Burning Characteristics of Polymers at Different Pressures and Oxygen Concentrations

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Background

- February 8, 2006 a UPS DC-8 was forced to land due to onboard fire.
- The crew survived, but the airplane and cargo were lost.
- FAA is researching the effectiveness of various fire suppressions to combat fires at altitude.

Motivation

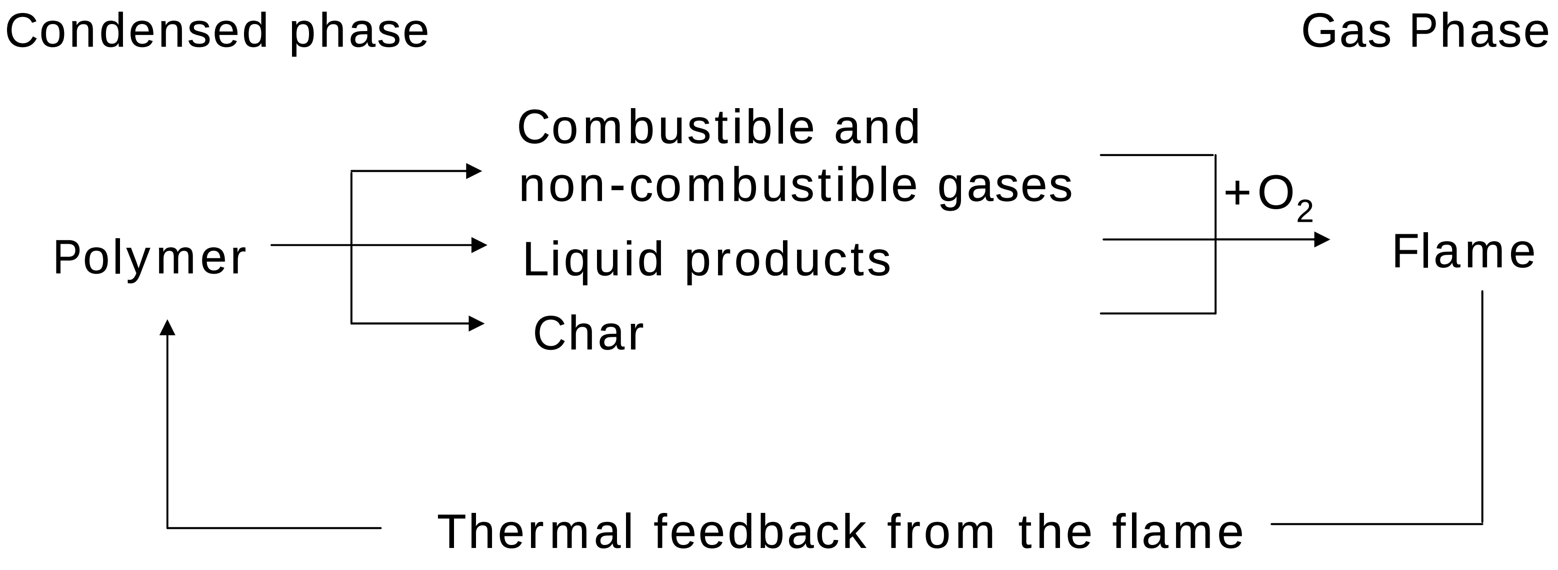
- Depressurization procedure as means to combat fires at altitude.
- Very limited research on the subject of high altitude fire so far.

Objective

- Use modifed Limited oxygen index (LOI) test to measure the HRR of polymers at different oxygen concentrations.
- Study the burning behavior of plastics at altitudes using the FAA pressure modeling facility.

Burning of plastics

- Feedback mechanism for sustained combustion



$$Function(Y_{O_2,\infty}, P)$$

Gas phase combustion

- Assumptions
  - Steady burning.
  - Purely convective heating. No radiant heat transfer.
  - Laminar flow.
  - All species have equal and constant specific heat.
- Due to these major assumptions the solution is not meant to give quantitative answers but to give physical insight into the fluid dynamics and combustion of the problem.

Gas Phase Combustion

- Mass loss rate:

$$\dot{m}'' = \frac{h}{c_p} \ln(1 + B)$$

- Spalding Transfer number:

$$B = \frac{Y_{O_2,\infty}(\Delta h_c / r) - c_p(T_s - T_\infty)}{L}$$

$h \rightarrow$ *convective heat transfer coefficient*

$c_p \rightarrow$ *specific heat of the gas*

$Y_{O_2,\infty} \rightarrow$ *ambient oxygen mass fraction*

$\Delta h_c \rightarrow$ *heat of combustion*

$r \rightarrow$ stoichiometric oxygen to fuel mass ratio

$L \rightarrow$ *heat of gasification*

Pressure dependence

- Assumptions
  - Laminar flame
  - Convective heat transfers

$$h = Nu\frac{k}{L}$$

$L \rightarrow$ characteristic length of surface
Nu $\rightarrow$ Nusselt number
k $\rightarrow$ Thermal conductivity

$$h = Ra^{1/4}$$

$$h = Gr^{1/4}$$

$$h \propto (\rho^2)^{1/4}$$

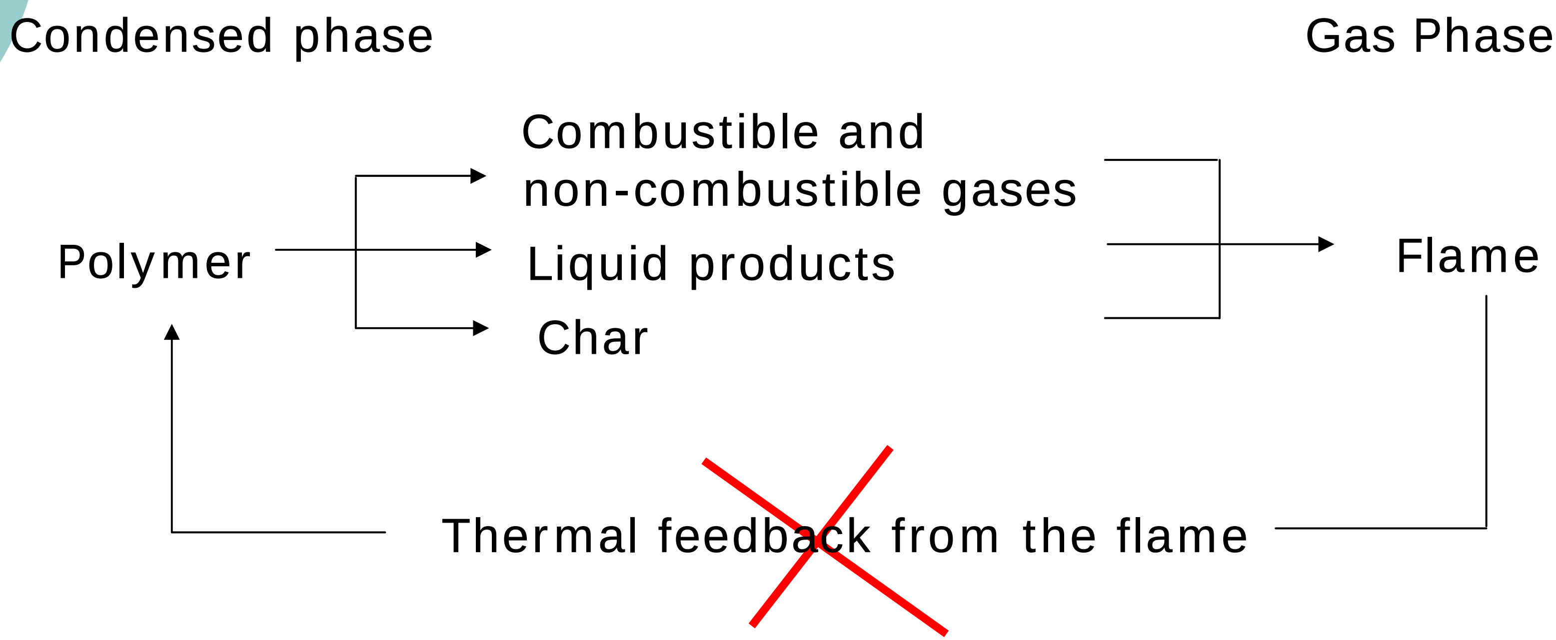
Ideal Gas Law $P = constant \times T \times \rho$

$$h \propto (P^2)^{1/4}$$

$\dot{m}'' \sim P^{1/2}$

Pressure dependence

- The reduction in pressure reduces the heat transfer back to the solid, and hence slowing down the combustion process.



$$Function(Y_{O_2,\infty}, P)$$

m” ~ P^1/2

Pressure dependence

- Time to ignition:
  - Convective heating from a flame

$$t_{ig} = \frac{\pi}{4} k \rho c_p \left(\frac{T_{ig} - T_\infty}{\dot{q}''}\right)^2 = \frac{\pi}{4} k \rho c_p \left(\frac{T_{ig} - T_\infty}{h(T_f - T_s)}\right)^2$$

$$t_{ig} \propto \left(\frac{1}{\rho^{1/2}}\right)^2 = \left(\frac{1}{P^{1/2}}\right)^2 = \frac{1}{P}$$

$t_{ig} \sim 1/P$

Pressure dependence

- Flame spread rate

$$v_f \approx \frac{flame\ heated\ length}{time\ to\ ignition}$$

$$v_f \propto \frac{1}{\frac{1}{P}} = P$$

Vp ~ P

Pressure dependence

- The burning rate and flame spread decrease as pressure decreases.
- The time to ignition scales inversely with pressure so as the pressure decreases the time to ignition increases.
- The overall effect of reduced pressure acts to inhibit the fire.

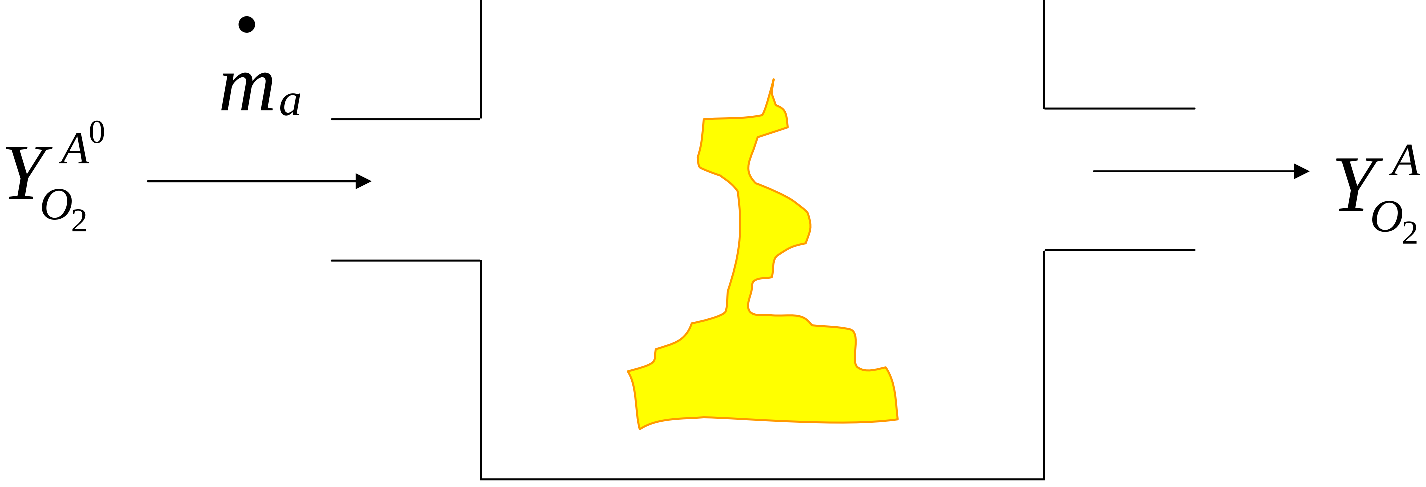
Oxygen consumption calorimetry

- The heat release rate calculated from oxygen consumption is based upon an observation that many polymers share similar heat of combustion per gram of oxygen consumed.

$$E = \frac{\Delta h_c}{r} = 13.1 \frac{kJ}{g - O_2}$$

Oxygen consumption calorimetry

- By simply knowing the inlet mass flow rate of incoming air and the molar concentration of oxygen at the inlet and the outlet the heat release of the fire can be obtained.



Oxygen consumption calorimetry

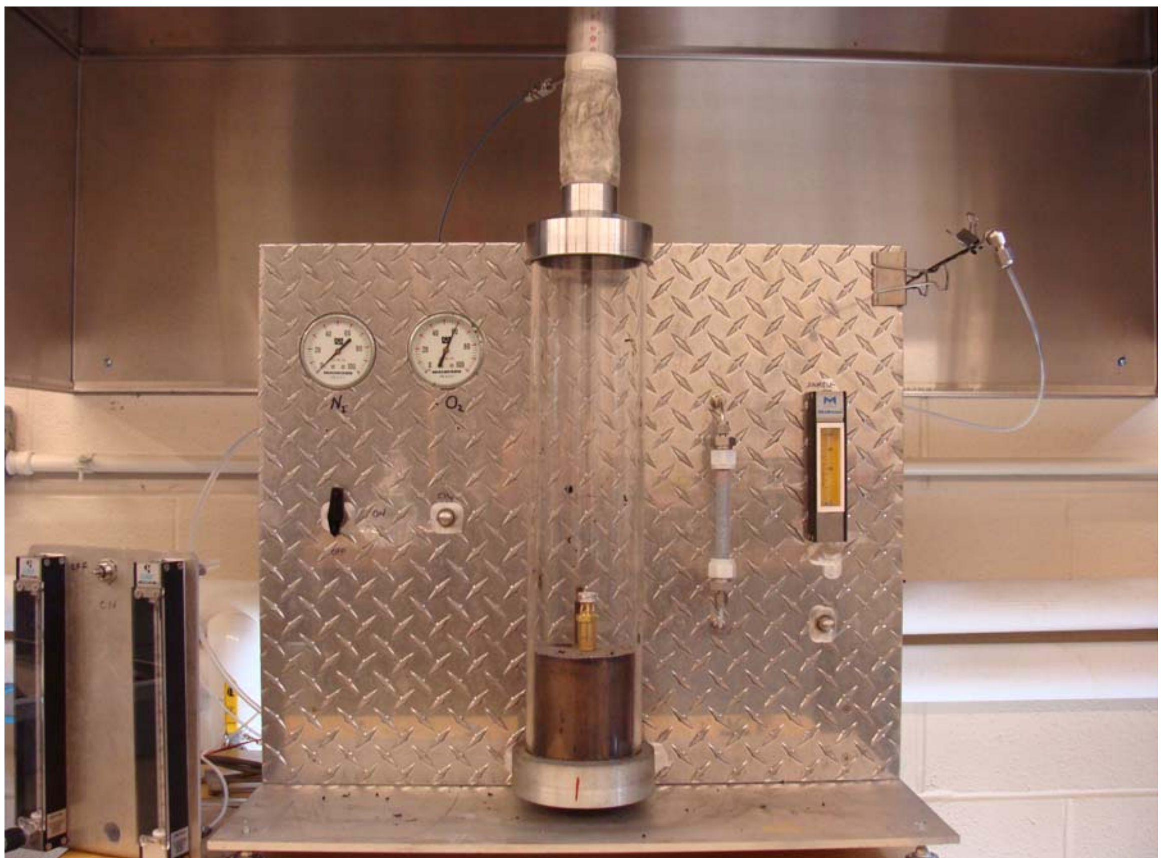
- Heat release rate:

$$\dot{q} = E\left[\frac{Y_{O_2}^{A^0} - Y_{O_2}^{A}}{1 - Y_{O_2}^{A}}\right]\dot{m}_a \frac{M_{O_2}}{M_a}$$

$\dot{q}$ = Rate of heat release (kW)
E = Heat released per O2 consumed (13.1 MJ k^{-1} of O2)
M_a = Molecular weight of the incoming air (kg $kmol^{-1}$)
M_{O_2} =Molecular weight of oxygen (kg $kmol^{-1}$)
$\dot{m}_a$ = Mass flow rate of the incoming air (kg s^{-1})
$Y_{O_2}^{A^0}$ = Mole fraction of incoming oxygen
$Y_{O_2}^{A}$ = Mole fraction of oxygen at the exit

Oxygen consumption calorimetry

- Limited oxygen setup (LOI) with oxygen consumption calorimetry capability.



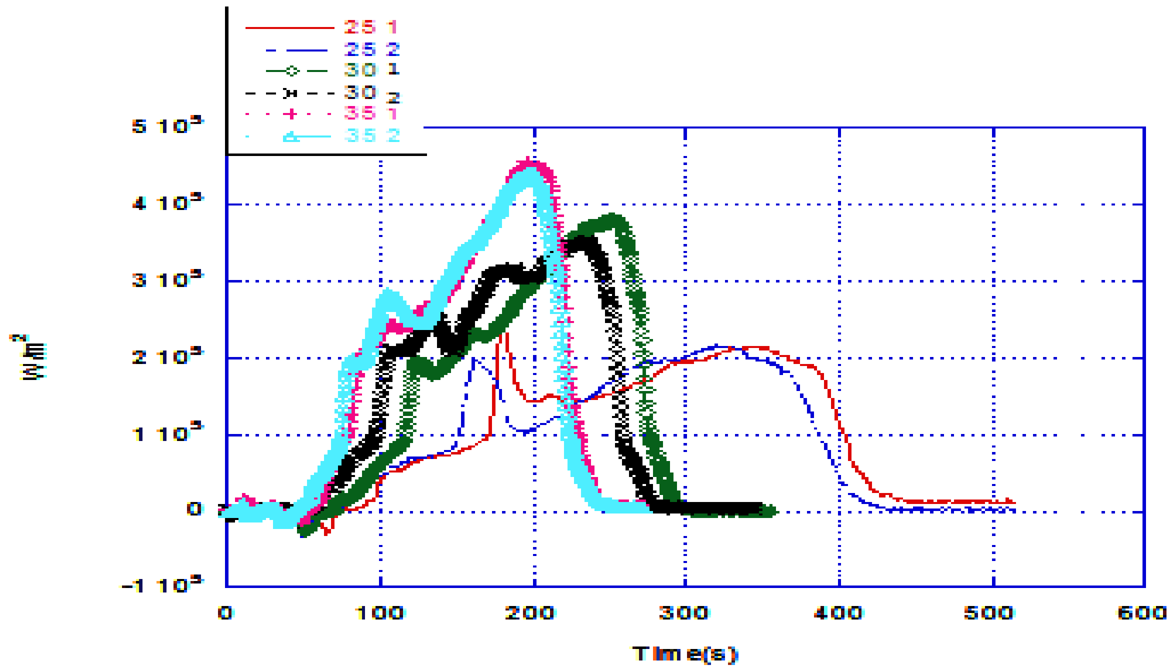
Oxygen consumption calorimetry

- Flame height and intensity comparison for different oxygen concentrations for polypropylene.

25% O_2 35% O_2 45% O_2

Oxygen consumption calorimetry

- 3 sets of 2 samples each were burned at 25, 30 and 35 % oxygen concentration.
- Heat release rate was calculated using the oxygen consumption calorimetry.
- Data shows higher peak heat release and shorter burning time with increasing oxygen.



Test Facility

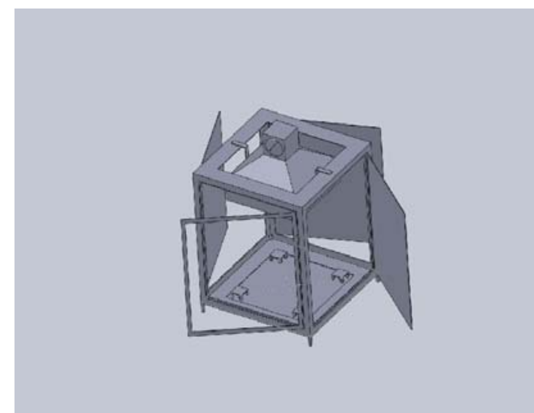
- FAA pressure modeling facility.

Test facility

- 353 ft^3 pressure vessel capable of supporting vacuum.
- PID controller
  - Adjustable valves
  - Pressure transducer
- Max vacuum ~60,000 feet
- Max vacuum with flow-through (15 cfm) ~ 40,000 feet

Instrumentation

Air supply → Flow controller → Pressure vessel



Mass loss as a function of time ←

O2 consumption ←

Controlled atmosphere container with mass loss calorimeter

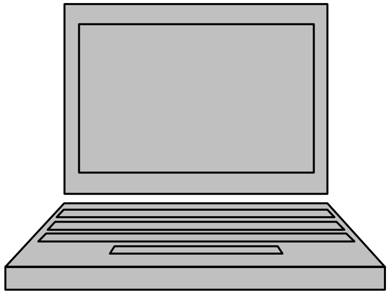
Instrumentation

- O2 Calorimetry Setup

Vacuum chamber

Sampling pump

Flow regulator → O2 sensor



LabView Data Acquisition software

Digital Readout

Preliminary results

- Sample sizes – 3 x 8 x 1/8 inch
- Qualitative comparison of flame spread for ambient and at altitude conditions.
- ~2.5 times reduction in flame spread at altitude compared to ambient conditions.

Ambient Conditions

15,000 feet

Current work

- Compare the mass loss data for several polymers (PMMA, POM, PP and Nylon) at different altitudes with those at ambient conditions.
- Obtain quantitative results for time to ignition, flame heat flux and mass loss rate.
- Obtain heat release rate using oxygen consumption calorimetry.