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Ignition Delay of Combustible Materials in Normoxic Equivalent Environments

Sara McAllister and Carlos Fernandez-Pello
University of California, Berkeley

Gary Ruff and David Urban
NASA John H. Glen Research Center

ABSTRACT

Material flammability is an important factor in determining the pressure and composition (fraction of oxygen and nitrogen) of the atmosphere in the habitable volume of exploration vehicles and habitats. The method chosen in this work to quantify the flammability of a material is by its ease of ignition. The ignition delay time was defined as the time it takes a combustible material to ignite after it has been exposed to an external heat flux. Previous work in the Forced Ignition and Spread Test (FIST) apparatus has shown that the ignition delay in the currently proposed space exploration atmosphere (approximately 58.6 kPa and 32% oxygen concentration) is reduced by 27% compared to the standard atmosphere used in the Space Shuttle and Space Station. In order to determine whether there is a safer environment in terms of material flammability, a series of piloted ignition delay tests using polymethylmethacrylate (PMMA) was conducted in the FIST apparatus to extend the work over a range of possible exploration atmospheres. The exploration atmospheres considered were the normoxic equivalents, i.e. reduced pressure conditions with a constant partial pressure of oxygen. The ignition delay time was seen to decrease as the pressure was reduced along the normoxic curve. The minimum ignition delay observed in the normoxic equivalent environments was nearly 30% lower than in standard atmospheric conditions. The ignition delay in the proposed exploration atmosphere is only slightly larger than this minimum. In terms of material flammability, normoxic environments with a higher pressure relative to the proposed pressure would be desired.

INTRODUCTION

The possibility of an accidental fire onboard space vehicles and facilities has been a concern since the beginning of the crewed spaceflight program [1-3]. Because these vehicles and facilities are built with a 20-year life expectancy and have flammable materials and sources of ignition onboard, the possibility of fire must be considered. The enclosed nature of space facilities, their limited egress, their dependence on electrical equipment with limited system redundancy, and the sensitivity of this equipment to soot and chlorinated combustion products means that a fire does not have to be large to have serious consequences. Consequently, understanding material flammability in the environments expected in space facilities is of utmost importance.

Flammability of solid materials is typically characterized by four parameters: ignition delay or ease of ignition, flame spread rate, heat release rate, and toxicity [4]. The last three parameters are only important if the solid has already ignited, so this work will focus on the ignition delay or ease of ignition.

Significant effort has already been applied to understanding ignition delay in microgravity conditions, both theoretically and experimentally [5-9]. The conclusion drawn from each of the above studies is that

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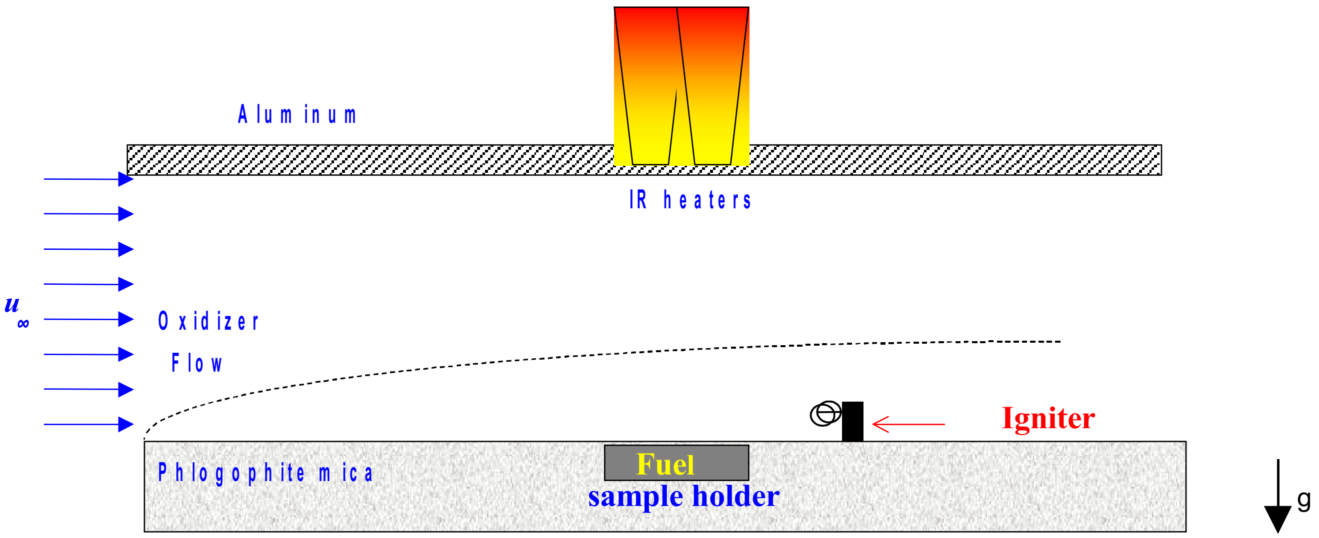

Figure 1. Simplified schematic of the FIST tunnel.

in the low velocity flows commonly encountered in space-based facilities, piloted ignition delay times are shorter than those in the buoyancy-induced flows of normal gravity. Additionally, the critical heat flux (CHF) for ignition in microgravity could be reduced significantly from the value required in normal gravity.

The bulk of this previous work has been done using standard atmospheric conditions - 101kPa with 21% oxygen by volume. However, NASA is designing the next generation of vehicles to operate with a different cabin environment to reduce the risk of decompression sickness and the pre-breathe time required for extra-vehicular activities (EVA) [10]. The proposed space exploration atmosphere (SEA) for the habitable volume of exploration vehicles uses a total cabin pressure of 52.7 to 58.6 kPa with an oxygen concentration of 30 to 34% by volume. Previous work in the Forced-flow Ignition and flame Spread Test (FIST) apparatus [11] has shown that the ignition delay decreases by 17% in air in the proposed cabin pressure. In the reduced pressure and elevated oxygen concentration of proposed space exploration atmosphere, the ignition time is reduced by 27% compared to the standard atmosphere currently used in the Space Shuttle and Space Station. Additionally, the critical heat flux for ignition was also shown to decrease in these environments, adding to the hazard. If the trends noted by other researchers in [5-9] apply, the ignition delay time in microgravity, low-flow conditions can be even shorter, resulting in a further increase in ignition hazard onboard.

The objective of the present study is to determine the safest cabin environment in terms of material flammability. To this end, ignition delay tests were performed using the FIST apparatus extending the tests over the range of "normoxic equivalent environments." In these habitable environments the partial pressure of oxygen remains constant as the total pressure is reduced. With this constraint, the lungs can function as they do in sea-level conditions [10].

DESCRIPTION OF EXPERIMENTS

All tests were performed in the Forced-flow Ignition and flame Spread Test (FIST) apparatus developed at UC Berkeley under NASA sponsorship [12]. A simplified schematic of the FIST tunnel is shown above in Fig. 1. The tunnel is 39.2 cm long in the streamwise direction, 14.9 cm wide, and 8.0 cm high. A fan at the downstream end of the tunnel induced a forced flow of 30 cm/s. An infrared radiant heater was used to preheat the samples and was arranged to produce a nearly constant heat flux of 14 kW/m^2 over the length of the sample. Ignition was induced with a 3-mm diameter coiled Kanthal wire mounted 10 mm downstream of the sample. The igniter was kept above 1000°C in all tests to minimize the gas-phase induction time.

The FIST flow tunnel is mounted horizontally in a containment chamber (shown in Fig. 2) that allows tests to be performed at a range of ambient pressures and oxygen concentrations. The chamber pressure was monitored using a pressure transducer. Table 1 shows the normoxic equivalent pressure and oxygen concentrations used. To achieve the desired atmosphere, room air was allowed to fill the chamber. The chamber pressure was then reduced below the chosen pressure and bottled oxygen was used to raise the pressure and oxygen concentration to the set point. The fan was set to the highest setting and the gases were allowed to mix for at least five minutes. To ensure that the chamber didn't heat excessively during the tests, the ambient gas temperature inside the chamber was monitored with a thermocouple placed near the inlet of the tunnel. The highest chamber temperature observed was 36°C.

Figure 2. Photograph of the FIST tunnel in the containment chamber.

Table 1. Tested normoxic equivalent environments

Pressure (kPa)	Pressure (psi)	O_2 Partial Pressure (kPa)	O_2 Partial Pressure (psi)	% O_2
101.3	14.7	21.3	3.1	21.0
89.6	13	21.3	3.1	23.8
82.7	12	21.3	3.1	25.8
75.8	11	21.3	3.1	28.1
68.9	10	21.3	3.1	30.9
62.1	9	21.3	3.1	34.3
55.2	8	21.3	3.1	38.6
48.3	7	21.3	3.1	44.1
41.4	6	21.3	3.1	51.5
34.5	5	21.3	3.1	61.7
27.6	4	21.3	3.1	77.8

RESULTS

The ignition delay times in normoxic equivalent atmospheres are shown below in Fig. 3. Each point represents the average of the three tests and the bars represent the spread of the data. The average spread or variation in the data was 2.3%.

The ignition delay times decrease as the pressure is reduced and the oxygen concentration is increased along the normoxic curve. The greatest drop in the ignition time occurs between atmospheric pressure and the normoxic environment at 89.6 kPa. As the pressure is reduced along the normoxic curve, the change in the ignition time decreases and the ignition delay curve flattens out. The average ignition delay time seems to reach a minimum in the range of 28-40 kPa total pressure. The total reduction in the ignition delay time was 29.5% between air at sea-level pressure and the normoxic atmosphere at 34.5 kPa (5 psi). For safety reasons, tests were not performed above 77% oxygen. Therefore it is not possible to preclude the possibility that the absolute minimum ignition delay time does not occur at a higher normoxic oxygen concentration than tested here, although it appears that an inflection point occurs at around 34.5 kPa (5 psi) pressure.

DISCUSSION

The piloted ignition of a solid combustible can be viewed as a series of three events [13, 14]. In the first, the solid must be heated to a high enough temperature for pyrolysis to occur. Once the pyrolysis gases are produced, they must mix with the oxidizer to form a combustible mixture. A gas-phase induction process, induced by the pilot, must then occur for thermal runaway to ignition. This three-step process results in three characteristic times that, when combined, equal the total ignition delay time: a pyrolysis or solid heating time, a mixing time, and an induction or chemistry time.

Phenomenologically, piloted ignition of a solid combustible occurs when sufficient pyrolysis gases are produced so that the mixture at the pilot is at or just slightly above the lean flammability limit. Once the mixture near the pilot has ignited, a premixed flame may propagate back towards the solid. In order to initiate sustained burning, enough pyrolysis gases must be generated at the surface so that the temperature of the approaching flame is great enough that the heat losses to the solid do not extinguish the flame. If this is the case, a diffusion flame will become anchored at the surface. In other words, there is a certain (critical) mass flow rate of pyrolysis gases from the solid in order for sustained burning to occur [15, 16, 17].

This description of piloted ignition can be used to describe the reported experimental trends. Reducing the pressure and increasing the oxygen concentration affects all three stages of the ignition process. For each stage, pressure and oxygen can operate in several different ways both independently and dependently. In the following discussion, an attempt will be made to describe these workings and interactions in terms of the convection heat loss, critical mass flux of fuel for ignition, pyrolysis rate, diffusivity, and the gas-phase reaction rate.

Pressure affects the heating time through the convection heat loss. For mixed forced and natural convection over a flat plate, the convective heat transfer coefficient can be represented as

$$h \propto \mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}\sqrt[4]{1+\frac{Gr}{\mathrm{Re}^2}\mathrm{Pr}^3} \qquad (1)$$

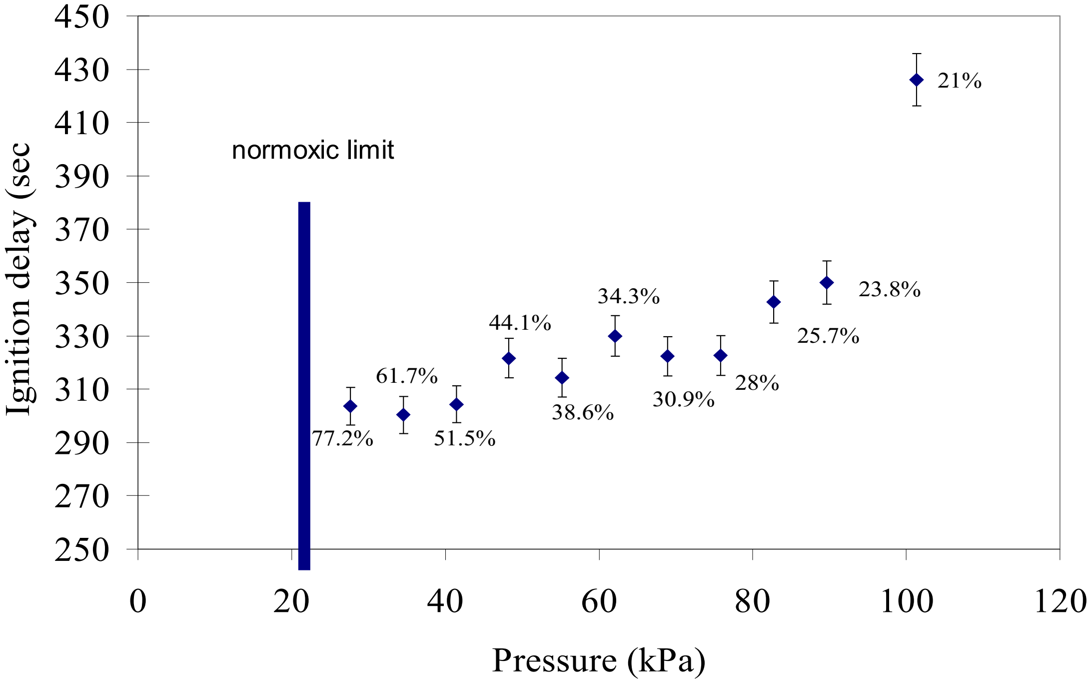

Figure 3 – Ignition delay time as a function of pressure with a “normoxic” [O$_2$]. The [O$_2$] is indicated for each pressure. The bars represent the spread of the data.

where *Re* is the Reynolds number, *Pr* is the Prandtl number, and *Gr* is the Grashof number [18]. For relatively high velocity flows, Equation 1 reduces to $h \propto \mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}$. The Prandtl number is not a function of pressure but the Reynolds number is directly proportional to pressure through the density term. In the limit of pure natural convection, the relation for mixed convection heat transfer coefficient becomes $h \propto Gr^{1/4}\,\mathrm{Pr}^{1/4}$. If the oxidizer is assumed to be an ideal gas, the Grashof number is proportional to the pressure squared. No matter what form of convective heat transfer, the heat transfer coefficient is found to be proportional to the square root of the pressure. Thus, when the pressure is decreased, the heat transfer coefficient decreases resulting in less convective heat loss from the solid. With less heat loss from the solid, the temperature at which the critical mass flux occurs should be attained sooner resulting in a shorter ignition time. The change in the heat transfer coefficient is evident in the surface temperature histories. Fig. 4 shows the surface temperatures as a function of time for a range of pressures in normoxic equivalent environments.

In these tests, an increase in oxygen concentration occurs simultaneously with the reduction in pressure (normoxic conditions). Due to the normoxic constraint (constant oxygen partial pressure), the mass flux of oxygen over the solid remains unchanged. Because the oxygen to fuel ratio at the lean flammability limit generally is not a function of pressure [19], no change in the critical mass flux of fuel is expected along the normoxic curve. An elevated oxygen concentration can, however, affect the solid pyrolysis process. For some materials the pyrolysis rate is increased by the presence of oxygen [20, 21]. Because this is the case for PMMA [20], the pyrolysis rate is greater at a given temperature when there is more oxygen present. Experiments performed by Rich *et al.* [15] and Rasbash *et al.* [16] have shown that the critical mass flux at ignition is insensitive to the oxygen content in the oxidizer for oxygen concentrations greater than 21% in atmospheric pressure. If this trend holds in reduced pressures, the critical mass flux of pyrolysis gases would be reached at an even lower temperature than in air, decreasing the ignition delay time. However, the effect of oxygen on the pyrolysis rate probably decreases at sufficiently low pressures because the collision rate of the oxygen molecules with the surface decreases.

To confirm these theories, the critical mass flux at ignition should be measured. However, this information is not currently available, but some insight can be gained by looking at the surface temperatures of the solid. The surface temperatures as a function of time are shown in Fig. 5. Fig. 5 shows that ignition occurs at a lower surface temperature when the pressure is reduced in normoxic equivalent environments as predicted.

Reducing the pressure will also affect the mixing time. Even when pure diffusion across the boundary layer is assumed to be the mixing mechanism, this characteristic time is on the order of only a few seconds [13] in atmospheric pressure. Diffusivity is inversely dependent on the pressure, so decreasing the pressure will increase the diffusivity and thus reduce the mixing

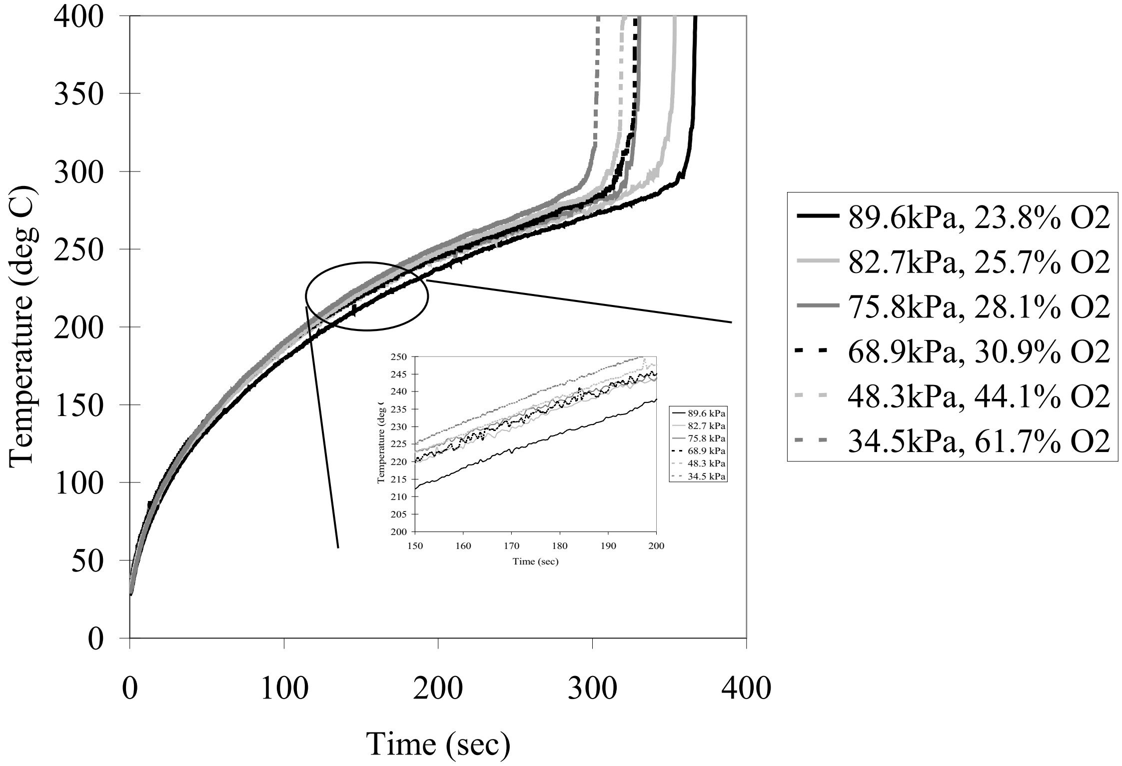

Figure 4 – Surface temperature as a function of time for several normoxic equivalent environments showing the effect of pressure on the heat transfer coefficient.

time further. Because the mixing time is so short relative to the heating time (and in some cases the chemistry time), this mechanism can be considered relatively unimportant.

At sufficiently low pressures, viz. about 50 kPa, another mechanism begins to influence the surface temperature prior to ignition. Generally, in piloted ignition the igniter is typically very hot (above 1000°C), essentially removing the chemistry time as a factor [13]. However, the gas-phase reaction rate is a function of the pressure and decreases as the pressure is reduced. As the chemical induction process begins to take a measurable amount of time, the solid has a chance to heat to a higher surface temperature before ignition. This transition can be seen in the surface temperature histories in Fig. 5 between a pressure of 55.2 kPa and 34.5 kPa. At pressures below 55.2 kPa, the surface temperature just prior to ignition begins to increase. If it were possible to test at lower pressures, it is predicted that the pressure's effect on the chemistry would become greater than its effect of the convective heat transfer coefficient and the oxygen's effect on the pyrolysis rate, resulting in a u-shaped curve of the ignition time as a function of pressure.

It is hypothesized that the large jump in the ignition delay time between atmospheric pressure and 89.1 kPa is due to the fact that the pressure is still high enough that the gas-phase reaction rate is still fast. The only mechanisms effecting the ignition time are the reductions in convective heat loss and the increase in pyrolysis rate which both act to reduce the ignition time. It is possible that the effect of pressure on the gas-phase reaction rate starts at pressures of about 80 kPa flattening out the ignition delay curve, but doesn't become a major factor until the pressure is reduced below about 55 kPa.

CONCLUSION

NASA is designing the next generation of space vehicles to operate with a different cabin environment than has been used previously. In previous work [11], it was shown that in the proposed environment, approximately 58.6 kPa and 32% oxygen, piloted ignition of solid materials occurs approximately 27% faster than in atmospheric pressure with air. In order to determine the safest cabin environment in terms of material flammability, ignition delay tests were conducted in habitable normoxic equivalent environments. It was shown that the ignition delay time decreases as the pressure is reduced with a corresponding increase in oxygen concentration at a constant oxygen partial pressure. The present results show that there are no major variations in the ignition delay time for oxygen concentrations above 28% over the corresponding range of pressures. This indicates that in this range of normoxic conditions, oxygen concentration and pressure effects balance each other making the ignition delay

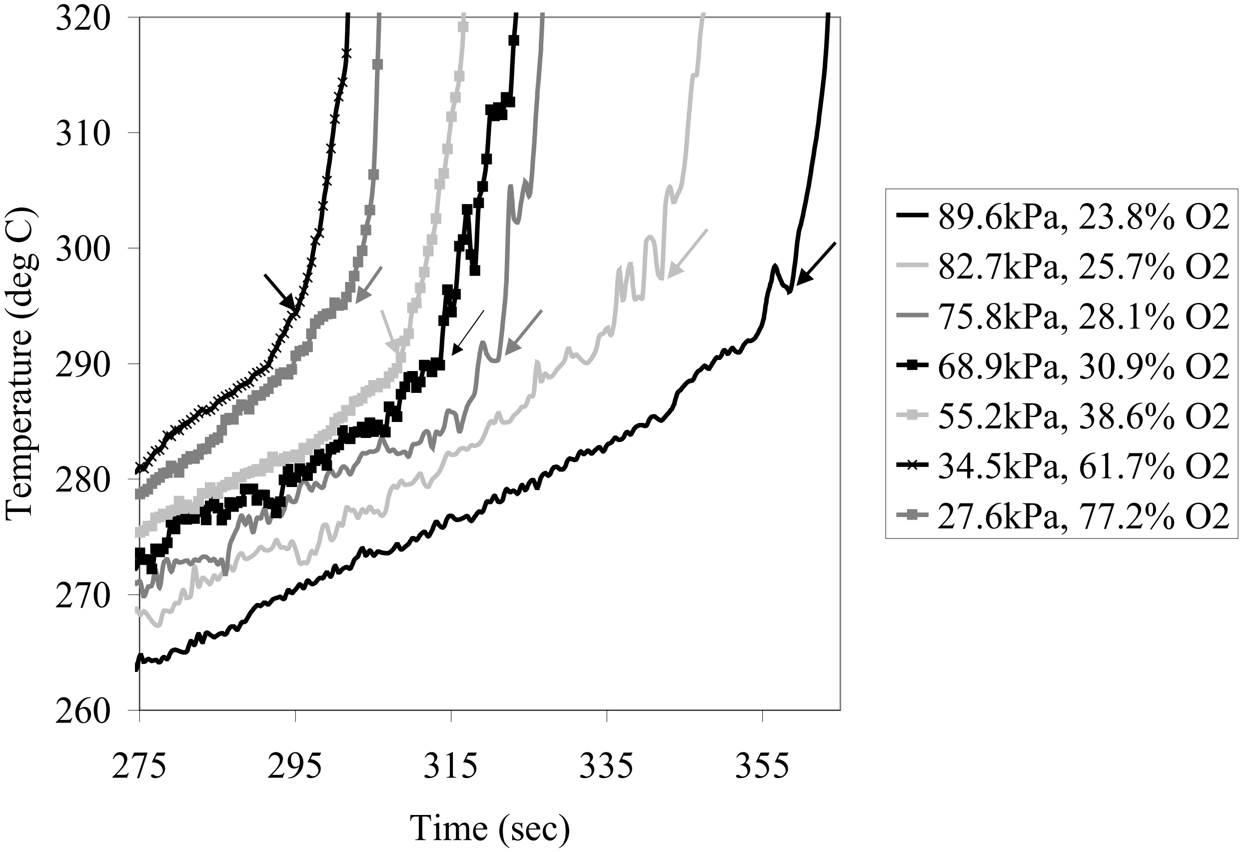

Figure 5 – Surface temperatures as a function of time just prior to ignition for several normoxic equivalent environments. The average variation in the surface temperature prior to ignition at a given environment is ±3℃.

insensitive to the normoxic ambient. It should be noted, however, that to get a complete picture of the flammability risk it is necessary to include flame spread and heat release rates. Both flame spread and heat release rates have been shown [22, 23] to dramatically increase with oxygen concentration, unless pressure is very low. It also should be pointed out that a compromise between the risks of material flammability and decompression sickness must be made and the results of this work provide more data to make an informed decision.

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