



An Experimental Study of Upward Burning Over Long Solid Fuels: Facility Development and Comparison

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Acknowledgments

This project was funded by the Fire Prevention, Detection and Supression (FPDS) project under the NASA Exploration Technology Development Program (ETDP). The authors would like to thank NASA GRC FPDS team: Gary Ruff, Paul Ferkul, Sandra Olson, Fletcher Miller, and James T'ien, design engineers Kenneth Gregg and Daniel Gotti, and the VF-13 facilities support team. Co-operative education student Tavis Hall performed most of the stacked-chamber facility tests, John Brooker modeled the flow field of the stacked-chamber facility, and Jay Owens supported the imaging setup and data acquisition for the VF-13.

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Abstract

As NASA's mission evolves, new spacecraft and habitat environments necessitate expanded study of materials flammability. Most of the upward burning tests to date, including the NASA standard material screening method NASA-STD-6001, have been conducted in small chambers where the flame often terminates before a steady state flame is established. In real environments, the same limitations may not be present. The use of long fuel samples would allow the flames to proceed in an unhindered manner. In order to explore sample size and chamber size effects, two large chambers were developed at NASA GRC under the Flame Prevention, Detection and Suppression (FPDS) project.

The first was an existing vacuum facility, VF-13, located at NASA John Glenn Research Center. This 6350 liter chamber could accommodate fuels sample lengths up to 2 m. However, operational costs and restricted accessibility limited the test program, so a second laboratory scale facility was developed in parallel. By stacking additional two chambers on top of an existing combustion chamber facility, this 81 liter "Stacked-chamber" facility could accommodate a 1.5 m sample length. The larger volume, more ideal environment of VF-13 was used to obtain baseline data for comparison with the stacked chamber facility. In this way, the stacked chamber facility was intended for long term testing, with VF-13 as the proving ground.

Four different solid fuels (adding machine paper, poster paper, PMMA plates, and Nomex fabric) were tested with fuel sample lengths up to 2 m. For thin samples (papers) with widths up to 5 cm, the flame reached a steady state length, which demonstrates that flame length may be stabilized even when the edge effects are reduced. For the thick PMMA plates, flames reached lengths up to 70 cm but were highly energetic and restricted by oxygen depletion. Tests with the Nomex fabric confirmed that the cyclic flame phenomena, observed in small facility tests, continued over longer sample. New features were also observed at the higher oxygen/pressure conditions available in the large chamber.

Comparison of flame behavior between the two facilities under identical conditions revealed disparities, both qualitative and quantitative. This suggests that, in certain ranges of controlling parameters, chamber size and shape could be one of the parameters that affect the material flammability. If this proves to be true, it may limit the applicability of existing flammability data.

1.0 Introduction

In order to select the best materials suitable for existing and new space vehicles, an understanding of material flammability is not only necessary, but crucial. The existing NASA standard, NASA-STD-6001 (Ref. 1), Test 1, has been successfully used for material screening since it was established. However, there are limitations to the test method that may cause it to be inadequate in realistic spacecraft scenarios.

In the standard test, an upward burning test apparatus is used to judge materials on a pass/fail basis using a fixed sample width and length, 2.5 and 12 in., respectively. If less than half of the total sample length is burned, and fails to ignite surrounding materials, the material is approved for use. What is not

addressed is the role of the sample dimensions. Width effects have been studied previously and are known to play a role in the flammability and flame spread characteristics (Ref. 2). Flame lengths, even at these widths, can grow quite long and exceed a 1 ft sample length. The resulting flow field effects could influence propagation length.

Likewise, most of the past upward burning studies (Refs. 3 and 4) were performed in small, laboratory-scale combustion chambers (~30 L). While 1 ft sample lengths were accommodated, the chamber size limitation necessitated narrow (≤ 1 in.) samples. This was done to minimize the oxygen depletion effects in a closed chamber (without influencing the flame with a forced flow field). Narrower samples also mean that edge effects play a larger role, both in terms of heat loss to the sample holder and the three dimensionality of the flow field over the flame width. The result is that the flame reaches a stable length within the restricted chamber size. Upward burning in large chambers, those in the range of hundreds of cubic feet, using wider and thicker fuel has never been reported.

The goal of this study was to explore whether a flame would reach a stable length given ample sample length and chamber size. After ignition, the sustainability of an upward burning flame is dictated by the energy balance between the heat generated from the flame and that lost through various mechanisms including; radiative heat loss to far field or chamber wall, conductive/convective heat loss to surrounding gases (if the surrounding space is sufficiently large that the heated air does not flow back to the flame region), and heat loss into the fuel thickness. If the losses are too great, the flame may shrink or self extinguish. When in balance, the flame should maintain, or oscillate around, a stable length. This is similar to the well known case of a vertical gas jet flame. A gas jet flame will reach its maximum flame length at a certain fuel flow rate. Any further increase of that flow rate will lead to flickering and/or soot emission of the flame, indicating the flame tip is being quenched by heat loss. While there are more losses in the case of solid fuel combustion (heat loss to the fuel surface), the same fundamental principle should apply.

Another objective of this study was to understand whether flame self-extinguishing phenomenon is material dependent or is it also affected by sample size and chamber volume. This is related to the validity of the NASA Standard 6001 test, which implicitly assumes that flame self-extinguishing is a material property. The third objective of this study was to verify the cyclic propagation feature of Nomex flames observed in earlier studies (Ref. 5). Limited by the sample size, the previous study showed no more than two cycles of Nomex flames. The last objective was to utilize the controllable oxygen/pressure environment to mimic a low gravity environment by reducing buoyancy effect. Flame spread rates in reduced gravity environments can be estimated based on the pressure scaling method (Ref. 3) at various oxygen concentrations. This correlation was verified on-board an aircraft flying parabolic trajectories at partial gravity levels.

Two large scale facilities were used in this study; Vacuum Facility (VF) 13 at NASA GRC and a laboratory scale facility consisting three stacked combustion chambers (27 L each). The VF-13 chamber provides a more ideal environment, but its operational costs are high, whereas the stacked chamber facility is more accessible with a lower operational cost, but is more size-limited. Tests in the two facilities were run in parallel so the VF-13 results could be used to validate and define the limitations of the stacked chamber facility, where a large number of future studies would be performed.

This document describes these facilities and the tests conducted in them within the project's time allotment.

2.0 Hardware

2.1 Vacuum Facility #13 (VF-13)

The vacuum facility VF-13 is a large volume chamber designed for tests requiring a high vacuum environment. Here, it was utilized to provide a controlled gas environment at reduced pressures (less than atmospheric). An experimental rack was built to integrate the test specific components, such as cameras,

sample holder, igniter, mixing fan, etc. into the facility. Control hardware outside the chamber included a chamber gas filling panel, an oxygen bottle, video recorders, and a control panel. These systems will be described in detail below.

2.1.1 Vacuum Chamber

The vacuum chamber VF-13 (Fig. 1) is a vertical cylindrical chamber with a 149.9 cm inner diameter and 360 cm height. The total internal volume of the chamber is 6.35 m³. The upper portion of the chamber is a removable cap (about 252.1 cm tall) with four viewing windows (~12.5 cm diameter each). The fixed base (107.9 cm deep) accommodates the electrical feed-throughs and gas line fittings. Since the chamber was originally designed for high vacuum applications, it is equipped with a roughing pump, which can lower the chamber pressure to 0.03 torr, and a diffusion pump, which can further reduce the chamber pressure down to 4×10^{-7} torr. For this experiment the diffusion pump was not needed.

Partial pressure gas mixing was used to achieve test conditions in lieu of premixed gas bottles. This was more cost effective given the large volume of gas, and offered more flexibility. Only nitrogen (from the facility reservoir) and oxygen (from K bottles) mixtures were used. An analog gas control panel was built to proportion the gases.

Each gas filling line consisted of two parallel paths; one was for fast filling controlled by a ball valve, the other was for slow filling through a metering valve and a ball valve, connected in series. A calibrated, precise pressure transducer (Setra, Model 270, 20 psia, ± 0.05 percent full scale accuracy) was used to monitor the chamber pressure during the filling process. A HIGHVAC* vacuum pump, model HVP 300 was installed on the chamber to evacuate the combustion products after each experiment run. The unique feature of this vacuum pump was that it had no moving parts in it, thus use of this pump could prevent the roughing pump from possible corrosive damage from the combustion products after each test run.

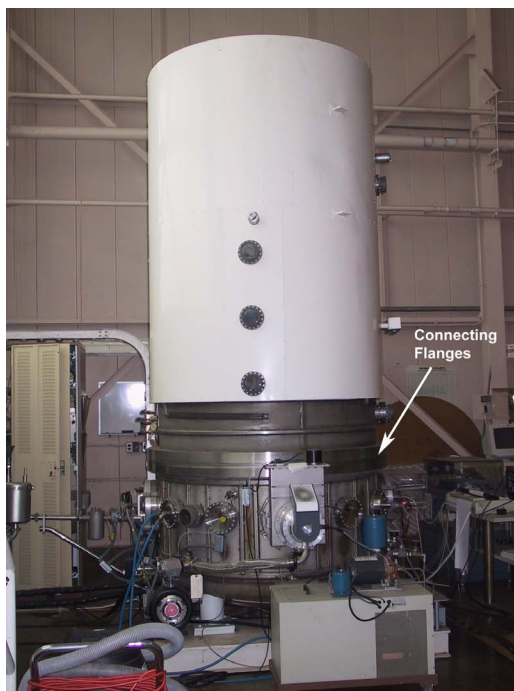


Figure 1.—The VF-13 chamber. Electrical and gas feed-throughs are located at the bottom part of the chamber. The white cylinder is the removable cap.

2.1.2 Experimental Rack

The frame of the experimental rack was made of aluminum BOSCH REXROTH* bars (45 Series Profiles with 10 mm T slots) with overall dimension of 229 cm high, 69 cm wide, and 125 cm long. The experimental components mounted on the rack included a removable sample holder, two reflecting mirrors, an igniter with a pneumatic actuator, a mixing fan, three video cameras and a long green LED strip for illumination. Figure 2 shows the rack assembly in the VF-13 chamber with the lid removed and Figure 3 shows a schematic layout.

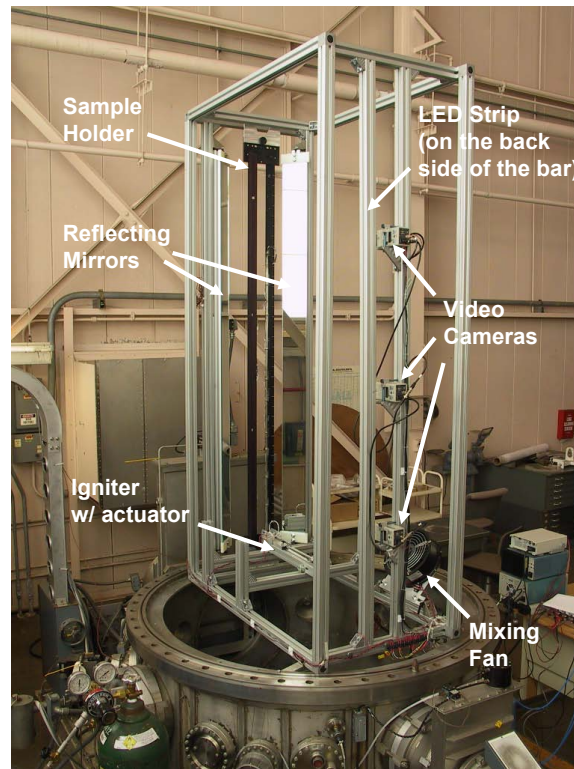


Figure 2.—The experiment rack is mounted on the bottom part of the VF-13 chamber with all the components installed.

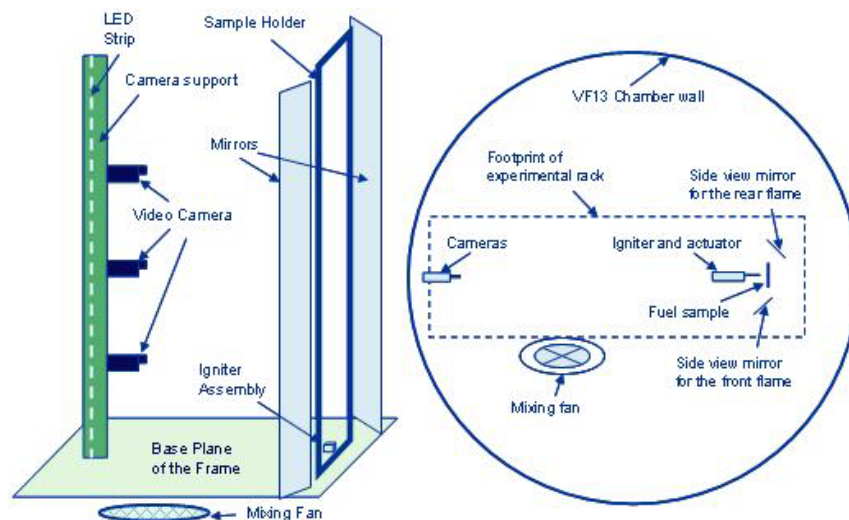


Figure 3.—Schematics of the experimental rack showing side (left) and top view (right).

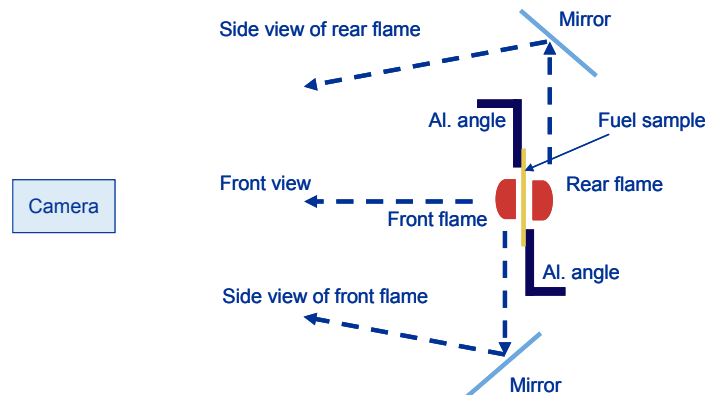


Figure 4.—Top view of the arrangement of the aluminum angles and the mirrors. This made it possible to image the front view and two side views of the flame with the same set of cameras.

2.1.3 Sample Holder

The sample holder consisted of two parallel pieces of angled aluminum bars (37 by 50 by 1950 mm) connected by two cross plates at the top and bottom. Conical lugs on the cross plates mated to dovetail slots on the experimental rack for easy mounting. The gap between the parallel bars could be adjusted to distances of 1, 2, 5, and 10 cm using set screws. This gap governed the burnable width of the samples, which were attached to the bars using adhesive aluminum tape (for thin flexible materials). Thick, rigid materials were directly attached to the holder using screws.

Figure 4 shows a top view schematic of the bars with the sample mounted. The vertical edges of the two aluminum angles faced opposite directions to accommodate the edge (side) views of the fuel sample. Two mirrors were positioned so that one displayed the side view of the rear flame and while the other displayed the side view of the front flame. In this manner, the same camera could image both edges as well as the front of the fuel sample.

Note: In several tests (indicated by and (*) in Section A.2.3) the sample card from the stacked chamber facility was used in VF-13. This was done to reduce the number of variables between the facilities.

2.1.4 Video and Imaging

Imaging the full 1.8 m viewable sample length posed some challenges. Cameras had to be mounted inside the vacuum vessel since the available window ports were not adequate to cover the sample length. The cameras were positioned as far from the sample as possible (850 mm) to avoid heat exposure. Three identical analog color CCD video cameras (Panasonic* VW-CP352) were used to record flame images. The cameras were mounted with the long side of the 6.4 by 4.8 mm CCD sensor in the vertical direction, to obtain a larger field of view. Using 12 mm lenses, each camera viewed 627 mm of the sample, which accounts for the full sample length with some overlap.

A time code generator was used to synchronize the three cameras and produce a time stamp in the video recordings. The signal from each camera went to a video amplifier which had two output ports. One port was connected to a DVCAM* tape recorder and the other to a designated computer that could perform real-time digitization of video image. The DVCAM* recording served as a backup for the digital system.

Green LED lights were installed inside the chamber to illuminate the pyrolysis front of the fuel. The green light was found to illuminate the fuel without saturating the flame front. Six LED strips were mounted to the camera boom. Each strip was 1 ft long and 1/2 in. wide printed circuit board, which could be separated into four basic sections, of three LEDs each. Connectors located at the two ends of each strip allowed the individual strips to be connected together, and powered in parallel. Thus, they all shared a 12 VDC power source where each additional strip would increase current draw from the power source.

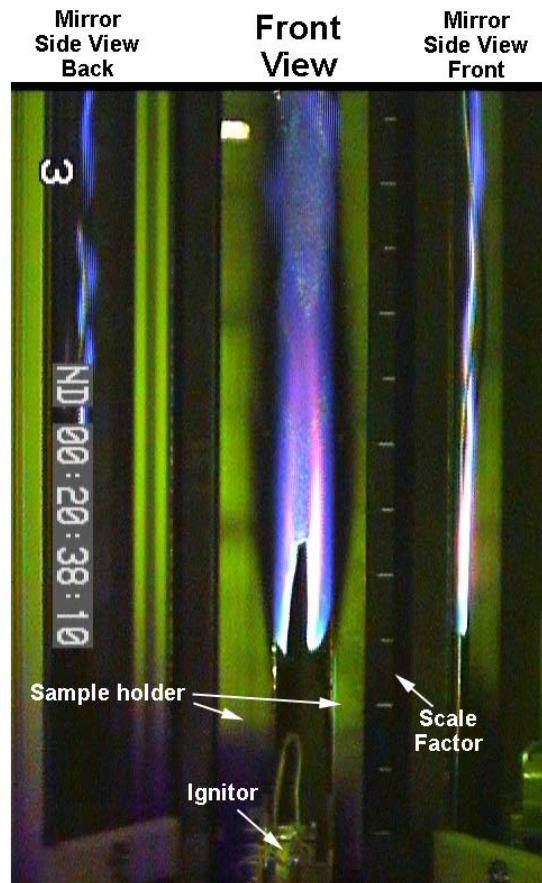


Figure 5.—A video frame showing a flame in VF-13. The front view is in the center with the two mirrors reflecting the side views on either side.

The wavelength of the green LED was 525 nm and the luminous intensity of each LED was 3000 millicandela (mcd) with 90° view angle. In this experiment, a total of 72 LEDs were used. They provided sufficient luminosity on the fuel example.

2.1.5 Reflecting Mirrors

Mirrors were used so that front and side views of the sample could be obtained using a single camera. The angle bars used to construct the sample cards provided structural support, but occluded the view of one side of the sample, as shown in Figure 4. The mirrors were oriented parallel to the sample and positioned to minimize heat exposure while remaining within the camera field of view. However, this distance and the angle relative to the sample holder could be adjusted to ensure proper imaging. The width of the camera field of view was 460 mm, therefore the distance from the center of the mirror to the center of the fuel sample was 183 mm. Because the distance of the mirrors to the camera was offset, these side view images were slightly out of focus.

2.1.6 Igniter and Igniter Actuator

The igniter used in VF-13 was a 24 VDC, 50 W Glo-stix* igniter, which had a 1 cm long silicon nitride heating tip and an insulated mounting plate (Fig. 6). Since silicon nitride does not react with oxygen when heated, it can be used repeatedly without deteriorating.

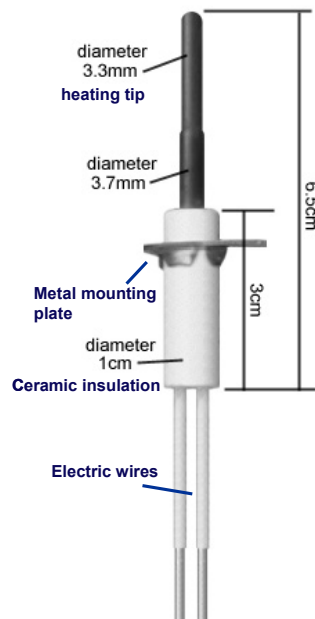


Figure 6.—The Glo-stix silicone nitride igniter.

The igniter reached its stable temperature (1200 °C) in 10 to 15 sec using the existing power supply. A pneumatic piston actuator controlled the position of the igniter so that it only contacted the sample after reaching its full temperature. If advanced prior to this, the slow heat up would create a pyrolysis hole in the fuel and there would be insufficient fuel in the igniter region to trigger an ignition. The actuator was driven by low pressure nitrogen gas. During the warm up period, the igniter remained about 3 cm from the fuel surface. When actuated, the igniter contacted the fuel surface, with slight over drive to ensure firm contact between the igniter and the fuel surface.

2.1.7 Gas System

Partial pressure mixing was used to obtain the desired gas concentration in the chamber. Because the oxygen and nitrogen are filled separately, there is potential for a non-uniform gas mixture. Pure molecular diffusion is a very slow process. Thus, a 550 cfm, 12 to 28 VDC fan with brushless motor was installed in the chamber to promote the mixing process. The capacity of the fan was large enough to circulate the entire chamber air 2.5 times per minute under standard conditions. The fan was run for 10 min after gas fill, followed by 2 hr of settling time before the test was initiated.

The gas filling procedure was also designed to promote gas mixing. The gas feed port was located at the bottom of the chamber. Thus, by filling the lighter gas (nitrogen) after the oxygen, the upward buoyant flow would encourage mixing. Inside the chamber, the gas feeding tube was installed tangentially to the chamber wall and slightly tilted upward. Thus the gas flow into the chamber would follow a spiral path, which would help mixing.

2.1.8 Electrical Power

Three Tektronix* PS280 DC Dual power supplies were used for a total of six power supply units. The maximum capacity of each unit was 2 A and 30 VDC. All power units were operated independently to power three cameras, the igniter, the mixing fan, the LEDs, and the pressure transducer.

A switch box was built to control the electric devices inside the chamber; each of the three cameras had its own designated switch, as well as the LED strip, the mixing fan and the igniter. The input ports were connected to the DC power supplies, while the output cable connected to the devices inside the chamber via an electric feed-through.

2.2 Stacked Chamber Facility

Though the VF-13 facility was well suited to the project's test objectives, it is expensive to operate and has limited availability. Therefore, a smaller volume, laboratory scale facility was developed for longer term test objectives. However, size restrictions of this smaller facility limited the range of test conditions in terms of sample width and environmental conditions. (Higher oxygen and/pressure conditions would lead to more energetic and larger flames. Heat loss to hardware and local oxygen depletion may result from the restricted volume). Data from the larger, less restricted, VF-13 were used to define the test range. If the results from the smaller facility compared well to VF-13, then an acceptable test condition in the stacked chamber facility was achieved.

2.2.1 Combustion Chambers

The combustion chamber for this facility (Fig. 7) consisted of three identical chambers stacked vertically. Each chamber was 53.7 cm tall and 25.4 cm in diameter (27 L), resulting in a stacked height of 161 cm (81 L). The bottom chamber was contained in a pre-existing combustion facility known as the Spacecraft Fire Safety Facility (SFSF), which was frequently used for low gravity testing aboard the NASA reduced gravity aircraft. This facility was already setup with an ignition system, instrumentation (pressure transducers, thermocouples, etc.), video recording, gas flow, control and data acquisition devices, and a designated computer with operational software. Thus the addition of the chambers to this facility was a simple, low cost, solution to achieve the test objectives.

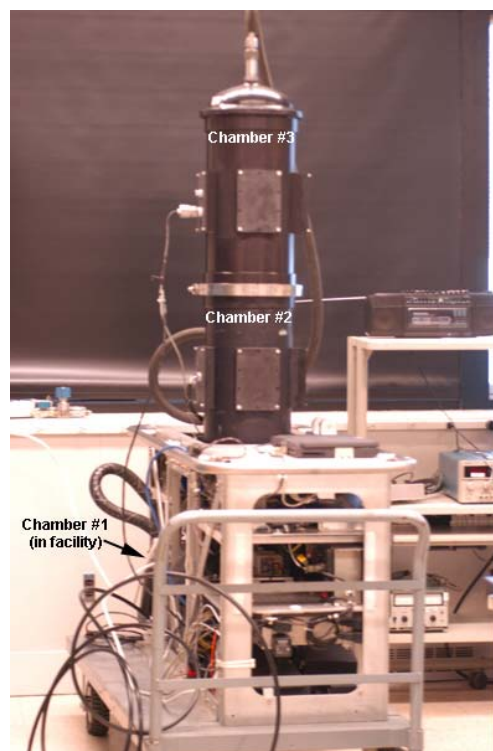


Figure 7.—The Stacked-chamber facility. A preexisting combustion facility with all the necessary support equipment is at the base with two chambers, identical to the pre-existing one, stacked on top to elongate the test section.

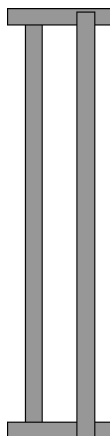


Figure 8.—A schematic of the stacked-chamber sample holder.

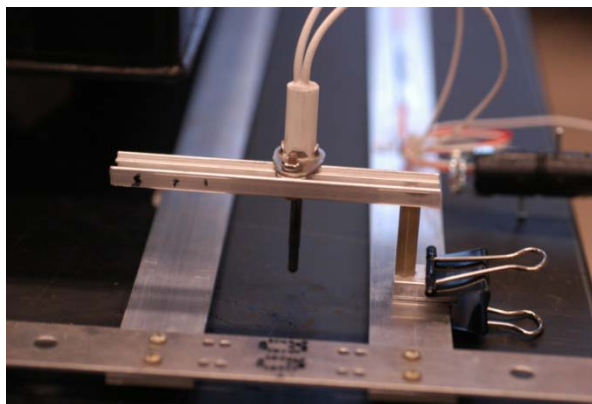


Figure 9.—The Glo-stix igniter on the stacked-chamber sample holder. The tip of the igniter contacted the fuel surface.

2.2.2 Sample Holder

The fuel sample was held on a thin metal card set in the middle of the chambers. This holder had two parallel aluminum rails with a 1 by 1/8 in. cross section area, connected by two crossbars at ends, and is shown schematically in Figure 8. The sample was taped to the rails such that the exposed area between was the burnable sample. The sample width could be adjusted to 1, 2, or 5 cm, and the maximum length was 1.5 m. Metal tape was used to affix the sample and prevent edge flames. A reusable glow plug resistance heater was used for ignition (Fig. 9) and placed such that its tip was in direct contact with the sample near its lower edge. An identical igniter was used in the VF-13 (Fig. 6), though the stacked-chamber facility igniter could not be retracted.

2.2.3 Gas System

Unlike the VF-13 facility, the stacked-chamber facility had a relatively narrow diameter, and thus a limited volume where oxygen depletion could be significant. To mitigate this effect, fresh oxidizer was flowed through the chambers at low speed. These gas flows were less than 10 cm/s, which was high enough to counter depletion (see Section 3.4.2 for the calculations) but well below the estimated buoyant flow velocity. The inlet flow was supplied by a gas cylinder (type K) containing the desired premixed oxygen/nitrogen concentrations, and regulated by a mass flow controller. Screens and honeycombs in the base of the bottommost chamber assured a uniform flow entering the chambers. A vacuum pump on the exit line drew the flow through a port at the center of the lid at the top of the stack. A backpressure valve which regulated the chamber pressure (3 to 14 psia) was autonomously controlled based on feedback from the chamber's pressure transducer.

2.3 Video and Imaging

As with the VF-13, the primary data acquisition was visual flame images. Due to the large aspect ratio of the chamber, video imaging was particularly difficult. While the individual chambers had windows, they were not spaced to allow for viewing of the entire sample. Therefore, the cameras had to be mounted inside the chamber (Fig. 10). The sample was mounted in the center plane of the chamber, whose radius was 12 cm. Allowing room for a camera mounting bracket, the distance between the lens and the fuel was 8.3 cm. Thus, nine cameras, each with a 2.5 mm lens, were needed to cover the total sample length with some field of view overlap (Fig. 11). Green LED lighting strips, identical to those in the VF-13 facility were installed to illuminate the sample.

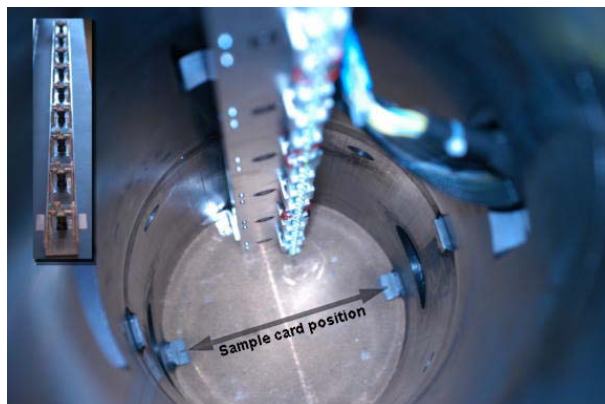


Figure 10.—Image of the camera mount looking down from the top of the stacked chamber. The LED light strip is shown beside the holes for the camera lenses. The sample card (not shown) would be located on the horizontal centerline. The inset image shows the back side of the camera mount.

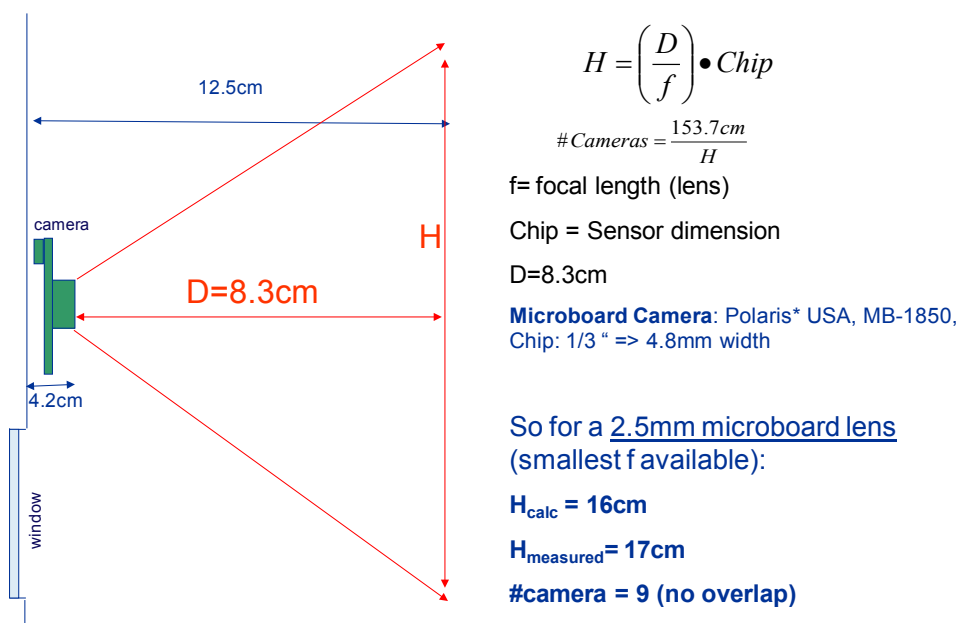


Figure11.—This graphic shows the dimensions and calculations used to determine the stacked-chamber facility imaging set up. Due to the size of the lens, there was significant distortion at either end of the image. The useable field of view was 17 cm assuming some overlap between the cameras.

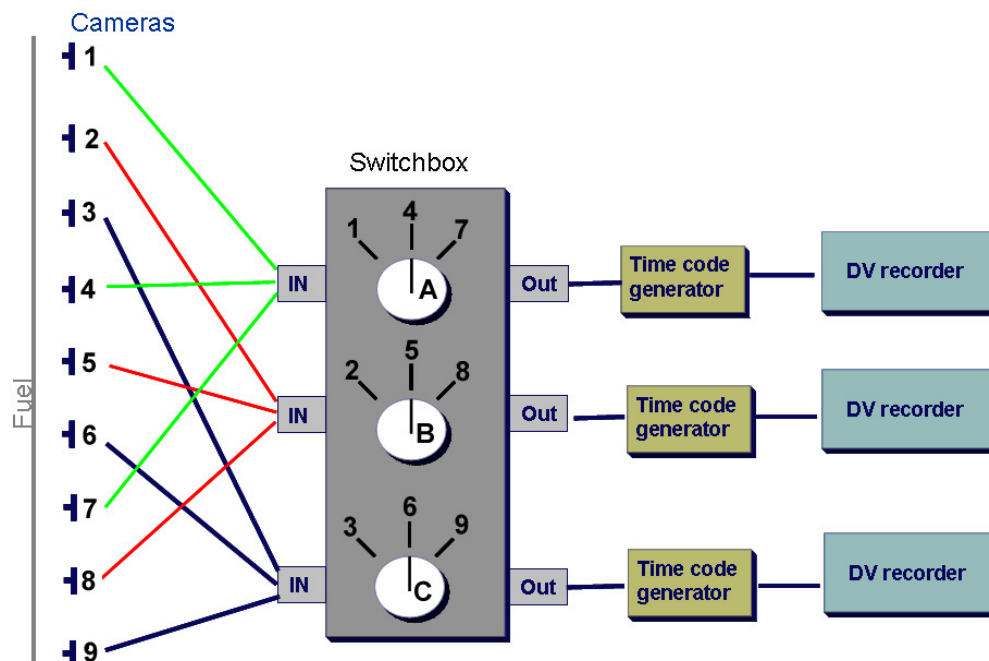


Figure 12.—A schematic showing the video switching system. Three video recorders were used, so at any time three of the nine camera views were recorded. Once the flame propagated out of field of view, the recorder was switched to the next camera view. For example, the switchbox was initially set to cameras 9, 8, and 7 (ignition in camera 9). Once the flame exits the field of view in camera 9, the switch C was advanced to camera 6.

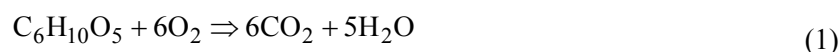
The nine camera signals were sent to three digital video recorders. A manual switchbox was used to toggle between camera views as the flame advanced. Figure 12 shows the arrangement of the cameras and the recorders. Ignition occurred in the field of view of camera 9, so the switch box was initially set: C:9, B:8, and A:7 (where the letter designates the recorder and the number designates the camera). Once the flame base propagated out view, switch box C was set to camera 6, and so on. The assumption was that the flame length would not exceed the field of view three cameras. This arrangement saved cost (fewer recorders and time synchronization signals).

3.0 Fuel Materials

Three types of fuel materials were tested in this project, all are hydrocarbons so the products were primarily water and CO₂, with trace amounts of CO. These materials all have some prior testing in an upward flame spread configuration.

3.1 Cellulose (Paper)

Paper fuels have been traditionally used in combustion experiments because they are widely available, used in many applications, and they typically burn out (little to no material remaining after flame spread). The primary products of combustion are H₂O and CO₂, with trace amounts of CO.



They are also convenient for low gravity experimentation because they ignite and spread quickly. This is conducive to the short test durations available in the ground based microgravity facilities (drop

towers and reduced gravity aircraft). Paper fuels were chosen in this application to make use of the existing knowledge and data. Many of the previous studies (Refs. 3 and 4) utilized Kimwipe paper (thin tissue paper used as laboratory wipes). However this material is only fabricated in 42 by 38 cm sheets. A continuous 2 m long, seamless sample was needed to make full use of the facilities.

The first set of tests were performed using adding machine paper which has an area density of 6.3 mg/cm^2 . Adding machine paper was a convenient choice since it is fabricated in long strips and was used in the study by Chu (Ref. 2). However, some unexpected flame behaviors were observed with this material, particularly in the stacked-chamber facility (Section 5.3.1). Since the main goal of testing was facility comparison, as opposed to fuel property characterization, a better performing material was found.

The new paper material was a 7 mg/cm^2 poster paper. This material is manufactured by Bienfang, part #321-128, is trade named “Brushmaster White Poster paper.” It has a basis weight of 18 lb and is manufactured in a long, seamless lengths.

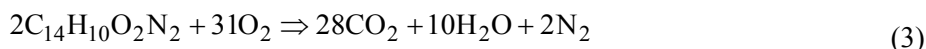
3.2 PMMA

Polymethyl methacrylate (PMMA) is a plastic material that can be formed into a variety of thicknesses. Therefore, this material was used to study sample thickness effects in VF-13. Clear cast PMMA plates from Professional Plastics 5.59 mm thick were used for this experiment. The primary products of combustion are H_2O and CO_2 , with trace amounts of CO and MMA.



3.3 Nomex

Nomex fabric is widely used in industries, including aviation and spacecraft, as a fire protection material, because it is not flammable at standard atmospheric conditions. However it is advantageous to employ higher oxygen, lower pressure conditions in spacecraft. To ensure health and comfort of the crew, the conditions are typically normoxic, where the oxygen partial pressure is the same as at sea level. At these conditions Nomex can become flammable (Ref. 5). Nomex is not completely consumed by flame; the remaining charred material is brittle, but retains structure. The primary products of combustion are H_2O and CO_2 , with trace amounts of CO and N_2O .



Different blends and weaves of Nomex fabric are available. The blend used in this study is called Nomex III, which contains 92 percent Nomex, 5 percent Kevlar, and 3 percent p-140 (carbon based anti-static material). This is the blend commonly used in flight suits. The weave was a 0.18 mm thick fabric with an area density of 11 mg/cm^2 and a thread count of 30×28 threads per centimeter.

Previous studies of this material (Ref. 5) showed unique cyclic flame phenomena, whereby continually elongating flames would break into two smaller propagating flames. Oxygen shadowing and heat loss mechanisms would drive one flame to extinction, leaving the remaining flame to elongate and repeat the cycle. This phenomenon was attributed to a two stage pyrolysis resulting from the material blend (the break off occurs when the lower temperature pyrolysis is triggered by the flame from the higher temperature reaction). The smaller chamber used in the previous study limited the test conditions and number of cycles that could be observed.

3.4 Oxygen Consumption

3.4.1 VF-13

Determination of flame spread rates requires well defined chamber conditions, i.e., the chamber pressure, temperature and oxygen concentration. However, VF-13 is a sealed chamber with no flow into or out of the system during combustion, so the oxygen is depleted as the flame propagates. In order to have a meaningful value of the flame spread rate, the oxygen depletion should be less than 10 percent of its initial amount. This requirement was maintained by setting a limit to the fuel mass that could be burned. The maximum allowable fuel mass that was calculated using the following equation.

$$m_{fa} = \frac{\eta V P_i C_{oi} M}{\varepsilon R T} \quad (4)$$

m_{fa}	maximum amount of allowable mass of fuel consumed in a test before the oxygen depletion in the chamber reaches the allowable limit, kg,
η	maximum amount of O ₂ allowed to be consumed in a test divided by the initial amount of O ₂ in the chamber, dimensionless,
V	The total volume of the chamber, 6.35 m ³ ,
P_i	The initial total pressure in the chamber, Pa,
C_{oi}	The initial mole concentration of O ₂ in the chamber, dimensionless,
M	Molecular weight of the fuel, kg/kMole, 162.1 for cellulose, 100 for PMMA and 238 for Nomex,
ε	Number of moles of O ₂ divided by number of moles of the fuel reacting with the O ₂ in a complete combustion condition, dimensionless, 6 for celluloses (paper) and PMMA, 14 for Nomex fabric,
R	Universal gas constant, 8.314 kJ/kMol/K,
T	Initial temperature of the gas in the chamber, 300 K.

The initial chamber pressure and the volumetric O₂ concentration were the two independent variables in the equation.

$$m_{fa} = r_f P_i C_{oi} \quad (5)$$

where r_f is a constant depending on fuel type with the unit to be kg/Pa.

$$r_f = \begin{cases} 6.878E-6 & \text{for Cellulose} \\ 4.243E-6 & \text{for PMMA} \\ 4.328E-6 & \text{for Nomex} \end{cases} \quad (6)$$

For example, in the case of a Nomex sheet in the initial chamber conditions of 9 psia (or 62053 Pa) total pressure and 30 percent O₂ concentration, the maximum mass of Nomex that could be burnt without consuming more than 10 percent of original amount of O₂ in the chamber would be

$$m_{fa} = 4.328E-6 * 62053 * 0.3 = 80.57E-3 \text{ kg} = 80.6 \text{ g} \quad (7)$$

In most tests with thin fuel sheets, the oxygen consumption was less than 10 percent of the initial amount. The above equation could also be used to check the validity of the test result, i.e., to see if the flame spread rate observed in test was within the oxygen variation limit.

Note: Since the chamber was closed, during combustion, the solid fuel that was consumed changed from solid phase to gas phase, resulting in an increase of total mole number in the gas phase. Thus 10 percent oxygen consumption should not be confused with 10 percent reduction of oxygen concentration.

3.4.2 Stacked Chamber Facility

In the smaller volume of the stacked-chamber facility a fresh oxidizer flow was needed to counter oxygen depletion. In order to maintain a buoyancy dominant flow field, the added oxidizer flow was kept low, under 10 cm/s. The following simple calculations were used to verify that the flow needed to counter depletion was below this value. The oxygen depletion rate was calculated assuming stoichiometric reaction

$$\text{moles}_{\text{ox_deplete}} = \gamma * \text{moles}_{\text{fuel_consumed}} \quad (8)$$

where γ is the mole ratio of oxygen to fuel.

The rate of fuel consumption is found using the flame spread rate and sample dimensions. The flame spread rates were approximated using prior test data (Refs. 3 and 5).

$$\dot{m}_{\text{fuel_consumed}} = \rho_{\text{fuel}} v_f w \tau \quad (9)$$

Where ρ_{fuel} is the fuel density, v_f is the flame spread rate, w and τ are the width and thickness of the fuel sample.

The flow of oxidizer into the facility is calculated

$$\dot{m}_{\text{ox_in}} = f_{\text{ox}} (\rho_{\text{air}} v A_{\text{chamber}}) \quad (10)$$

where f_{ox} is the oxygen mole fraction fill gas, ρ_{air} and v are the density and velocity of the fill gas, and A_{chamber} is the cross-sectional area of the chamber. Combining these equations and solving for velocity:

$$v = \frac{MW_{\text{ox}} (\rho_{\text{fuel}} v_f w \tau) \gamma}{MW_{\text{fuel}} \rho_{\text{air}} A_{\text{chamber}} f_{\text{ox}}} \quad (11)$$

Table 1 shows example calculations for a typical test conditions. For most tests a flow of 5 cm/s was used.

TABLE 1.—CALCULATIONS SHOWING THE FLOW RATE NEEDED TO COUNTER OXYGEN DEPLETION

	Cellulose	Nomex	PMMA
Spread rate	0.427 cm/s	1.12 cm/s	0.5 cm/s
fuel area density	0.00185 g/cm ²	0.011 g/cm ²	0.119 g/cm ²
Thickness	0.031 cm	0.018 cm	0.1 cm
fuel width	2 cm	2 cm	2 cm
Oxygen fraction	0.21	0.21	0.21
MW fuel	162.14 g/mol	238.16 g/mol	101.1 g/mol
MW O ₂	32 g/mol	32 g/mol	32 g/mol
Pressure	10 psia	10 psia	10 psia
	0.680 atm	0.680 atm	0.680 atm
density fill air	0.000802 g/cm ³	0.0008023 g/cm ³	0.00080229 g/cm ³
Area of chamber cross s	506.71 cm ²	506.71 cm ²	506.71 cm ²
mol Ox/ mol fuel	6	15.5	6
mass flow ox needed	0.00 g/s	0.05 g/s	0.23 g/s
velocity needed to counter ox consumption	0.02 cm/s	0.60 cm/s	2.65 cm/s

3.5 Toxicity Analysis of Combustion Products

A toxicity analysis was performed to meet safety regulations. The primary toxic byproduct of all three fuels was CO₂. Table 2 shows the CO₂ generation for the “worst case” experimental scenarios, those in which the maximum possible sample dimensions were used and in which complete consumption of either the material or oxygen (40 percent) (whichever occurs first) was assumed. These were very conservative measurements since the materials were not completely consumed, and the flame would self-extinguish long before all of the oxygen was consumed. The actual tests conducted never reached these extreme conditions. The results show that only PMMA exceeds the OSHA PEL for CO₂ of 5000 ppm. In all tests, the combustion products were vented outside the building prior to opening the chamber, so the concentration of CO₂ in the room would never reach OSHA’s limit.

TABLE 2.—TOXICITY FOR THE POTENTIAL EXPERIMENTAL MATERIALS

	Cellulose	PMMA	Nomex
Sample size (cm)	185 by 5 by 0.031	185 by 5 by 0.56	185 by 5 by 0.018
Density (g/cm ³)	0.597	1.19	0.611
CO ₂ Produced (ppm in chamber)	2637	115110	2500
CO ₂ Produced (grams released)	28	1312	27

3.6 Test Matrices

3.6.1 VF-13

The tests encompassed three different goals, listed below. Refer to Section A.2 for the log of all tests performed in the VF-13 chamber.

1. Obtain baseline data to use for comparison with a smaller volume chamber known as the stacked-chamber facility. The geometry of the stacked-chamber facility poses some limitations of the flame size (including oxygen depletion concerns, and sample width restrictions). These limitations could be explored by comparing the results from the two facilities, where the more ideal VF-13 environment was used as the baseline. Paper fuel samples were used for this comparison.
 - a. Early tests were done in a small (27 L) chamber of the GIFFTS (Gravitational Influences on Flammability and Flame spread Test System) facility. A significant amount of reduced gravity and ground based tests were done using this facility. Due to the small size, most fuel samples were 2 cm in width or less. Several tests were done in VF-13 were done at these conditions for comparison.
 - b. Previous work (Ref. 3) showed that spread rates of reduced gravity flames could be demonstrated in normal gravity by reducing the pressure environment. This pressure/gravity correlation was used in several tests in VF-13 for comparison.
2. Examine flame spread over long samples of Nomex III fabric. Earlier testing performed in small (27 L) chambers indicated a cyclic flame phenomena (Ref. 5). Using the large VF-13 facility, the full extent of this phenomena could be explored; including longer sample lengths and higher oxygen mole fractions.
3. Explore the steady state flame lengths of thick fuel samples. With the large chamber volume, the flames were free to reach their full lengths without hindrance. Samples of 0.5 cm thick PMMA were used.

This report primarily covers objective #1, the comparison of the two facilities. The results from the Nomex III fabric tests (objective #2) will be briefly mentioned in this report for completeness. A later publication will provide detailed description of the cyclic flame phenomena observed in VF-13 facility. Only a limited number of thick fuels tests (objective #3) were performed and will be addressed here. This objective cannot be met using the current configurations, hardware modifications would be required.

3.6.2 Stacked-Chamber Facility

The test matrix for the stacked-chamber facility was more free-form than that of the VF-13 facility. This laboratory facility was easily accessible, inexpensive, and could be operated quickly on an as needed basis. Section A.2.4 shows the log of all tests performed in the facility during this program.

The goal was to obtain spread rate data of paper samples for comparison with VF-13 tests. However, several phenomena were noticed that could not be readily explained (covered in more detail in Section 5.3.1). Many different hardware configurations and fuel samples were used to explore these phenomena.

4.0 Data Reduction

The primary metric for these tests was flame spread rate. This was determined by tracking the flame position in the video frame by frame using an image processing software called “spotlight” (Ref. 8). The output of the software was a pixel location per time, which would then be converted to distance using a scale factor. A scale in the video field of view was used to obtain these factors. This process is well documented (Ref. 9).

Unlike previous studies, multiple cameras were needed to capture the entire sample length. These flame positions had to be synchronized between the camera views, taking into account field of view overlap and (especially in the case of the stacked-chamber facility) lens distortion. The following sections describe the procedure for these data reductions. All the post processing was performed using Microsoft Excel (Microsoft Corporation), with customized macros to perform the data merging.

4.1 VF-13

Due to cracking in the paper fuel, especially over the 5 cm width, it was difficult to identify a single flame base location. To obtain a representative value, the average of three locations was used; the leading edge of the crack, the flame along the right edge of the sample, and the flame along the left edge. Figure 13 shows an image identifying these locations as well as the pyrolysis front.

In order to merge the three camera views, a visual marker was placed near the junction of the camera views. This marker, which could be seen in two cameras, defined the overlap in the field of views (Fig. 14). The length of each camera field of view was 640 pixels, where the origin is at the top. (Recall that the cameras were positioned sideways to maximize the field of view). The gray colored marker in Figure 14 was located at pixel position 500 in camera 1 and at pixel position 70 in camera 2. Therefore there the first 70 pixels of camera 2 are the same image as the last 140 pixels in camera 1. Accounting for the total overlap, there are a total of 1645 unique pixels in the system reference frame.

To merge the camera views, the pixel position of each individual camera had to be converted to the system coordinates. Equations were developed that could be applied to the tracking file of each camera. In the following equations “pix” is the location (pixels) of the flame at a given time step, in a given camera reference frame. The result of the equation is the flame location (centimeters) in the system frame of reference (where the origin is the bottom of camera 3). The terms “OL” are the overlap positions (pixels) as defined in Figure 14. Finally, “SF” are the scale factor (pixels/cm) for each camera.

$$\text{Camera 3: } \frac{640 - OL_3}{SF_3} = \text{position (cm)}$$

$$\text{Camera 2: } \frac{640 - OL_3}{SF_3} + \frac{OL_{2-3} - pix}{SF_2} = \text{position (cm)} \quad (12)$$

$$\text{Camera 1: } \frac{640 - OL_3}{SF_3} + \frac{OL_{2-3} - OL_{2-1}}{SF_2} + \frac{OL_1 - pix}{SF_1} = \text{position (cm)}$$

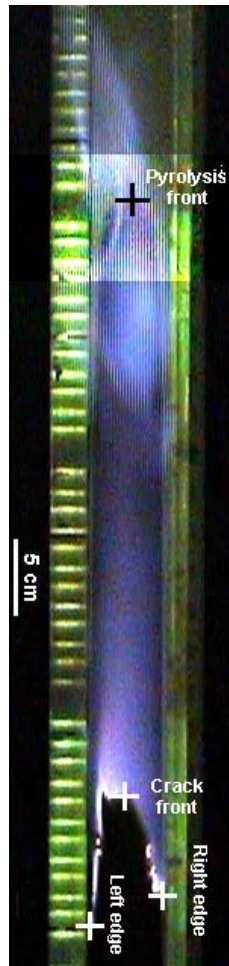


Figure 13.—An image of a flame in the VF-13 facility. The cross hairs represent the flame positions which were tracked.

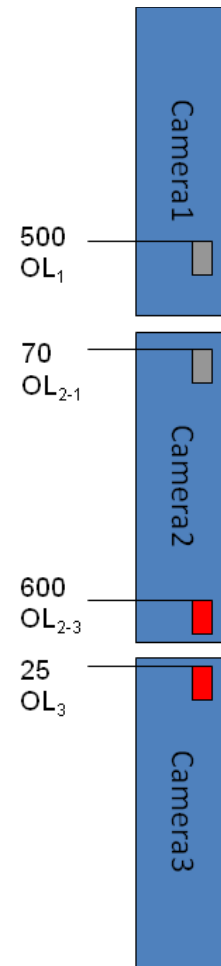


Figure 14.—A schematic of the overlapping method used to mesh the three VF-13 camera views. The red and gray markers are visible in two cameras.

In addition to the flame position, the time stamp from the tracking files also had to be merged appropriately. The video recorded at 30 Hz and since the tracking file logged the video frame number for each pixel position, the elapsed time could be calculated. The system time was available as a synchronized time stamp in all three camera views. The time stamp in the first tracked video frame was used as the reference point to convert elapsed time to system time.

4.2 Stacked-Chamber Facility

A similar procedure was used to reduce the stacked-chamber facility data, but with an added complication in the scale factors. The 2.5 mm lens permitted a wide field of view, but also distorted the image severely (Fig. 15). This meant that the scale factor was dependant on the pixel position, instead of being uniform over the entire field of view.



Figure 15.—Images from a stacked chamber facility camera showing a flame (left) and scale (right). Note: the “fish-eye” distortion effect caused by the lens.

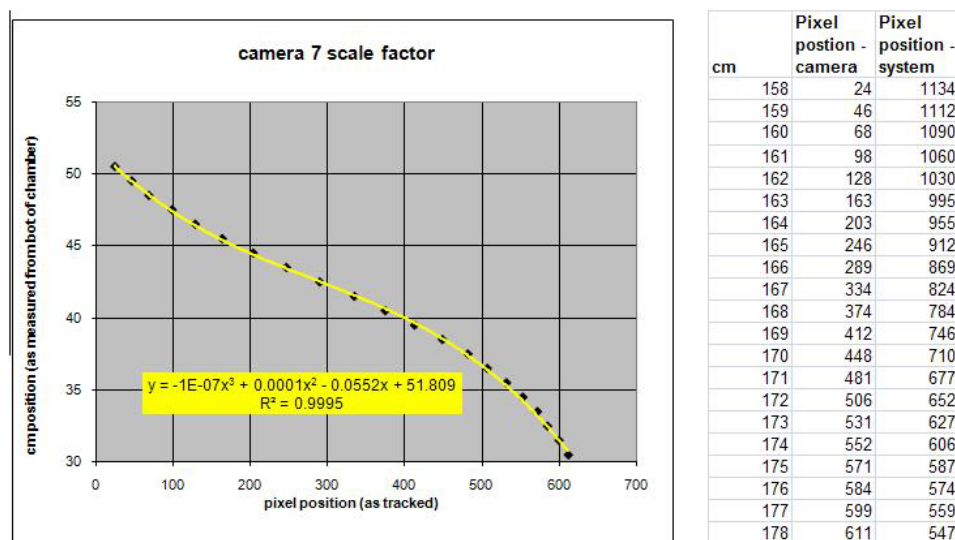


Figure 16.—The position dependant scale factor calculated for the image in Figure 14. Equations were determined for each of the 9 cameras and applied to the data.

A tape measure was placed along the entire length the sample card. Images were taken with each camera, like Figure 15, which were used to determine the scale factor for each camera. The pixel positions of the scale marks were recorded (for example the 66 in. mark in Figure 15 corresponds to pixel location of 360). These pixel positions were converted to system wide coordinates using the same method used for VF-13. In this case the overlap markers were the tape measure marks. Equations (12) were used without the scale factor (neglect the “SF” terms in the denominator) so that the result is a system pixel position instead of centimeters. This pixel position was plotted against its corresponding tape measure position (cm) and curve fit to obtain the position dependant scale factor equation. Figure 16 shows an example of this. The resulting scale factor equations can be applied directly to the tracking data to give a flame distance in system wide coordinates.

Temporally, the data was merged using the same time stamp method as with VF-13.

5.0 Results

5.1 Nomex III Fabric Tests in VF-13

As discussed in Section 3.3, Nomex III fabric is a fire protection material, that not only becomes flammable at elevated oxygen conditions, but also demonstrates a unique cyclic flame phenomena during upward burning. The flame elongates, separates into two flames. One flame ultimately blows off, while the other continues, and repeats the cycle. Limited by sample length, only one or two cycles were observed in those earlier tests.

VF-13 chamber provided an ideal environment to investigate this phenomenon further. A total of 8 tests with Nomex III fabric were performed in VF-13 with various oxygen concentrations and chamber pressures. The results of those tests confirmed that the cyclic dual-flame behavior continued over the long samples. Additionally the cyclic behavior demonstrated two different modes: continuous-lower-flame mode and continuous-upper-flame mode. In the former, the lower flame consistently survived after the upper flame blew off. In the later, the lower flame consistently blew off while the upper flame stabilized. A test condition of 9 psia and 30 percent oxygen concentration seemed to be the turning point, below which the flame tended toward the continuous-lower-flame mode and above was the continuous-upper-flame mode.

Details of the Nomex III tests will not be presented here. The main purpose of this report is to compare the tests performed in VF-13 and stacked-chamber facilities. Nomex was not used in the stacked-chamber facility. A detailed description and analysis of the Nomex III tests in the VF-13 chamber will be documented in a separate publication.

5.2 PMMA Plate Tests in VF-13

Cast PMMA, i.e., poly(methyl methacrylate), plates have been used widely in solid fuel combustion research because of several unique features the material possesses. It can be made clear or opaque and can be burned completely without charring and with little to no dripping. PMMA was used in the VF-13 chamber to see if the flame length of an upward burning flame over a thermally thick fuel could reach its steady state flame length. A flame that reaches a stable flame length can be treated as a steady state combustion problem in the fixed flame coordinates. The flame front, the pyrolysis front, the flame base and all the temperature or concentration profiles would travel at the same speed along the fuel, thus simplifying modeling efforts.

Two identical PMMA fuel samples were burned in the VF-13 chamber. The sample dimensions were 5.59 mm thick, 70 mm wide (50 mm burnable width) and 1850 mm long. The sample length consisted of two PMMA sheet butted together; the bottom sheet was 1219 mm long, whereas the top was 631 mm.

Figure 17 shows the arrangement of the fuel sample and the sample holder. The sample holder width was set to 50 mm, with extra fuel material (10 mm on each side) used to mount the fuel to the sample holder with screws. The chamber conditions for the two tests were 21 percent O₂ concentration and 5.58 psia (i.e., the lunar equivalent condition), and 30 percent O₂ concentration and 10.29 psia (the normoxic condition of 30 percent O₂).

In the first run, the lunar equivalent condition, the flame grew continually after ignition. It took almost 15 min for the fuel to burn out at bottom edge. Figure 18(a) was taken at 10 min and 45 sec after ignition at which time the flame was 60 cm long. Figure 8(b) was taken at 13 min and 50 sec where the flame length was over 70 cm, with the flame base still anchored at the bottom edge of the fuel. In Figure 8(c), 20 min and 38 sec after ignition, the flame base had advanced 15 cm from the bottom of the fuel. Significant oxygen depletion caused the flame to weaken and became very blue, thus preventing it from achieving a steady state length. Then the flame extinguished soon afterward.

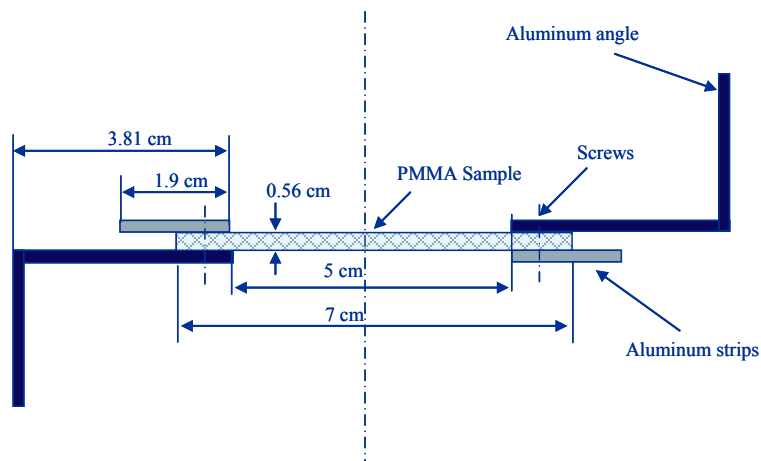


Figure 17.—The cross section view of the PMMA sample and the sample holder. Since the fuel was thick, two aluminum strips were installed to hold the sample in place and to quench the flame edges. The vertical distance between neighboring screws was 30 cm.

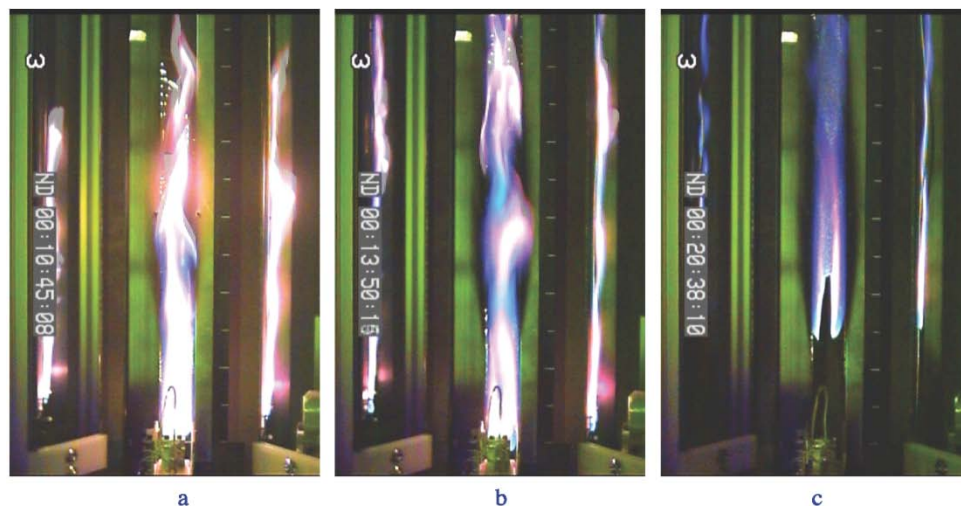


Figure 18.—PMMA flame images at three different times after ignition. a) 10 min and 45 sec, flame was 60 cm long, b) 13 min and 50 sec, flame was 70 cm, with flame base still anchored to fuel bottom edge, and c) 20 min and 38 sec, the flame base advanced 15 cm.

Post test stoichiometric calculations show that 136.64 g or 1.366 g-moles PMMA fuel were consumed, with a corresponding O_2 consumption of 8.2 moles (1.366×6). The original oxygen in the chamber was 20.6 gr-mole, so about 40 percent of the oxygen was consumed leaving 12.6 percent mole fraction at the end of test. The actual oxygen concentration near the fuel surface would have been even lower. With such low oxygen concentration, flame extinction was inevitable.

The second PMMA test was performed at 30 percent oxygen and 10.29 psia, a point on the normoxic curve. Since the oxygen mole number was much higher than the first run, the flame quickly became very energetic and turbulent. In about 10 min, the chamber pressure increased from 10.29 to 13.52 psia, and the temperature at the bottom of the chamber rose from 23.4 to 36.6 °C, causing two of the three video cameras to shutdown. The flame length exceeded 1 m long. For the safety considerations, the flame was extinguished by evacuating the chamber. A total of 481.2 g of PMMA was consumed, about of 55 percent of the original fuel mass. Post test examination indicates that the sample holder was not able to quench the flame at fuel edges. The fuel material that was sandwiched between the sample holder and the aluminum bars was found softened and melted, indicating that the full 7 cm sample width had reacted. Thus, the chamber condition was too energetic for the study of the steady state flame length.

The two tests mentioned above suggested that the current configuration of VF-13 was not suitable to study thick fuel upward burning at these conditions. To do so, continuous oxygen supply and product gas removal should be maintained during the test to avoid excessive oxygen depletion.

5.3 Paper Fuel Tests

All tests with the paper material were done in the presence of 21 percent oxygen/nitrogen gas mixture. This was chosen because 1) a similar test condition could be easily achieved in the stacked-chamber facility, and 2) previous studies regarding pressure scaling to simulate low gravity (Ref. 3) were performed at this mixture.

The first material chosen for testing was Adding Machine paper. This thin paper is available in long rolls and seemed well suited for the tall chambers. However some unusual, and ultimately unresolved, flame behavior prompted the use of poster paper instead. This material was used in both facilities for comparison. Below, the difficulties with the adding machine paper will be discussed as well as the results of the poster paper tests in both facilities.

5.3.1 Stacked-Chamber Facility—Adding Machine Paper

During 13 tests of the adding machine paper in the stacked-chambers facility, 11 experienced one-sided burning, i.e., flames extinguished on one side of the material during propagation. This phenomenon is typically reserved for thicker, denser materials, so a hardware issue was suspected. Despite several theories, summarized below, and extensive testing, no definitive cause could be found.

1. The thickness of the sample holder could have been acting as a heat sink on one side of the material. The sample was originally mounted to the sample holder as shown in Figure 19A. The rails of the sample holder were 1/8 in. thick, and mounting the sample in this manner biased the full thickness of this metal to one side of the material. To test if this caused a heat sink effect, the sample was instead mounted across the rails as shown in Figure 19B (the rails themselves were shifted so that the sample surface remained fully perpendicular to the cameras). In this way, the sample was mounted symmetrically with respect to the sample holder thickness. The tests performed in this manner failed to show any significant affect on the one-sided burning. However, this mounting method was maintained through all subsequent testing.

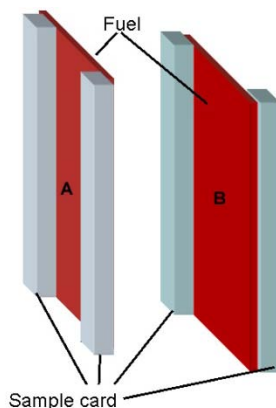


Figure 19.—The method of mounting the fuel to the sample holder is illustrated. (A) The original method with fuel on one side of the sample holder. (B) The revised method using a cross mounting method to better distribute the thermal mass of the sample holder.

The chamber was also temporarily configured to accommodate a thinner (1/32 in.) sample holder that has typically been used in a single 27 L combustion chamber. Despite a decrease in the thermal mass of the sample holder, one sided burning persisted.

2. The camera mount could have been acting as a heat sink on one side of the material. In the majority of tests demonstrating one-sided burning, the flame blew out on the side of the fuel facing the cameras. Due to the chamber size, the camera mount was only 8.3 cm from the fuel surface. While this distance was considerably greater than the flame stand-off distance, some heat loss effect could be present.

To test this, an identical piece of metal channel stock was placed on the opposite side of the chamber. In this way, the internal profile of the chamber became symmetric. However, the effect on the flame was not significant, and the one-sided burning effect persisted.

3. The igniter only contacts one side of the fuel. The one sided burning could have been an ignition effect. The configuration of the chamber only allowed video viewing of one side of the sample. When the flame extinguished on the camera side, a slowly propagating pyrolysis front, and reflection of the flame through the sample, indicated a flame on the opposite side. The chamber windows, typically covered to improve imaging, were used by the test operator to manually confirm the one sided flame. However, the ignition event could not be manually monitored in this way due to the proximity of the control interface.

To explore this theory, disposable hot wire igniters were used in place of the glow plug. These 2.7 Ω Kanthol wires were bent into a saw-tooth shape and interleaved around the edge of the fuel sample. In this way, the hot igniter prongs contacted both sides of the material to ensure two sided ignition. Additionally, a low quality video camera was added to a chamber window to confirm the ignition. The ignition was always two-sided, with the flame blowing out on one side further downstream.

4. Flow effects inside the chamber could have been causing the blow off on one side. A low speed (5 cm/s) flow was used during the tests to counter O_2 depletion. It entered through a series of screens and honeycombs to ensure a uniform flow. The flow exited at the top of the chamber through a 1 in. orifice. If this orifice was too restrictive, combustion products could build up at the create recirculation cells.

To test this, the flow was deactivated in several tests. The tests were run at the same reduced pressure condition used in the previous tests (the flames were better behaved at reduced pressure). One sided burning still occurred, verifying that the flow velocity was not the cause.

Tests were also performed with the lid removed to check if the outlet orifice was too restrictive. Since the chamber was open to atmosphere, it could not be performed at a reduced pressure. The resulting flame was far more energetic, which likely overcame any other factors that may have played a role in one sided burning. While the flame did not blow out on one side, it was observed to slow at intervals, with flickering in the flame base. This would indicate that the cause of the one-sided burning was still present.

Any other flow effects caused by chamber obstructions or the aspect ratio itself would be difficult to observe experimentally. Since the flow field was dominated by the flame itself, flow visualization by most techniques was impossible. A numerical model of the chamber was explored examine potential flow field effects, but the project ceased before conclusive results could be obtained.

5. The effect could have been caused by the fuel itself. One sided burning could be caused by either the material composition itself or a surface coating (though not apparent on the adding machine samples). Several other paper materials were tested at the same conditions to see if the one sided burning was fuel dependant or hardware configuration dependant. Three additional paper samples used were;

- Kimwipes: 2 mg/cm² (laboratory tissue paper wipes)
- Masking paper: 5 mg/cm² (used in painting, etc.)
- Poster paper: 7 mg/cm²

Note: that the adding machine paper has an area density of 6.3 mg/cm² which was in this range. All three new materials demonstrated full two-sided flames through the entire propagation length with no signs of reduced spread rate or flickering in the flame base.

While the cause of one-sided blow off is still unresolved, time restraints prohibited further exploration. Since the other materials did not demonstrate the phenomenon, the poster paper was chosen for continued testing in both the VF-13 facility and stacked-chamber facility.

5.3.2 Poster Paper—Both Facilities

A total of 4 tests, two in each facility, were performed using poster paper for comparison purposes. The two test conditions were: 21 percent oxygen, 5.58 psia, 5 cm width (case 1) and 21 percent oxygen, 8 psia, 2 cm width (case 2).

All the tests were planned to be at the same pressure, 5.58 psia, which mimics flame spread in lunar gravity according to the pressure scaling correlation. However, the 2 cm wide material failed to burn at 5.58 psia (Test #8, 9) in VF-13. While the extinction limit has not been explicitly defined for this material, the pressure limit for similar materials is well below 5.58 psia. The same conditions in the stacked-chamber facility resulted in a strong flame that consumed the entire 1.2 m sample (Stacked chamber test 5/19/2008 #1). The sample holder from the stacked-chamber facility was used in the VF-13 to reduce facility differences, but failed to solve the problem. Due to the limited number of tests available in the VF-13 facility, this phenomenon could not be fully explored or tested for reproducibility. Therefore, the higher pressure, 8 psia, was used to ensure successful flame propagation at a 2 cm sample width. The stacked-chamber sample card was maintained in an effort to reduce the disparities between the two facilities.

Results for the two successful VF-13 poster paper tests and two tests in the stacked-chamber facility are presented in Figures 20 and 21. The pyrolysis spread rates, displayed on the graphs, were obtained by curve fitting the “steady” portion of the flame spread. The curve fit does not include the transient ignition region, which ends when the flame length ceases to grow and approaches a nearly constant value.

It should also be noted that the data reduction is quite complex, particularly for the stacked-chamber facility. In both facilities there are multiple cameras, and therefore multiple videos. To analyze flame spread during a test, data from these videos must be merged and synchronized temporally and spatially, as described in Section 4.0. Multiple iterations of this data merging processes were performed. Errors found in the early iterations significantly affected the results.

Since the project ended prior to completion, a full uncertainty analysis has not yet been performed. A meaningful uncertainty analysis would require a multiple repeated tests under the same test conditions, which was unfeasible under the various constraints of this project. However, the standard deviation in the curve fit equations indicates it can predicted flame position within ± 3 cm. Missing data points in the stacked chamber data was caused by camera switching. Likewise, some sudden slope changes may be artifacts of data merging.

Table 3 shows a direct comparison of the spread rates. A steady flame should imply that the spread rate of the base and pyrolysis front are the same, but both spread rates fluctuate. They can never be exactly “steady.” Thus, the table shows some variation between the two. The highest of these is the VF13 Case 1 test which shows a 0.58 cm/s difference between the pyrolysis and base spread rates. The plot in Figure 20 indicates a stable flame length, supporting the steady state claim. The larger flame base spread rate is due to the crack propagation.

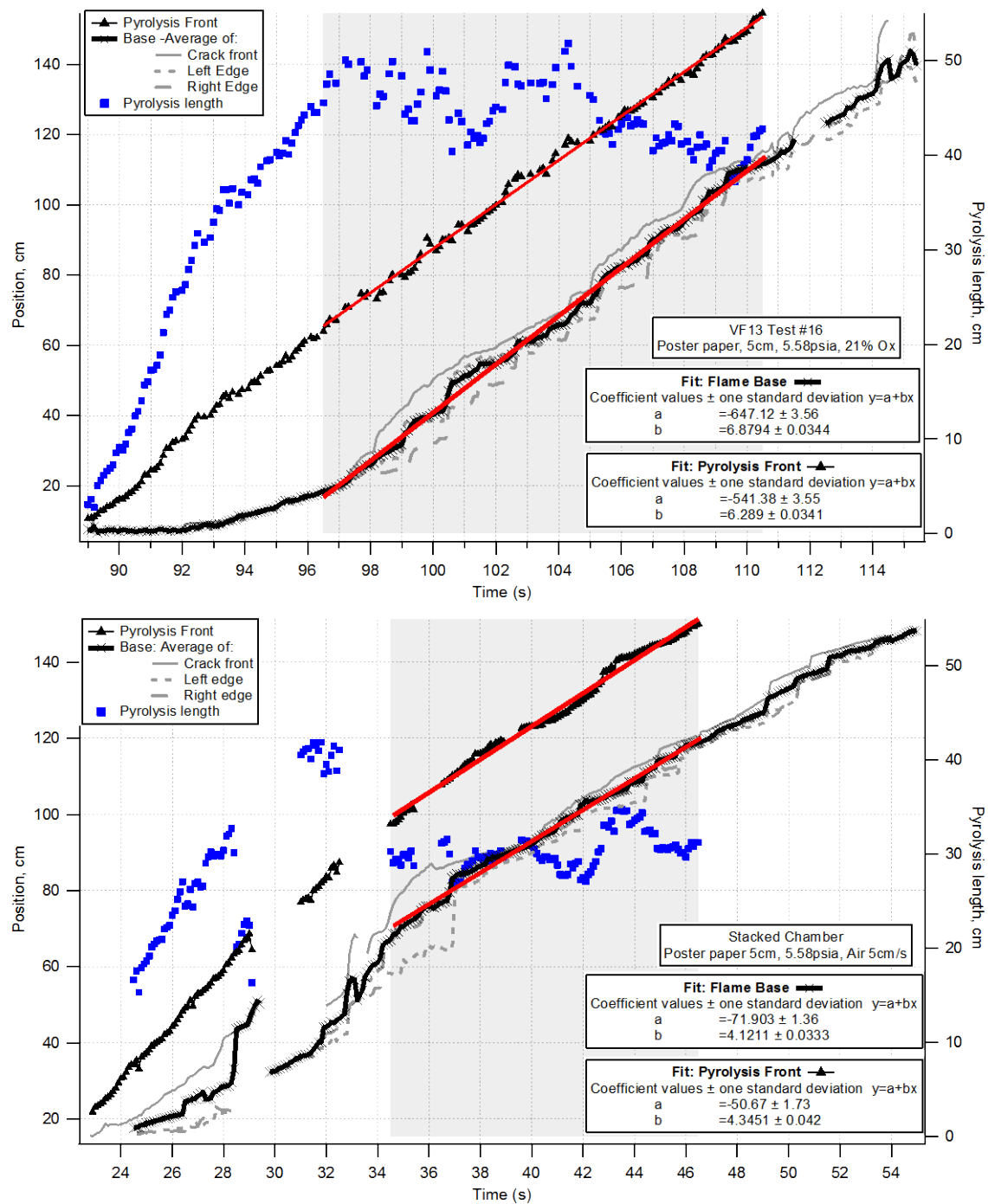


Figure 20.—Case 1: Position versus time plots for the VF-13 (top) and Stacked Chamber (bottom) comparison tests at 5.58 psia and 5 cm fuel width. The linear curve fit equations are shown for the steady region, which is highlighted in light gray.

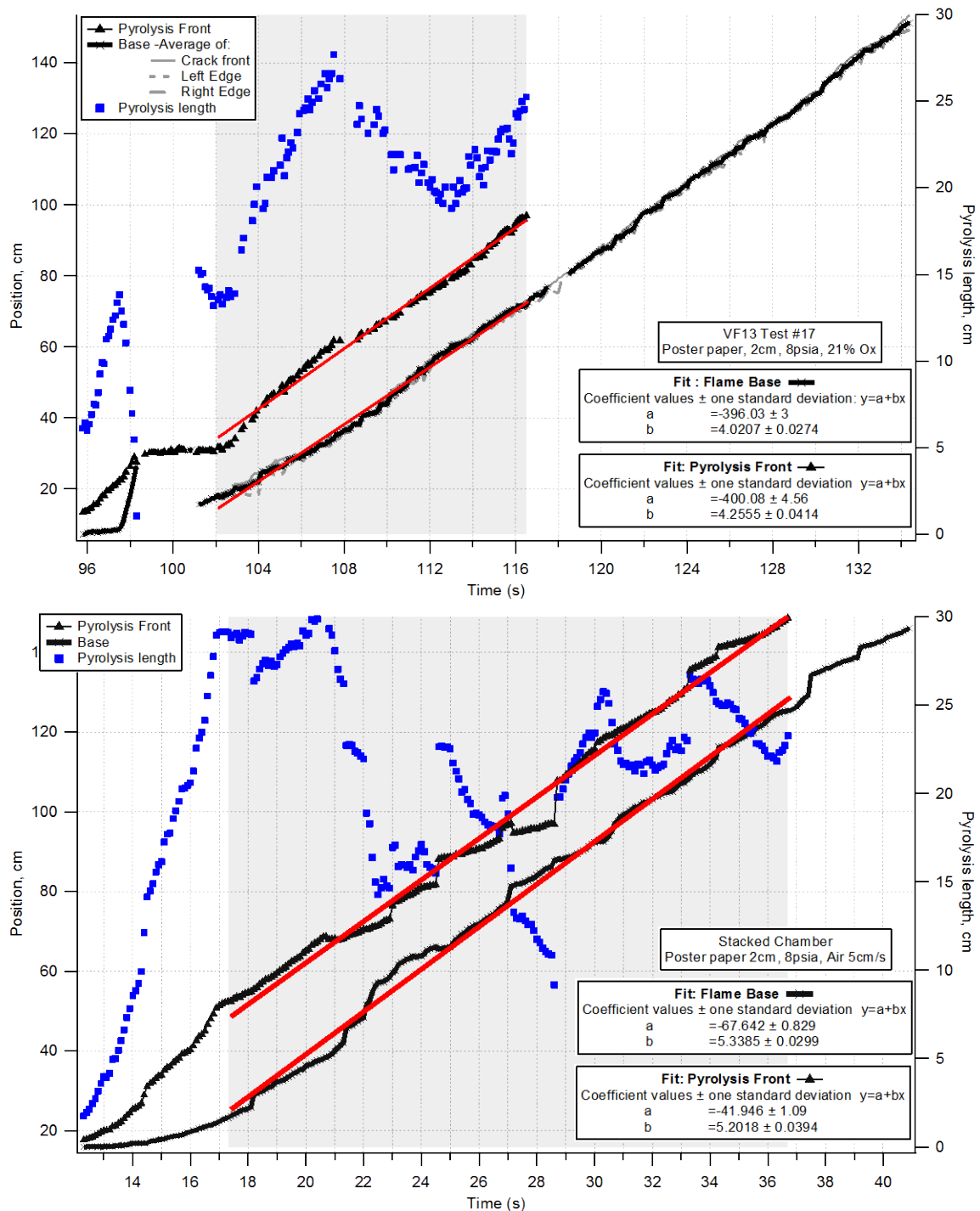


Figure 21.—Case 2: Position versus time plots for the VF-13 (top) and Stacked Chamber (bottom) comparison tests at 8 psia and 2 cm fuel width. The linear curve fit equations are shown for the steady region, which is highlighted in light gray. Note: the stacked chamber test at these conditions was the first to be analyzed. Only one flame base position was tracked (a visual average position). In all other tests the base position was an average of three tracked points.

TABLE 3.—A COMPARISON OF SPREAD RATE IN THE VF-13 FACILITY TO THOSE IN THE STACKED-CHAMBER FACILITY

[All VF-13 tests were done in 21 percent oxygen/nitrogen environment while the stacked-chamber used filtered room air.]

		VF-13		Stacked-chamber	
		Base, cm/s	Pyrolysis front, cm/s	Base, cm/s	Pyrolysis front, cm/s
Case 1	5 cm width 5.58 psia	6.88	6.30	4.12	4.34
Case 2	2 cm width 8 psia	4.02	4.26	5.33	5.20

The spread rates are different between the two facilities. In Case 1 the flame spreads faster in the VF-13. The opposite is true of Case 2, the 2 cm wide sample. Also note that the difference in spread rate between Case 1 and 2 in the VF-13 facility is greater than that in the Stacked-chamber. Possible causes could not be explored in detail, but flow or edge effects caused by the small diameter of the Stacked-chamber facility may be muting effects of the other variables.

6.0 Closing Remarks

The two large chamber facilities have great potential for materials flammability testing. The types of materials and the variety of test conditions possible in these facilities are more extensive than the smaller facilities traditionally used.

For thin samples (papers) the flame was able reach a steady state length using these long samples. In previous small chamber tests, sample widths were restricted to 1 or 2 cm where flame lengths were largely determined by edge effects, including heat loss to the sample holder and the 3D nature of the entraining air. The use of 5 cm sample widths in the large chambers demonstrated that flame length may be stabilized even when the edge effects are reduced.

The thick sample tests using PMMA resulted in highly energetic, long flames. It took over 10 min for the flame base to propagate off the lower edge of the fuel. Even in the large volume of VF-13, oxygen depletion began to play a role. As such, a flame spread and steady state flame length could not be determined. However the flame length reached 70 cm, which would not have been possible in other facilities.

Tests of both thin and thick fuels suggest that an upward burning flame can reach a steady flame length given sufficient fuel, oxidizer, and an unrestricted environment.

Tests with the Nomex fabric in VF-13 verified that the cyclic flame phenomena was not a chamber dependant or transient phenomena. The cycles continued over the entire 2 m length. Additionally, the ability to tests at more energetic conditions revealed new cyclic modes dependant on environmental conditions. Details of this will be published separately. It is believed that this cyclic phenomena is due to the composition of the Nomex fabric which may contain materials with distinct pyrolysis temperatures. No existing flame model currently addresses this cyclic flame phenomenon.

Limited time and numerous technical issues hindered taking full advantage of either facility. Several open questions remain, which would need to be resolved to make either facility viable.

- Ignition difficulties in the VF-13 facility
 - There were difficulties igniting 2 cm wide paper samples. While an ignition flash did occur, the flame failed to sustain. This occurred in tests #3 and #9. In test #17, a higher pressure was used to create a more flammable condition. While the flame did sustain, there was a brief blow-out on one side several seconds into the test. The flame recovered and continued to propagate. Tests done in the same conditions in the stacked-chamber

facility ignited and burned the entire sample length without interruption, implying that this is a configuration issue.

- One sided burning in the stacked-chamber facility
 - In many of the early 2 cm sample width tests, the flame blew out on one side of the material, while continuing to propagate on the other. This is an unexpected phenomenon for a thin homogenous material. While considerable effort was expended to trace the cause, it remains unresolved. However, the phenomenon was only observed using adding machine paper and did not occur for other types of paper materials.
- Data reduction schemes
 - The merging of data from up to 9 different cameras adds significant complexity and error to the data reduction process. The process underwent several iterations, which significantly impacted the results. While the current method seems rigorous, a full uncertainty analysis has not been performed.

Despite the open questions, it was clear from both the qualitative and quantitative results that the flames in the two facilities behaved differently. Despite using the same fuels size, sample holder, oxygen and pressure conditions, the spread rates were significantly different. This raises significant question regarding the impact of the sample size and test facility on the flame behavior. Traditionally, flame properties for a material have been studied in relatively small or high aspect ratios chambers, including the NASA test standard STD 6001. But it is not clear how applicable those results are to a real world fire scenario, which may occur in a variety of different enclosures (an electronics box or storage compartment on a spacecraft) or in a larger open space. The shape of the enclosure or the objects in the environment impacts the flow field, which directly affects the transport of oxygen to the flame region. Likewise, the way the sample is held and the proximity of other objects may hinder or even encourage the flame spread. While more study is needed, this indicates the need for improved test standards.

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Appendix A.—Test Matrix

A.1 Procedures

A.1.1 VF-13

The experimental procedures for the VF-13 facility are listed below:

1. Adjust the position of the aluminum angles of the sample holder to have the desired lateral distance between the two angles (aka: set the fuel width).
2. Install the fuel sample on the sample holder. If the fuel is a thin sheet of paper or Nomex, use adhesive aluminum tape to attach the sample on the aluminum angles. Make sure the sample is flat and evenly stretched. For thick fuel of PMMA, use screws to mount the PMMA plate on the sample holder.
3. Install the sample holder w/ fuel sample on the experimental rack.
4. Manually move the igniter to verify that the igniter tip is centered on the sample.
5. Operate the switches on the panel to activate the igniter actuator to verify that the igniter can reach the fuel sample with adequate pressure of nitrogen gas.
6. Check the mixing fan, cameras and the led strips via the switch box to make sure they are all functional.
7. Put the upper portion of the chamber on top of the lower portion and secure it with C clamps.
8. Evacuate the chamber with the roughing pump to the pressure lower than 0.15 torr.
9. Turn on the excitation voltage of the pressure transducer and the power of the readout volt meter.
10. Check the oxygen line to the chamber to make sure the check valve on the valve panel is closed.
11. Open the valve on the oxygen bottle and adjust the pressure regulator to get 50~60 psig at the outlet of the regulator.
12. Fill the chamber with oxygen via the ball valve on the valve panel, while monitoring the chamber pressure via the pressure transducer voltmeter. Adjust the filling speed as needed to prevent overfilling.
13. Switch to the metering valve for more finite control when the chamber is close to the desired oxygen partial pressure.
14. Close the oxygen line with ball valves on the valve panel.
15. Fill the chamber with nitrogen via the ball valve on the nitrogen line on the valve panel while monitoring the chamber pressure via the voltmeter.
16. Switch to the metering valve on the nitrogen line when the chamber pressure is close to desired total chamber pressure. Slowly adjust the metering valve as the chamber pressure approaches the desired total pressure.
17. Close the nitrogen line when the chamber pressure reaches the desired total pressure.
18. Turn on the mixing fan. And monitor the current the fan consumes which should be below 1 A during stable operation.
19. Turn the mixing fan off after running about 10 min.
20. Turn the LED chamber lights on.
21. Turn each camera on at separate time to see if the fuel sample can be seen.
22. Turn all cameras and LED chamber lights off.
23. Wait for 2 hr for chamber gas to be well mixed and residual flow to diminish.
24. Connect the DV cam recorders.
25. Load the video tape to the recorders.
26. Connect the video signal to the real-time image digitizing computer.
27. Turn the LED chamber lights on.
28. Power on all three cameras.
29. Start the time code generator and make sure all the video recording devices are receiving good signals.

30. Turn the igniter power on and record the time in the test notebook.
31. Monitor the electrical current of the igniter which should start with a high value and decrease to a stable value around 2 A. And monitor the image on the camera #3. A very bright igniter should be seen after about 20 sec it was turned on.
32. Turn the igniter control switch to “in” position to actuate the igniter actuator to move the igniter to the fuel. Record the time in the test notebook.
33. When the ignition is confirmed, turn the control switch to “retract” position to retract the igniter.
34. Monitor the flame spread during the burning. If the flame extinguishes because of either self-extinguishing or exhausting all the fuel, turn off video devices. If the flame becomes too violent and causes significant chamber pressure and temperature increases, inject nitrogen to the chamber to put the flame off. Then turn the video device off.
35. Evacuate the chamber with the HIGHVAC Venturi pump.
36. Recharge the chamber with room air.
37. Open the chamber after the chamber pressure reaches equilibrium with room pressure.
38. Inspect the burned sample and remove the chamber holder from the rack for the next run.

A.1.2 Stacked-Chamber Facility

The following list outlines the test procedures for operation of the stacked -chamber facility:

Sample Preparation

1. Remove the lid and undo the wire connections to the sample holder.
2. Remove the sample holder from the chamber.
3. Remove the igniter and spent sample from the holder.
4. Adjust the sample holder to the appropriate width for the next test.
5. Cut the new sample to the desired width and tape the sample to the holder using Scotch tape.
6. Use adhesive aluminum tape along the inner edge of the sample holder, to act as an inert (non flammable) edge.
7. Position the igniter, secure it to the sample holder, and plug it into the wiring on the sample holder.
8. Insert the sample holder into the chamber and make the electrical connections.
9. Verify that all wiring is away from the sample. If any wire is too close to the fuel sample (at risk of flame exposure), tape it to the side of the chamber.
10. Verify that all cameras have clear view of the sample (again, tape wiring out of the way if needed)
11. Clamp the lid onto the chamber

Power Up and Run Test

1. Turn on all the power supplies.
2. Activate the appropriate systems on the SFSF and start the control software (LabVIEW)
3. Set the 3 camera selection switches to the highest numbers. (A:7, B:8, C:9) to accommodate the three lowest cameras in the chamber (ignition is at the bottom)
4. Load and queue the Digital Video tapes
5. Set the source gas bottle regulator and turn on the vacuum pump.
6. Purge the chamber of room gases by activating the “purge” sequence in the control software.
 - a. This sequence will vacuum the chamber
7. Enter the desired Fill pressure and execute the “fill sequence”
 - a. This sequence will fill the chamber with source gas to the set-point pressure.
8. Enter the desired test pressure and the flow velocity, and begin the “Flow oxidizer” sequence
 - a. This sequence will begin flow of source gas through the chamber and regulate the chamber to the desired pressure using the mass flow controller and back pressure valve.

9. Monitor pressure and wait for it to level off at the set pressure
10. Verify the camera selection switches are set to the appropriate camera feeds and start recording
11. Start the time code generators.
 - a. The time code will appear in all video recordings and is needed to synchronize the camera views during data analysis.
12. Activate the igniter and monitor video
13. Once the flame base has moved off the igniter, deactivate the igniter
14. As soon as the flame propagates out of the field of view (FOV) of a camera, switch to the next camera on the switchbox. For example: once the flame moves out of camera 8's FOV, switch selector B to "5", then monitor camera 7. Once the flame is out of its FOV, switch selector A to "4", and so on until the flame extinguishes
15. Once the flame has extinguished activate the "*Vent*" sequence
 - a. This sequence will vacuum the chamber to vent combustion by-products.
16. Stop the video recorders
17. Verify the chamber is equilibrated with atmospheric pressure and open the chamber lid.
18. Prepare sample for the next test or power down the system.

A.2 Test Log

A.2.3 VF-13

The test matrix of the VF-13 facility experiments. The (*) next to the test number indicates that the sample card from the stacked chamber facility was used. Fuel abbreviation AMP is "Adding Machine Paper," while PMMA is Poly(methyl methacrylate). Oxygen percentages are molar fraction balanced with Nitrogen. The chamber pressures listed are the setpoint pressures, actual pressures are within ± 0.012 psi of this amount.

Date	Test	Fuel	Width, cm	Ox, percent	Pressure, psia	Purpose	Results
11/21/07	1	AMP	5	21	5.58	Lunar equivalent spread rate	5.78 cm/s flame 5.94 cm/s pyrolysis
11/27/07	2	AMP	5	30	10.6	Normoxic condition considered by future space craft	~15.88 cm/s flame Energetic, difficult to track, pyrolysis not visible
11/30/07	3	AMP	2	21	5.58	Lunar equivalent, smaller width for previous small chamber (GIFTS) compare	NO PROPAGATION
12/5/07	4	AMP	2	30	10.6	Normoxic, width for previous small chamber (GIFTS) compare	6.84 cm/s flame
12/12/07	5	PMMA	5	21	5.58	To see if thick fuel can reach steady state flame length in upward burning	Fuel thickness is 0.56 cm and flame extinguished after consuming 136.6 g of fuel
12/18/07	6	PMMA	5	30	10.6	To see if flame can continue at higher O ₂ concentration	HIGHLY energetic

Date	Test	Fuel	Width, cm	Ox, percent	Pressure, psia	Purpose	Results
1/10/08	7	Nomex	2	27	9	Comparable to small chamber (GIFTS) tests, but with longer length to see if cyclic continues	2 cycles then extinguish
4/17/08	8	Poster paper	2	21	5.58	Lunar equivalent spread rate	Extinguished shortly after ignition. Blue flame
5/2/08	9	Poster paper	2	21	5.58	Serve as baseline test for stacked chamber. 2 existing tests in stacked chamber, both burned the whole sample, flame length of ~20 cm	No propagation
5/8/08	10*	Nomex	5	30	6	Look for cyclic phenomena. This is a consistently flammable point at 2 cm width, so should be away from 5 cm limit (undefined). If the flame is too energetic, it may self extinguish during a blow off cycle (previous data).	3 cycles, then extinguished (secondary flame stabilized in last cycle). Blue flame.
5/12/08	11*	Nomex	5	27 (20 actual)	9	Examine cyclic phenomena. The cycles should be shorter with less chance of secondary flame survival at this condition.	No propagation. Error in oxygen fill pressure. Actual oxygen of test was 20 percent, below flammability limit.
5/13/08	12*	Nomex	5	27	9	Repeat of test 11 at correct oxygen	Full propagation! Flame continued to cycle through entire test.
5/14/08	13*	Nomex	5	30	9	Higher oxygen, but same pressure as test 12. Examine how oxygen effects cycles.	3 cycles, then extinguished (secondary flame stabilized in last cycle). Orange flame.
5/20/08	14*	Nomex	5	35	9	Do cycles continue at higher ox? Does 2nd flame survival cause extinction like in test 13? Or do we overcome 2 stage pyrolysis?	Continuous cycling, multiple breakups. Full propagation.
5/23/08	15*	Nomex	5	32	9	Provide another points in the curve of test 12 to 14	Full propagation. Continuous cycling. Secondary flame always survives.

Date	Test	Fuel	Width, cm	Ox, percent	Pressure, psia	Purpose	Results
5/28/08	16*	Poster paper	5	21	5.58	Look at flame shape and compare to stacked chamber (edge effect indicator).	
5/30/08	17*	Poster paper	2	21	8	Better behaved tests (more “trackable”) for stacked chamber compare	Ignited, one side blew out briefly. Re-ignition and full propagation
6/5/08	18*	Nomex	5	30	9	Repeat for comparison	Full propagation. Varied between primary and secondary flame survival. Almost extinguished after 1st breakoff.

A.2.4 Stacked Chamber

The test record from the stacked chamber experiments. Fuel type abbreviations include: AMP for Adding machine paper, Poster, Kimwipe, and Masking all identify types of paper samples. Whereas SIBAL is a specialized fabric used for a previous project (Ref. 10). Some test objective reference the “GIFFTS” facility which was a single 27 L chamber used in previous testing.

Date	Test #	Fuel	Oxygen, percent	Pressure, psia	Flow, cm/s	Width, cm	Sample Length, cm	Test purpose	Flame status
2/14/08	1	AMP	21	8	5	2	120	Turn off lights and watch for one or two sided flame through window	Ignition and flame one sided entire time Extinguished: camera 6
2/14/08	2	AMP	21	8	5	2	120	Add a second dummy camera mounts to see if cam mount is a heat sink	Two sided, blowout on cam side, Extinguished: camera 6
2/14/08	3	AMP	21	8	5	2	120		Two sided ignition blow out on camera side, Extinguished: camera 6
2/21/08	1	AMP	21	8	5	2	120	Tape sample only on camera side to see if sample holder as heat sink	Two sided ignition blow out on camera side, Extinguished: camera 7
2/21/08	2	AMP	21	8	5	2	120	Tape sample only on camera side to see if sample holder as heat sink	Two sided ignition blow out on back side, Extinguished: camera 5
2/21/08	3	AMP	21	8	5	2	120	Tape sample only on back side to see if sample holder as heat sink	Two sided ignition, became one sided flame and blow out on camera side, Extinguished: camera 6
2/25/08	1	AMP	Shop	8	5	2	120	Extended sample card holder, taped to “thin” side, “thick” side to camera check sample holder as heat sink	No ignition
2/25/08	2	AMP	Shop	8	5	2	120	Repeat	One sided flame, blowout on cam side

Date	Test #	Fuel	Oxygen, percent	Pressure, psia	Flow, cm/s	Width, cm	Sample Length, cm	Test purpose	Flame status
2/25/08	3	AMP	Shop	8	5	2	120	"Thin" side to camera	
2/26/08	1	AMP	Shop	11	5	2	120	Extended, "thick" side to cam, higher pressure check if near limit	Two sided ignition then one sided flame, blowout on cam side, Extinguished: camera 6
2/26/08	2	AMP	Shop	11	5	2	120	Extended, "thin" side to camera, higher pressure check if near limit	Two sided ignition then one sided flame blowout on cam side, Extinguished: camera 5
2/26/08	3	AMP	Shop	11	0	2	120	Extended, no flow check flow problem	Two sided ignition then one sided flame, blowout on cam side, Extinguished: camera 6
2/28/08	1	AMP	Shop	11	5	1	80	Small sample card holder check sample holder	Two sided ignition then one sided flame blowout on cam side, Extinguished: camera 7
3/3/08	1	AMP	Shop	11	5	5	120	Wider sample, symmetric holder check near limit	Two sided, Full propagation
3/3/08	2	AMP	Shop	11	5	2	120	Same as previous but thinner check width factor	Two sided ignition then one sided flame, blow out on camera side, Extinguished: camera 5
3/3/08	3	AMP	Shop	8	8	2	120	Upped flow to highest possible try to "blow out the blow out effect", rig can't go too high without blowing pressure window	Two sided ignition but not sure of flame, two sided or one sided cam side, slow flame so probably one sided, Extinguished: camera 6

Date	Test #	Fuel	Oxygen, percent	Pressure, psia	Flow, cm/s	Width, cm	Sample Length, cm	Test purpose	Flame status
3/3/08	4	AMP	Room	Room	0	2	120	Lid off checking lid effect	Two sided, Extinguished: camera 6
3/3/08	5	AMP	Room	Room	0	2	120	Repeat of previous	Two sided, one blowout on cam side but with restart, Full propagation
3/3/08	6	Masking	Room	Room	0	2	120	Repeat	Two sided, Full propagation
3/3/08	7	AMP	Room	Room	0	2	120	Repeat	Two sided, one near extinction, Full propagation
3/4/08	1	AMP	Shop	~14	0	2	135	Lid on, no flow replicate room pressure w/ lid checking lid effect	Two sided, one near extinction, Full propagation
3/4/08	2	AMP	Shop	11	5	2	103	Light at top of cam 7, 47 cm from bottom check "cam 6 problematic area"	Two sided, two near blowouts, one at cam 6 and 5 (was struggling), one at camera 1 (skipped paper), close call in camera 2, Full propagation
3/5/08	1	Masking	Shop	8	5	2	120	Green paper, lower pressure back to 8 try to get new paper to blow out	Two sided, Full propagation
3/6/08	1	AMP	Shop	8	5	5	120	Wider sample check "near limitness"	Two sided, Full propagation
3/6/08	2	AMP	Shop	6	5	5	120	Lower pressure check "near limitness"	Two sided, Full propagation

Date	Test #	Fuel	Oxygen, percent	Pressure, psia	Flow, cm/s	Width, cm	Sample Length, cm	Test purpose	Flame status
3/10/08	1	AMP	Shop	Room	5	5	135	Lid off with flow check to see if flow helps	Two sided, Full propagation
3/10/08	2	Masking	Shop	6	5	2	120	Change paper, lower pressure try to make blow outs occur by dropping pressure	Two sided, Full propagation
3/10/08	3	Masking	Shop	4.35	5	2	120	Try to make blow outs occur by dropping pressure	Two sided, Full propagation
3/12/08	1	Kimwipes	Shop	4.35	5	1	?	Compare with gifts small chamber facility	Two sided, Full propagation
3/17/08	1	Kimwipes	Shop	4.35	5	1	?	Repeat of 3/12/2008 Test 1	Two sided, Full propagation
3/17/08	2	AMP	Shop	8	5	2	120	Flipped paper check to see if paper burns different (may have a coating)	Two sided ignition then one sided flame cam side, flame propagation: 42 cm
3/17/08	3	AMP	Shop	8	5	2	120	Repeat of 3/17/2008 Test 2	Two sided ignition then one sided flame back side, flame propagation: 60 cm
3/18/08	1	AMP	Shop	Room	5	2	120	Lid off with flow check to see effect of flow	Two sided, near blow out on camera 7, Full propagation
3/18/08	2	Kimwipes	Shop	4	5	1	?	Compare with gifts small chamber facility	Two sided, Full propagation
3/18/08	3	Kimwipes	Shop	4	5	1	?	Repeat of 3/18/2008 Test 2	Two sided, Full propagation

Date	Test #	Fuel	Oxygen, percent	Pressure, psia	Flow, cm/s	Width, cm	Sample Length, cm	Test purpose	Flame status
3/18/08	4	AMP	Shop	8	5	2	120	Repeat	Two sided ignition then one sided flame
3/24/08	1	Poster	Shop	8	5	2	120	Denser paper see if blow out occurs with denser paper	Two sided, Full propagation
3/24/08	2	Poster	Shop	6	5	2	120	Lower pressure looking for blowout	Two sided, Full propagation
3/26/08	1	SIBAL	Shop	11	5	2	120	Looking for blowout with new fuel	Two sided ignition then one sided flame, blow out in chamber 2, flame continued on front side, full propagation
3/26/08	2	SIBAL	Shop	11	5	2	120	Repeat of 3/26/2008 test 1	One sided entire time: ignition to end, Full propagation
3/31/08	1	AMP	Shop	5.58	5	5	120	Compare to test done in VF 13	Two sided, mini blow out in camera 1, Full propagation
3/31/08	2	AMP	Shop	5.58	5	5	120	Repeat of 3/31/2008 Test 1	Two sided, blow out cam side, Extinguished in camera 2
4/1/08	1	Masking	Shop	6	5	2	120	Test to see if the slow down effect happens with masking paper	Two sided, Full propagation
4/1/08	2	Masking	Shop	6	5	2	120	Epeat of 4/1/2008 test 1	Two sided, Full propagation
4/3/08	1	Poster	Shop	6	5	2	120	Test to see if the slow down effect happens with poster paper	Two sided, Full propagation

Date	Test #	Fuel	Oxygen, percent	Pressure, psia	Flow, cm/s	Width, cm	Sample Length, cm	Test purpose	Flame status
4/3/08	2	Masking	Shop	4	5	2	120	lower pressure to 4 psia test to see if the slow down effect is caused by test being near limit	Two sided, Full propagation
4/9/08	1	Denim	Shop	11	5	2	120	Testing denim	Two sided full propagation
5/19/08	1	Poster	Shop	5.58	5	2	100	Glo plug ignitor, ignite in cam 7, 35 cm from bottom compare to test done in VF 13	Two sided full propagation
5/19/08	2	Poster	Shop	5.58	5	5	120	Glo plug ignitor compare to test done in VF 13	Two sided full propagation
7/8/09	1	Poster	Shop	5.58	no	5	120	Glo plug ignitor, ignite at 8 compare to test done in VF 13	Two sided full propagation
7/9/08	2	Poster	Shop	5.58	no	5	120	Glo plug ignitor, ignite at 8 compare to test done in VF 13	Two sided full propagation

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 01-06-2011		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE An Experimental Study of Upward Burning Over Long Solid Fuels: Facility Development and Comparison				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Kleinhenz, Julie; Yuan, Zeng-Guang				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER WBS 253225.01.03	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191				8. PERFORMING ORGANIZATION REPORT NUMBER E-17689	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001				10. SPONSORING/MONITOR'S ACRONYM(S) NASA	
				11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2011-217024	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category: 34 Available electronically at http://www.sti.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT As NASA's mission evolves, new spacecraft and habitat environments necessitate expanded study of materials flammability. Most of the upward burning tests to date, including the NASA standard material screening method NASA-STD-6001, have been conducted in small chambers where the flame often terminates before a steady state flame is established. In real environments, the same limitations may not be present. The use of long fuel samples would allow the flames to proceed in an unhindered manner. In order to explore sample size and chamber size effects, two large chambers were developed at NASA GRC under the Flame Prevention, Detection and Suppression (FPDS) project. The first was an existing vacuum facility, VF-13, located at NASA John Glenn Research Center. This 6350 liter chamber could accommodate fuels sample lengths up to 2 m. However, operational costs and restricted accessibility limited the test program, so a second laboratory scale facility was developed in parallel. By stacking additional two chambers on top of an existing combustion chamber facility, this 81 liter "Stacked-chamber" facility could accommodate a 1.5 m sample length. The larger volume, more ideal environment of VF-13 was used to obtain baseline data for comparison with the stacked chamber facility. In this way, the stacked chamber facility was intended for long term testing, with VF-13 as the proving ground. Four different solid fuels (adding machine paper, poster paper, PMMA plates, and Nomex fabric) were tested with fuel sample lengths up to 2 m. For thin samples (papers) with widths up to 5 cm, the flame reached a steady state length, which demonstrates that flame length may be stabilized even when the edge effects are reduced. For the thick PMMA plates, flames reached lengths up to 70 cm but were highly energetic and restricted by oxygen depletion. Tests with the Nomex fabric confirmed that the cyclic flame phenomena, observed in small facility tests, continued over longer sample. New features were also observed at the higher oxygen/pressure conditions available in the large chamber. Comparison of flame behavior between the two facilities under identical conditions revealed disparities, both qualitative and quantitative. This suggests that, in certain ranges of controlling parameters, chamber size and shape could be one of the parameters that affect the material flammability. If this proves to be true, it may limit the applicability of existing flammability data.					
15. SUBJECT TERMS Flammability; Flame propagation; Spacecraft environments; Fire prevention					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 47	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: help@sti.nasa.gov)
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 443-757-5802

