

# Limiting Oxygen Concentrations of Burning PMMA Cylinders under External Radiant Heating and Subatmospheric Pressure

Christina Liveretou<sup>1</sup>, Charles Scudiere<sup>2</sup>, Jose Rivera<sup>3</sup>, Carlos Fernandez-Pello<sup>4</sup>, Michael Gollner<sup>5</sup>  
*University of California, Berkeley, California, 94720, USA*

Sandra Olson<sup>6</sup> and Paul Ferkul<sup>7</sup>  
*USRA; NASA John H. Glenn Research Center*

**This work considers the effect of ambient pressure and an external radiant flux on the limiting oxygen concentration (LOC) for flames spreading downward over the surface of cylindrical samples of black polymethyl methacrylate (PMMA). The objective is to determine the effect of an external radiant flux on the LOC of combustible solid materials in environments expected in future spacecraft cabins. The experimental apparatus and testing methodology is a combination of the LOI and LIFT test apparatuses. The radiant heating ranges from 0 to 3.3 kW/m<sup>2</sup> and the ambient pressures tested from 100 kPa to 40 kPa. An upward forced flow of a mixture of oxygen and nitrogen with a velocity of 10 cm/s is used to determine the LOC of the PMMA as a function of ambient pressure and external heat flux. Results show that increasing the ambient pressure or external radiant flux increases the flame spread rate and decreases the LOC of the PMMA. Correlating the LOC data in terms of the partial pressure of oxygen and the ambient pressure shows that the LOC occurs at an approximately constant oxygen mole fraction that depends weakly on the ambient pressure and radiant flux. The combustion mechanisms leading to this result are discussed based on simple equations and phenomenological arguments. The data from this work will be compared with data from experiments to be conducted in the International Space Station (ISS) under the SoFIE-MIST project, to provide further understanding of the effect spacecraft environments on the LOC of materials. The results will give further insight into the flammability of materials, particularly at subatmospheric ambient pressures, such as in spacecraft, aircraft, and high-altitude locations.**

## Nomenclature

$P$	=	pressure [kPa]
$V$	=	volume [m <sup>3</sup> ]
$X$	=	molar fraction
$n$	=	molar coefficient
$q''$	=	heat flux [W/m <sup>2</sup> ]
$l_h$	=	heated length ahead of flame front [m]
$V_f$	=	flame spread rate [m/s]
$T$	=	temperature [K]
$h$	=	convective coefficient [W/m <sup>2</sup> K]

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<sup>1</sup> PhD Student, Department of Mechanical Engineering, 60 Hesse Hall, University of California, Berkeley, CA 94720, USA.

<sup>2</sup> Postdoctoral Scholar, Department of Mechanical Engineering, 60 Hesse Hall, University of California, Berkeley, CA 94720, USA.

<sup>3</sup> PhD Student, Department of Mechanical Engineering, 60 Hesse Hall, University of California, Berkeley, CA 94720, USA.

<sup>4</sup> Professor of the Graduate School, Department of Mechanical Engineering, 6105A Etcheverry Hall, University of California, Berkeley, CA, 94720, USA.

<sup>5</sup> Associate Professor, Department of Mechanical Engineering, 6105A Etcheverry Hall, University of California, Berkeley, CA, 94720, USA.

<sup>6</sup> Spacecraft Fire Safety Researcher, 21000 Brookpark Road, OH 44135, MS 77-5, Cleveland, OH, 44135, USA.

<sup>7</sup> Spacecraft Fire Safety Researcher, Low Gravity Exploration Technology Branch, 21000 Brookpark Road, Cleveland, OH 44135.

$U$	=	gas flow velocity [m/s]
$\varphi(Da)$	=	function of the Damkohler number
$C$	=	generic constant related to the type of flow
$k$	=	gas thermal conductivity [W/mK]
$l_p$	=	pyrolysis length [m]
$Gr$	=	Grashof number
$Re$	=	Reynolds number
$Pr$	=	Prandtl number
$Da$	=	Damkohler number
$\mu$	=	dynamic viscosity [kg/ms]
$\rho$	=	density [kg/m <sup>3</sup> ]
$\beta$	=	coefficient of thermal expansion [K <sup>-1</sup> ]
$g$	=	force of gravity [m/s <sup>2</sup> ]
$t$	=	time [s]
$\alpha$	=	thermal diffusivity [m <sup>2</sup> /s]
$A_0$	=	Arrhenius constant
$E_a$	=	activation energy [J]
$\hat{R}_u$	=	universal gas constant [J/molK]
$m_f$	=	gasification rate of fuel [kg/m <sup>2</sup> s]
$L$	=	heat of pyrolysis [J/kg]

### Subscripts

$amb$	=	ambient
$ext$	=	external
$O_2$	=	oxygen
$cig$	=	critical for ignition
$f$	=	flame
$fr$	=	flame radiation
$rs$	=	re-radiation from the solid
$s$	=	solid
$p$	=	pyrolysis
$fl$	=	flow
$c$	=	characteristic
$ch$	=	chemical
$r$	=	reaction

## I. Introduction

Fire safety in spacecraft environments is an important concern for space travel<sup>1,2</sup> particularly because of the criticality of such an event. Inside a spacecraft cabin or a space facility, there are combustible materials and conditions that can ignite them, thus posing the risk of initiating a fire. Also, the enclosed nature of space facilities, where egress is difficult, means that the consequences of a fire could be catastrophic for the crew's safety. The fire risk will increase as the time spent in space is increased with the operation of proposed long space missions, and the establishment of facilities on the Moon and Mars. A further challenge is that the environmental conditions encountered inside the cabin of a spacecraft or a space facility are very different from those encountered on Earth. Inside a spacecraft/space facility there is microgravity, or reduced gravity, low velocity flows, and potentially low pressure and elevated oxygen concentration<sup>3</sup>. These atmospheric conditions are referred to as Space Exploration Atmospheres (SEA) and are designed to reduce the preparation time required before Extra Vehicular Activities (EVA)<sup>4</sup>. Although few fire accidents have occurred in spacecraft, and most were put out quickly<sup>5</sup>, the unique conditions in a spacecraft require that all materials are held to strict flammability standards. Consequently, understanding solid material flammability in the cabin environments expected inside space facilities is necessary to better characterize their fire risk.

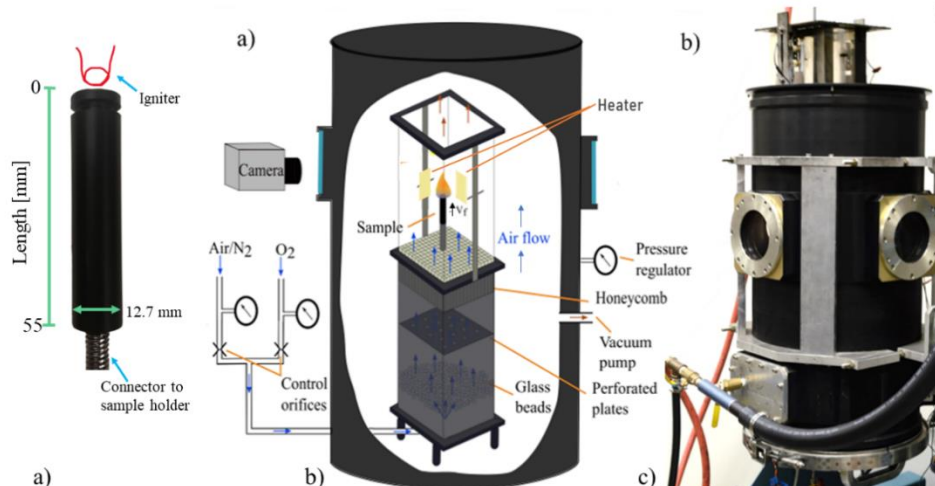
Currently, most materials taken aboard a NASA spacecraft are tested per NASA's fire safety standard STD-6001B test #1, which is a pass/fail upward flame test<sup>6,7</sup>. The test uses upward concurrent flame spread to rank the materials and determine their fire risk. However, some materials do not undergo this test, or fail it, but are still used in spacecraft

due to the needs or wants of the crew. Another test method that is of current interest, although not used by NASA, is the Limiting Oxygen Index (LOI), ASTM 2863<sup>8</sup>, which determines the minimum oxygen concentration needed to sustain flame spread and burning of combustible solids. The LOI test uses a vertical cylindrical rod of the material to be tested, placed in a vertical cylindrical tube 75-100 mm in diameter. A forced flow of controlled oxygen concentration of 5 cm/s is flown upward in the tube past the rod. The sample is ignited on the top of the cylinder such that flames spread downward opposing a mixed (free and forced) flow. The oxygen concentration is reduced slowly as the sample burns, until the flame stops spreading and is extinguished.

In this work, we are specifically interested in the effect of sub-atmospheric pressure and external heating on the flame spread rate and LOC of materials. Sub-atmospheric pressures are present in various environments such as spacecraft and space habitats with SEA atmospheres, aircrafts, and high-altitude locations. In the presence of gravity, reduced pressure reduces buoyancy forces and results in thermo-fluid effects similar to reduced gravity. External radiant heating is included to simulate the effect of heating from a nearby fire or overheated equipment. External radiant heating is also used in another flammability test method, the Lateral Ignition and Flame Spread Test (LIFT) of ASTM E-1321<sup>9</sup>. This test uses a lateral, horizontally placed fuel sample which is ignited on one end and the flame is allowed to propagate laterally to the other end. A panel of radiant heaters is located parallel to the sample at an angle, such that the ignition occurs at the maximum heat flux, and the flame propagates in a decreasing radiant flux. The experimental method used in this work draws inspiration from the LOI and LIFT tests to determine the LOC of vertical PMMA rods in a low velocity opposed flame spread and an incident decreasing radiant flux, in sub-atmospheric pressures. The objective is to determine the effect of an external radiant flux on the LOC of combustible solid materials. The results of this work provide data for comparison with experiments to be conducted in the International Space Station (ISS) under the SoFIE-MIST project<sup>10</sup>. The comparison between LOC data in normal gravity and microgravity would provide further understanding of the LOC of materials in SEA, and in turn information about the fire safety in future spacecraft and space facilities.

## II. Experimental Setup

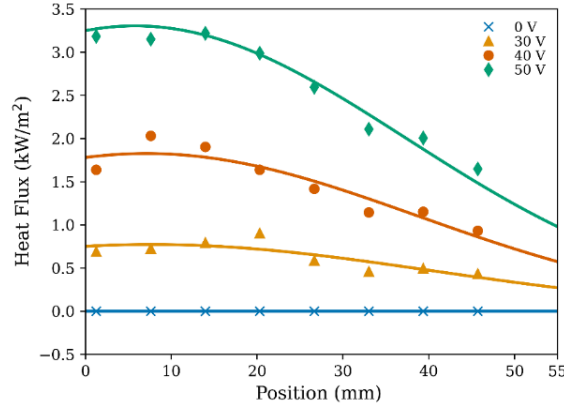
The experimental apparatus consists of a laboratory scale combustion tunnel that has a 125 mm by 125 mm cross section and is 600 mm in length, divided between a flow straightener section at the bottom and the test section at the top. This experimental setup has been previously used to study material flammability of combustible solids and further details can be found in Ref. 11. The flow duct is inserted inside a 105 L pressure chamber (Figure 1) that allows control of ambient conditions at which the sample is tested. The chamber has a flow system that provides constant supply and exhaust of gases. Nitrogen and oxygen are supplied through critical nozzles (O'Keefe Controls) to the bottom of the duct while at the same time evacuating the chamber to maintain constant pressure inside the chamber. The chamber pressure is controlled by a high-capacity vacuum pump (Welch DuoSeal 1376) and monitored in real time with an electronic pressure transducer (Omega Engineering, Inc. PX309-015A5V). Exhaust gases are sampled and analyzed with an Enerac 700 gas analyzer. The forced flow velocity is fixed to 10 cm/s in all the tests, a value which is similar to that induced by the Environmental Control and Life Support System (ECLSS) of a spacecraft. Furthermore, because the experiments are performed in normal gravity conditions, the flame is also exposed to a self-induced buoyant flow in addition to the forced flow. Thus, during the experiments the flame is exposed to a mixed (free and forced) flow condition.



**Figure 1. Experimental setup detailing a) PMMA Sample b) Combustion tunnel c) Pressure chamber.**

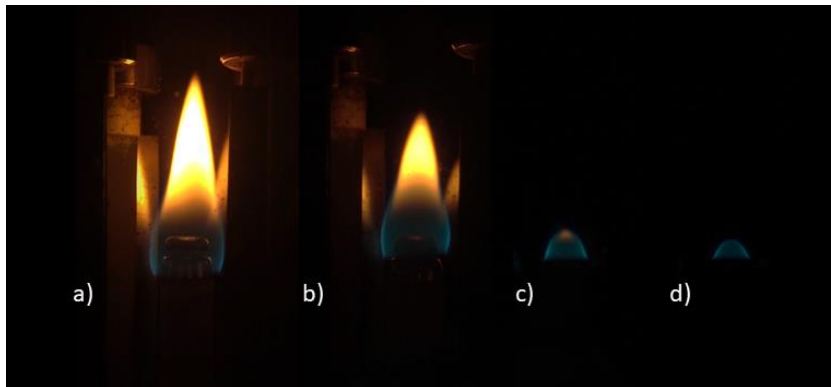
A cylindrical black casted PMMA sample measuring 12.7 mm in diameter and 55 mm in length is placed vertically inside the test section of the flow duct and is connected at the center of the test section using an aluminum sample holder. The black color is selected to maximize the absorptance of thermal radiation at the rod's surface. A subtracted notch at the top of the sample serves to straighten the flame front right after ignition. The samples are ignited using a 26-gauge NiCr ignition wire. The wire is shaped into a coil and hovers just above the sample, such that when a current is passed through it, it will heat up and cause the sample to ignite. The current passed through the ignition wire is energized using a variable transformer (STACO Energy model 3PN1210B). The ignition and subsequent flame spread were video recorded through the chamber windows using a Sony RX10-III camera to visualize the front view of the sample.

Four equispaced flat ceramic heaters (Bach Resistor Ceramics GmbH) surround the sample and are the source of the external radiant heat flux. The heaters are powered by a variable AC power supply and measure 14.7 mm in width and 75 mm in height, with 50 mm being the heated section. There is a distance of 29.85 mm from the surface of each heater to the center of the duct. Placed 18.5 mm behind each heater is a parabolic reflector made of electropolished stainless steel and measuring 70 mm in height and 51 mm in width. The heaters and reflectors are vertically aligned with the middle of the sample and are positioned 83 mm and 93.2 mm from the top of the duct, respectively. Although the heaters provide a radially uniform heat flux to the sample, the heat flux in the vertical direction is variable along the length of the heater. The peak incident heat flux is at the center of the heater, which corresponds to 10 mm from the top of the sample. As seen Figure 2, the heating profile is a half-gaussian function along the surface of the rod. This heat flux profile is similar to that used in the LIFT test<sup>9</sup> and it is suited for investigating the effects of external heating on flame spread. The peak heat flux values tested ranged from 0 to 3.3 kW/m<sup>2</sup> (labeled as 0 to 50 V in the legend, corresponding to the voltage of the heaters). This range was selected to match experiments expected to occur on the ISS, as well as to maintain safe working conditions inside the pressure chamber.



**Figure 2. Profile of incident heat flux on sample.**

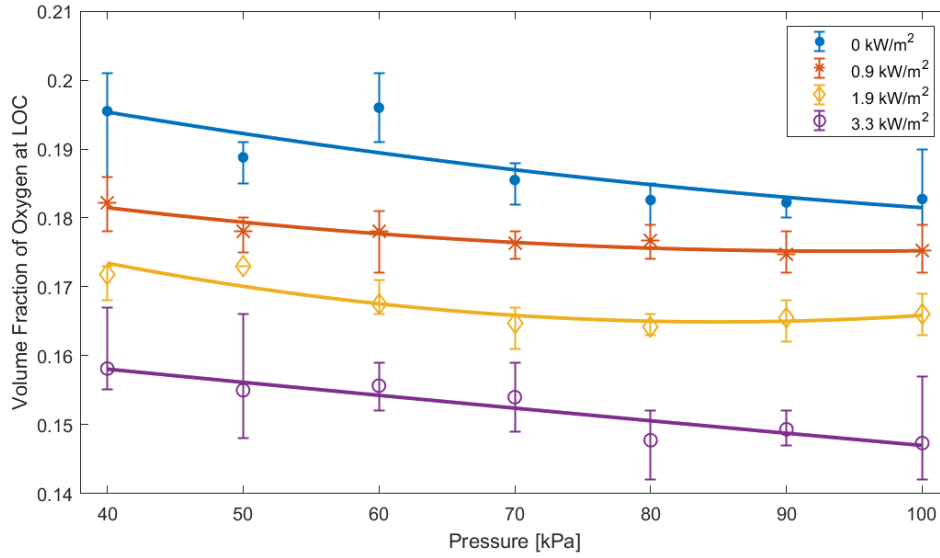
An experiment begins by starting an inflow of 21 vol% at the desired ambient pressure and switching on the heaters while the sample is raised out of view of the heaters, until a steady state temperature is reached. Once the sample is ignited, it is subsequently lowered into the view of the heaters using two linear actuators (Firgelli Automations FA-35-S-12-12) that are attached to the sample holder rod. After two minutes, the flame has stabilized and the oxygen concentration is reduced per the LOI test, until extinction of the flame occurs. The ambient pressure is kept constant through each experiment, and only the oxygen concentration is changed. Although the oxygen concentration is controlled through critical nozzles, an ENERAC 700 portable gas analyzer is used to confirm the oxygen concentration of the gas flowing into the test section. Figure 3 shows the progression of a flame during an experiment at a given ambient pressure. Frame *a* is taken just after ignition, when the oxygen concentration is at 21 vol%. In frame *b*, the oxygen concentration has been reduced, the flame has weakened, and the flame length has decreased. Frames *c* and *d* depict the process of flame extinction at a given oxygen concentration that is recorded as the LOC for that pressure. As the oxygen concentration is reduced the flame size shrinks considerably, and the temperature of the flame reduces until the flame is a blue semicircle hovering over the flat area at the top of the sample.



**Figure 3. Collage of the process of flame extinction as the oxygen concentration is reduced. Note that the flame is also visible in the heaters' reflectors.**

### III. Results

Experiments were conducted within the range of 40 kPa to 100 kPa ambient pressures with an interval of 10 kPa. At each pressure condition, tests were conducted at external heat fluxes of 0 kW/m<sup>2</sup>, 0.9 kW/m<sup>2</sup>, 1.9 kW/m<sup>2</sup> and 3.3 kW/m<sup>2</sup>. The LOC is a difficult point to identify, because at low oxygen concentrations, any minor perturbation can be enough to extinguish the flame<sup>12</sup>. To reduce the error caused by this instability, the oxygen fraction was reduced in small intervals so as not to suddenly deplete the flame of oxidizer. Additionally, at every environmental condition experiments were repeated between three and five times and the LOC values were averaged to produce Figure 4.



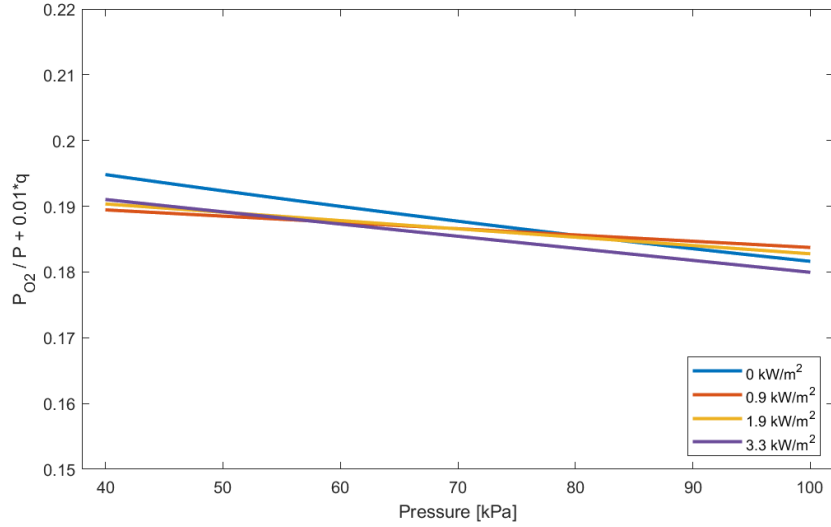
**Figure 4. Experimental results of LOC versus Pressure for four heat fluxes tested.**

A few observations can be made from Figure 4. A higher external radiant flux results in a lower volume fraction of oxygen at extinction, i.e., a lower LOC. This is because the added energy provided by the heaters preheats the sample ahead of the flame front, and therefore increases the flame spread rate. Thus, a reduction in oxygen will be needed to reduce the spread rate to extinction. For all the radiant fluxes tested, reducing the ambient pressure increased the LOC, although not strongly. This is due to the deterrent effect of ambient pressure on the flame spread rate<sup>11</sup>.

The data of Figure 4 can be correlated in terms of an equation of the form

$$\frac{P_{O_2}}{P_{amb}} + 0.01q_{ext}'' = 0.185 \quad (1)$$

where  $q_{ext}''$  is the maximum heat flux that the PMMA rods are exposed to (Figure 2). The resulting correlation is shown in Figure 5. The overall error associated with using this equation is 1.9%, whereas the error at the lower ambient pressures is 2.4%. The correlation can be improved by using a slightly more complicated formula, but for simplicity of the interpretation of Eq. (1), the equation is left as is.



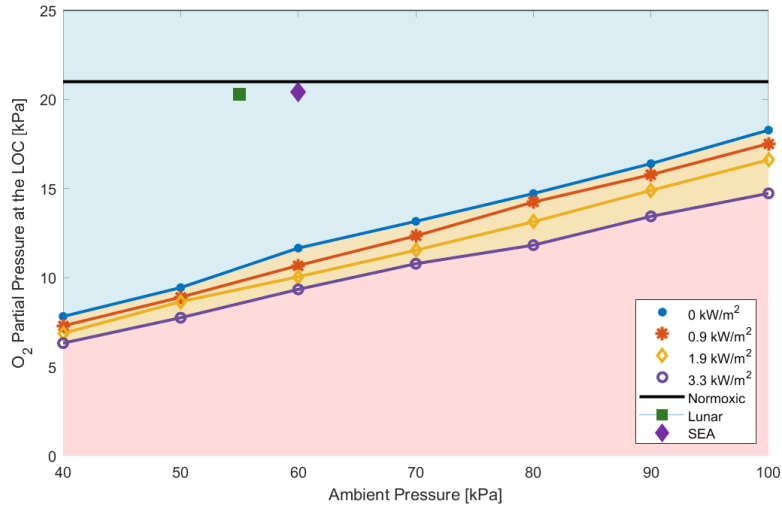
**Figure 5. Correlation of the data of Figure 4 with Eq. (1).**

Since  $P_{O_2}/P_{amb} = X_{O_2}$ , with  $X_{O_2}$  being the mole fraction of oxygen<sup>13</sup>, from Eq. (1) with  $q_{ext}'' = 0$  it is concluded that the LOC for PMMA is approximately at an average mole fraction of oxygen of 0.185, although it increases with decreasing pressure from a value of 0.182 at 100 kPa to a value of 0.195 at 40 kPa. The presence of the radiant flux reduces the mole fraction of the air according to Eq. (1). A nondimensional form of Eq. (1) could be,

$$\frac{P_{O_2}}{P_{amb}} = X_{O_2} - 0.01 \frac{q_{ext}''}{q_{cig}''} \quad (2)$$

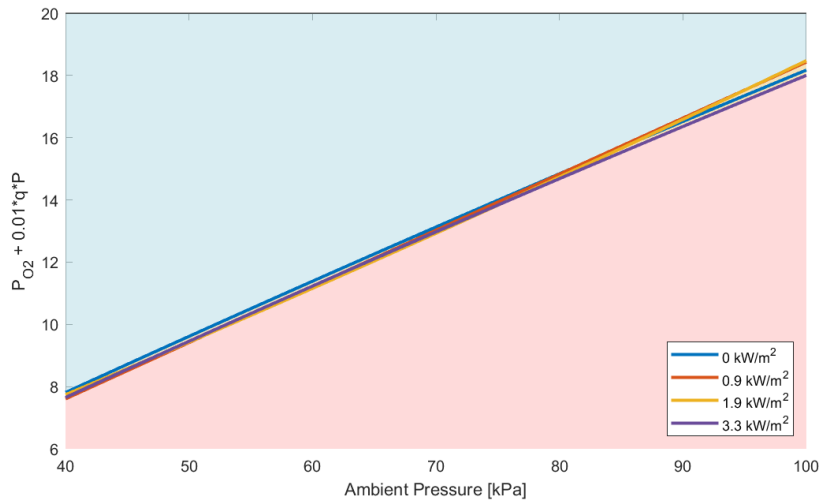
where the external heat flux has been normalized with the critical heat flux for ignition,  $q_{cig}''$  at standard pressure. The critical heat flux for ignition has been selected as the parameter for normalizing of the equation because it determines the external heat flux on the solid that matches the heat flux from the flame to the solid<sup>9,14</sup>. Consequently, the flame propagates without the need for the flame to heat the solid ahead of it. Thus, the critical heat flux for ignition determines a limiting boundary between creeping flame spread and piloted ignition<sup>13</sup>. The data of Olson et al.<sup>12</sup> appear to support Eq. (2), although the selection of  $q_{cig}''$  is not based on a mechanism specific of the LOC.

In tests conducted to determine the LOC of different combustible materials, Olson et al.<sup>12</sup> and Harper et al.<sup>15</sup> observed that the variation of the LOC data plotted in terms of the partial pressure of oxygen gave a linear dependence pressure. Determining the partial pressure of oxygen in the context of flammability limits is important because it provides an objective basis for comparing experiments conducted in various environmental conditions, as it combines the oxygen concentration and the ambient pressure into a single term<sup>16</sup>. Following this approach, the data of Figure 4 was converted into partial pressure of oxygen through the relation  $P_{O_2} = (V_{O_2}/V)P_{amb}$ . The averaged data points presented in Figure 4 in terms of partial pressure of oxygen at the LOC are shown in Figure 6 as a function of the total ambient pressure. The plot also includes the Lunar Exploration, and Space Exploration Atmospheres (SEA), in air for reference. It is seen from Figure 6 that all the data for each heat flux are almost linearly related, with a reduction of the partial pressure of oxygen, and a slight reduction in the slope for higher heat fluxes. Since for a given total ambient pressure solid fuels are flammable for partial pressure of oxygen above the LOC, from the results of Figure 6 it is determined that PMMA is flammable for partial pressures of oxygen well below the oxygen partial pressure of air. Furthermore, in SEA air environments PMMA is flammable for pressures smaller than approximately 110 kPa. The presence of an external heat flux decreases the LOC partial pressure of oxygen even further.



**Figure 6. Partial pressure of oxygen at the LOC as a function of ambient pressure for the four heat fluxes tested, normoxic conditions, as well as Lunar Exploration and Space Exploration Atmospheres (SEA).**

The correlation of the data of Figure 6 with Eq. (1) is shown in Figure 7. It is seen that Eq. (1) correlates well the data of Figure 4 in terms of the partial pressure of oxygen, providing an easy presentation of the LOC with and without an external heat flux.



**Figure 7. Correlation of the data of Figure 6 with Eq. (1).**

#### IV. Discussion

The above result that the LOC of a combustible solid is determined by the oxygen mole fraction is somewhat surprising, although phenomenological arguments can be used to support it. The simplified analysis of flame spread developed by Fernandez-Pello<sup>17,18</sup> is a possible path to discuss this issue. In that work, an expression was derived to describe the flame spread over a solid fuel based on the concept that the flame spreads over the solid as a series of ignition steps where the flame acts both as a heat source for fuel pyrolysis, and as an ignition pilot of the pyrolyzate and oxidizer gas. The analysis provides an analytical formula for the opposed flame spread rate obtained from the ratio of the solid heating length ahead of the pyrolysis front and the time required to heat, pyrolyze and ignite the solid. Assuming for simplicity that the PMMA rods behave as flat and thin, the following expression describes the flame spread rate.



$$V_f = l_h \left[ \frac{h (T_f - T_p) + \dot{q}_{fr}'' - \dot{q}_{rs}'' + \dot{q}_{ext}''}{\rho_s s c_s (T_p - T_o) + L_p} - C \varphi(Da)^{-1} \right] \quad (3)$$

Here,  $V_f$  is the flame spread rate,  $l_h$  the characteristic heated length ahead of the flame front,  $\dot{q}_{fc}'' = h (T_f - T_p)$  is the convective heat flux from the flame to the solid surface,  $\dot{q}_{fr}''$  is the flame radiant flux to the solid,  $\dot{q}_{rs}''$  the re-radiation from the solid,  $\rho_s$  and  $c_s$  are the solid density and specific heat and  $s$  is the solid thickness.  $T_f$  is the flame temperature, and  $T_p$  and  $T_o$  are the pyrolysis and initial temperatures of the solid,  $L_p$  is the heat of pyrolysis,  $C$  is a constant related to the ignition time in the gas and  $\varphi(Da)$  is a function of the Damkohler number<sup>17</sup>. The expression in Eq. (3) can be easily modified to a cylindrical fuel<sup>19</sup>.

The first term inside the parenthesis in Eq. (3) describes the heat transfer mechanisms of the flame spread over a thin fuel and the second term represents the gas phase chemical kinetics mechanisms<sup>16</sup>. For large Damkohler numbers, i.e., fast reaction rate, gas phase chemical kinetics do not play a role in the flame spread rate. This is because all the fuel is consumed at the flame, and consequently the heat released is determined by the gasification rate of the fuel, which in turn is determined by the heat flux at the solid surface. In this case only the first term in Eq. (3) determines the flame spread rate by balancing the heat needed to heat the fuel to its vaporization temperature that vaporizes the solid fuel. This normally is referred to as the heat transfer regime of flame spread. The resulting equation is basically the well-known De Ris equation for opposed flame spread<sup>20</sup> for fast chemical kinetics, and other similar equations based on models of the heat transfer mechanisms of flame spread<sup>21-24</sup>.

For small Damkohler numbers (slow reaction rate), gas phase chemical kinetics start to play a more and more important role because not all the fuel is consumed at the flame, the flame temperature decreases and so does the heat flux from the flame to the fuel surface. The chemical kinetics affect the heat transfer term through the flame temperature<sup>16</sup>. Thus, both terms in Eq. (3) play a role in the flame spread process and must be considered. In the present work, three environmental conditions are varied: pressure, oxygen concentration and external heat flux. These conditions affect both the heat transfer and chemical kinetics term in Eq. (3), thus, determining how these variables affect the different parameters in Eq. (3) should provide insight into the nature of the LOC results. Here only a summary of this approach is given to reduce duplication. More details of the analysis can be found in references 16-18.

#### A. Heat transfer mechanisms:

In this subsection, a summary is presented of how the problem variables affect the different parameters in the first term of Eq. (3). The first parameter is the convective heat transfer from flame to solid. Regarding the convective heat transfer from the flame to the solid,  $\dot{q}_{fc}'' = h (T_f - T_p)$ , the heat transfer coefficient,  $h$ , is directly related to the boundary layer thickness through  $h = k/\delta$ , where  $k$  is the gas thermal conductivity and  $\delta$  the boundary layer thickness. For a mixed flow, forced and free, as that of the present experiments, the average convective heat transfer coefficient can be expressed in terms of the Reynolds Number ( $Re$ ) and the Grashof number ( $Gr$ ) as<sup>25</sup>:

$$h = C \frac{k}{l_p} Gr^{1/4} \left( \frac{Re^4}{Gr^2} + 1 \right)^{1/8} Pr^{1/3} \quad (4)$$

where  $C$  is a generic constant related to the type of flow and the pyrolysis length,  $l_p$ , has been selected as the characteristic length of the problem. Then,  $Re = \rho U_f l_p / \mu$ ,  $Gr = g \beta \Delta T l_p^3 \rho^2 / \mu^2$ , and  $Pr$  is the Prandtl number.  $U_f$  represents the forced flow velocity component of the mixed flow,  $\mu$  is the dynamic viscosity,  $\rho$  is gas phase density,  $\beta$  is the coefficient of thermal expansion and  $g$  is gravity level. From Eq. (4) it is seen that as the pressure is reduced, the heat transfer coefficient decreases because the  $Re$  and  $Gr$  numbers decrease as the density decreases. This, in turn results in the thickness of the boundary layer and the flame stand-off distance to increase. As a consequence, the convective heat flux from the flame to the solid and the flame spread rate decrease.

Assuming that the gas behaves approximately as an ideal gas, then the flame temperature is proportional to the ambient oxygen concentration and is not strongly dependent on ambient pressure until the pressure is low enough to affect the reaction rate and consequently heat release rate at the flame. The pyrolysis temperature is weakly dependent

on the oxygen concentration and for the present purpose can be assumed as constant. Since the oxygen concentration is reduced, the flame temperature is reduced, the convective heat flux from the flame to the solid reduces and so does the flame spread rate. The flame radiant flux is approximately proportional to  $T_f^4$ , therefore the radiant heat flux decreases strongly as the oxygen is reduced. Consequently, the flame spread rate decreases strongly as the oxygen concentration is decreased<sup>17</sup>.

### B. Chemical kinetics mechanisms:

The chemical kinetic mechanisms affect the flame spread rate primarily through the second term of Eq. (3) that is approximately dependent on the Damkohler number, Da. The Da is the ratio of the flow time to the chemical time. The flow time can be defined as  $t_{fl} = l_c/U_m$  if convection is dominant or  $t_{fl} = l_c^2/\alpha$  if diffusion is dominant. The chemical time is defined as  $t_{ch} = \frac{\rho}{\dot{q}_r}$ , where  $\dot{q}_r$  is the reaction rate, which for a single step, the overall reaction can be expressed as<sup>26</sup>

$$\dot{q}_r = A_0 \exp\left(-\frac{E_a}{R_u T}\right) [Fuel]^a [O_2]^b = A_0 \exp\left(-\frac{E_a}{R_u T}\right) x_{fuel}^a x_{O_2}^b \left(\frac{P}{R_u T}\right)^{a+b} \propto P^{a+b} \quad (5)$$

For a second order reaction, a=b=1 and the reaction rate is proportional to  $P^2$ . For a convective dominated flow, the Damkohler number becomes:

$$Da = \frac{t_{fl}}{t_{ch}} = \frac{l_c}{U_m} \frac{q_r}{\rho} \quad (6)$$

Note that pressure affects, through the gas density, both the thermal diffusivity  $\alpha = k/\rho c$  and the mixed (free and forced) flow velocity<sup>18</sup>.

$$U_m = \sqrt{U_f^2 + (g l_f^2 \beta (T_f - T_a) \rho / \mu)^2} \quad (7)$$

From Eqs. (5), (6) and (7) it is seen that the dependence of the Damkohler number on pressure is not straight forward, since it affects the buoyant velocity, the characteristic length, and the reaction rate. However, considering that the reaction rate is the dominant mechanism in the chemical kinetics term of Eq. (3), it is inferred that Da decreases as the pressure is decreased. The effect of oxygen concentration is clearer since the flame temperature decreases as the same time as the oxygen concentration, and in turn so does the reaction rate, the buoyant velocity, and the flame length. Consequently, as the oxygen concentration is decreased, Da decreases and so does the chemical kinetics term in Eq. (3). Furthermore, since as the flame temperature decreases the convective and radiative heat fluxes from the flame to the solid also decrease, the heat transfer term in Eq. (3) also decreases and in turn so does the flame spread rate.

It is interesting to notice that for a second order reaction the reaction rate (Eq. (5)), depends linearly on the mole fraction of oxygen and the mole fraction of fuel. In this work we reduce the mole fraction of oxygen in searching for the LOC, and since the Damkohler number is strongly dependent on the reaction rate, it is understandable that the LOC is determined by the mole fraction of oxygen. It should also be noted that the mole fraction of fuel is determined primarily by the mass gasification rate, or burning rate, of the solid, since it is the only source of gaseous fuel, which depends on the heat flux at the fuel surface. The gasification rate is approximately determined by the ratio of the heat flux at the surface and the heat of gasification, or pyrolysis, of the solid<sup>27</sup>.

$$m_f'' = \frac{q_s''}{L} \quad (8)$$

where  $m_f''$  is the gasification or pyrolysis rate,  $L$  is the heat of pyrolysis, and  $q_s''$  the overall heat flux at the solid surface<sup>27</sup>, which is also the numerator in the heat transfer term in Eq. (3).

$$q_s'' = h(T_f - T_p) + \dot{q}_{fr}'' - \dot{q}_{rs}'' + \dot{q}_{ext}'' \quad (9)$$

Thus, the fuel gasification rate, and consequently the mole fraction of fuel, also depend on pressure and oxygen concentration through the heat flux at the surface. The relevance here is that this is a specific aspect of the combustion of solid fuels, in contrast with gas fuel combustion where both the mole fraction of oxygen and fuel are prescribed. Thus, the mechanisms controlling the flammability limits in the combustion of solid fuels are significantly more complicated than those for gaseous fuels. Consequently, care should be taken when applying the concepts traditionally used for gaseous fuel combustion to solid fuel combustion.

### C. LOC mechanisms:

In this work, the LOC is experimentally determined by observing when the flame stops propagating and the burning fuel downstream from the flame front extinguishes. This is done by fixing the ambient pressure and gradually reducing the oxygen concentration until the LOC is reached. From Eq. (3) it is seen that this limit is determined by the balance of the heat transfer and chemical kinetics terms in the equation. Reducing the oxygen concentration reduces the flame temperature and consequently both the convective and radiative heat fluxes from the flame to the solid are reduced, and so is the heat transfer term in Eq. (3). Also, as the oxygen concentration is reduced, the  $Da$  decreases and the chemical kinetics term increases. Eventually both terms balance each other, and the spread of the flame stops. This is the marker of the LOC for flame spread. If the fuel downstream of the flame front continues to burn, the oxygen concentration continues to be decreased, which results in a lower flame temperature, lower gasification rate and lower Damkohler number. Eventually the reduction of the oxygen concentration leads to the extinction of the flame because of the lower mole fraction of fuel and the lower reaction rate. This is a LOC for burning that is close to the LOC for flame spread because of the sensitivity of the fuel burning to the oxygen concentration.

If the pressure is reduced at a fixed oxygen concentration, the heat transfer term decreases because the boundary layer thickness increases since the  $Re$  and the  $Gr$  numbers decrease as the density decreases. This causes the convective and radiative heat transfer from the flame to the fuel to decrease and in turn the heat transfer term in Eq (3) to decrease. The chemical kinetics term is also reduced, because of the dependence of the reaction rate on pressure. If the heat transfer term in Eq. (3) is reduced to the point that it is equal to the chemical kinetics term, then the flame stops spreading. This is therefore another potential LOC mechanism, although the effect is weaker than when the oxygen concentration is reduced.

The external heat flux counteracts the decrease of the convective and radiative heat from the flame to the solid, as the oxygen concentration and pressure are reduced. It also counteracts the lower mass gasification rate as the heat flux from flame to the solid decreases. Consequently, applying an external heat flux reduces the LOC both for flame spread and mass burning.

## V. Conclusion

Understanding fire behavior in extreme conditions, such as in low pressure environments with high incident radial heat flux and a variable oxygen concentration is important for the improvement of flammability safety standards for aircraft and space craft. In this paper, the limiting oxygen concentration is studied as a function of ambient pressure and external heat flux for cylindrical samples made of PMMA. It is found that the partial pressure of oxygen, and by extension the molar fraction of oxygen, is instrumental in determining the oxygen concentration below which flame spread and mass burning cannot be sustained. Over the ranges tested, this relationship can be described to an acceptable degree of accuracy through a simple linear equation, which evades the need for detailed experimentation at each condition.

Additionally, experiments showed that in the unfortunate case that a fire breaks out in a low pressure or low gravity environment, reducing the ambient oxygen concentration by as little as 5% can quickly extinguish the fire, although a rapid depressurization may be as, or more, effective. This knowledge could help in the selection of fire safe materials to be used in spacecraft.

Therefore, it is important to continue researching the subject. Future research should include considering the transient characteristics of the extinction process at each oxygen concentration because reducing the oxygen in a cabin

to put out a fire can only be used as a temporary safety measure. It is also worth studying the probability of fire extinction at oxygen concentrations slightly above the LOC.

### Acknowledgements

The work presented here was supported by NASA Grants NNX10AE01G and NNX13AL10A. The authors would like to thank Carina Romero, Sebastián Quiroz, Andrew Petrak, Abhik Dutta, and Jason Guardado for their help with the experiments. Additionally, Christina Liveretou would like to thank the Onassis Foundation for partially supporting her studies through the Onassis Foundation Scholarship.

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