordova et al. [12].

## The FIST

The FIST, shown on Figure 2, consists of a cylindrical structure, which is designed to fit inside the combustion chamber of NASA's Spacecraft Fire Facility [13]. Inside the cylindrical structure is a setup of 4 electrical heaters, wired in pairs in series, to provide the external heat flux. The electrical heaters were chosen, as opposed to the LIFT's gas heaters, because of safety and since the electrical heaters' heat flux is less variable in a micro-gravity environment. The heaters are operated digitally to ensure a constant temperature, and therefore a constant heat flux is maintained throughout the test. These heaters are capable of providing a maximum heat flux of 50 kW/m$^2$. Each pair of heaters is hooked up to a solid state relay which controls the AC voltage going into the heaters so this constant heat flux is maintained. Next to the heaters are 4 slide rails. Two of these rails hold the sample holder, which can slide up and down the rails. The sample hoider is capable of holding three samples. A heat shield slides down he other two rails blocking the heat radiation to the non-exposed samples.

The sample holder is moved using a stepper motor attached to a chopper drive. The chopper drive enables the user to output voltage pulses at a very high rate to the motor. The motor is used for two reasons. First, the stepper motor is very accurate, moving the sample to the exact same spot everytime within 1 mm. The second reason the motor is used is because the FIST is placed inside the combustion chamber, which has a controlled flow, so the movement of the sample holder needs to be entirely automated.

Above the sample a Kanthal wire coil is placed and used as the igniter. The Kanthal wire is connected to an adjustable AC current source. The protocol requires for a strong igniter so that the gas phase induction time can be neglected. To determine the necessary current to achieve consistent ignition delay times, a series of preliminary tests were conducted and a minimum current was obtained.

NASA's Spacecraft Fire Facility contains primarily 4 parts, the combustion chamber, the video imaging system, the data acquisition system, and the flow system [13]. Using this facility along with the FIST allows the user to input a heat flux, a material, and a flow, and will receive data regarding the test as well as a videotape of the test. The procedure can be preformed on ground, at normal gravity, with natural and mixed convection and in micro-gravity with a pure forced flow.

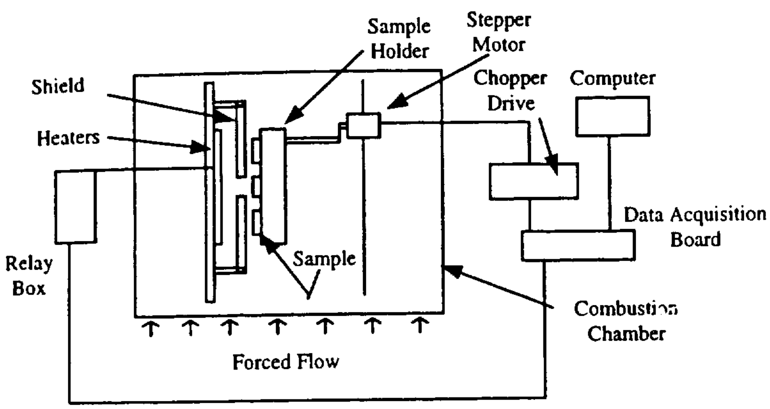


**Figure 2** – The FIST apparatus

## Results

Validation of the protocol was conducted at normal gravity for different forced flow velocities ranging from 0-0.15 m/s. PMMA, polymethyl methacrylate was used because of its well-defined material properties. Piloted ignition is a more critical event, therefore, was made a priority for validation. Tests were, thus, conducted for different heat fluxes and the ignition delay time was determined. Figure 3 shows data for the FIST, the LIFT (different sample sizes) and data reported by Quintiere [10]. The data presented corresponds to $\frac{2}{\sqrt{\pi}}\frac{a}{\sqrt{k\rho C}}$ as a function of the external heat flux. This value is an inherent property of the material and is extracted from the approximate expression of the ignition delay time as proposed by Quintiere [10].

$$\frac{1}{\sqrt{t_{ig}}}=\frac{2}{\sqrt{\pi}}\frac{a}{\sqrt{k\rho C}}\frac{\dot{q}_i''}{(T_P-T_\infty)} \quad (1)$$

where $\dot{q}_i''$ is the external heat flux, $T_P$ and $T_\infty$ the pyrolysis and ambient temperatures, k the thermal conductivity, $\rho$ the density and C the specific heat of the material. As observed from Figure 3, the ignition data from the FIST correlates very well with the data from the LIFT, therefore validating the FIST protocol for ignition. Close to the critical heat flux for ignition, the assumptions inherent to equation (1) break-down and a deviation from the constant value (approximately 0.8) is observed, $\dot{q}_i''<15\,kW/m^2$.

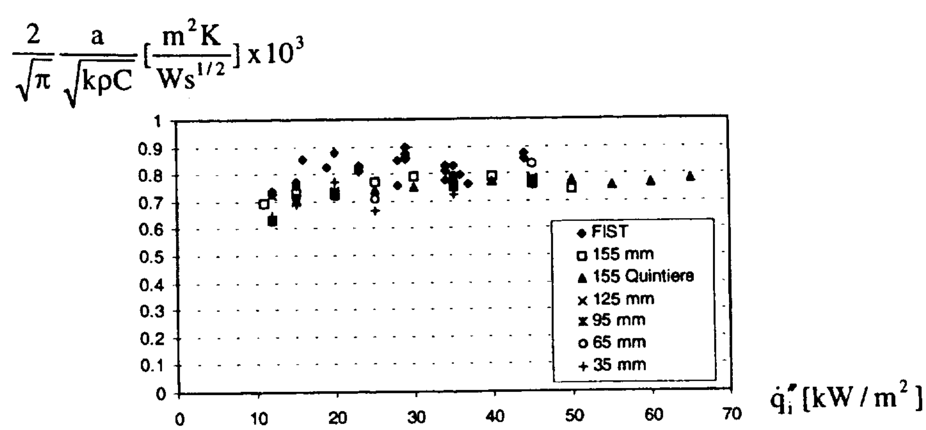


**Figure 3** – FIST, LIFT (different sample sizes), and Quintiere [10] ignition delay times as a function of incident heat flux.

## Conclusions

The "Upward Flame Propagation Test" as a mechanism to assess material flammability for micro-gravity environments has come under considerable criticism in the last few years mainly based on combustion results obtained under similar conditions to those found in spacecraft. Two common criticisms are the inability to test the behavior of materials when subjected to an external heat flux and the absence of information on material properties aiding opposed flame spread (found to be more persistent than forward spread in micro-gravity). The LIFT provides complementary information that addresses the effect of external radiation and opposed flame spread. A reduced scaled version of this test, called the FIST, suitable for micro-gravity environments has been developed and validated. Experimental results indicate, that at least for PMMA, there is a firm agreement between the data from the LIFT, tests with the LIFT at a reduced scale and data from the FIST.

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