PREDICTION OF FLAMMABILITY LIMIT OF A THIN SOLID MATERIAL IN MICROGRAVITY ENVIRONMENTS

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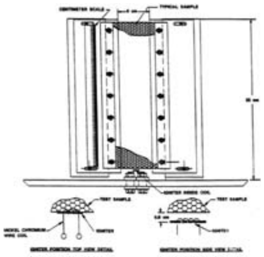
Objectives of the FLARE Project

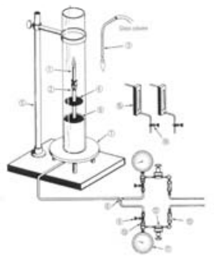
- To investigate the flame spread behavior over solid materials in microgravity.
- **To establish an evaluation method to give an index to the material** used in reduced gravity environments for developing ISO Standard.

The FLARE project is the International Space Station orbital experiment conducted by international team; JAXA, NASA, ESA etc.

Problems of the current flammability test



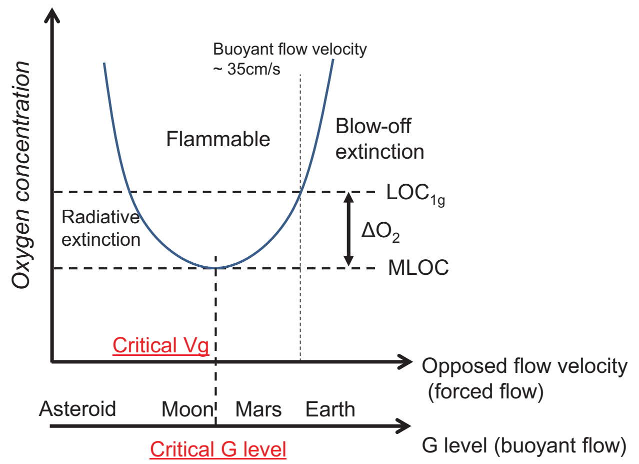
NASA STD-6001 B Test1



ISO 4589-2 (Oxygen Index)

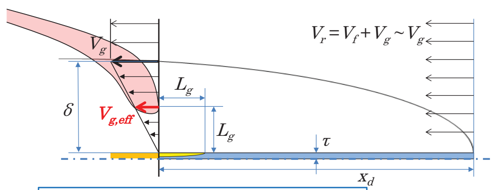
- Pass/fail test is not a convenient method for choosing materials for space use. An index method is preferable.
- Both downward and upward spreads are **influenced by buoyant flow significantly.**

Flammability limit in reduced gravity environments



- Most materials have lower limiting oxygen concentration than LOC_{1g} in a mild flow, which can be realized only in the reduced gravity environments.
- The gap between LOC_{1g} and the minimum limiting oxygen concentration (MLOC), **ΔO_2, is an important value** to discuss the flammability of the material in reduced gravity environment.

Scale analysis of flame spread in an opposed flow



Heat balance with including radiation loss and finite kinetic effect

$$V_f \rho_s c_s L_{sy} W (T_v - T_\infty) + \varepsilon(1-\alpha_{abs})\sigma\left(T_v^4 - T_\infty^4\right) L_g W \sim \left(1 - \frac{1}{Da}\right)\lambda_g \frac{(T_f - T_v)}{L_{gy}} L_{gx} W$$

$$\Rightarrow \quad \eta + R_{rad} + \frac{1}{Da} = 1 \quad \text{where} \quad \eta \equiv V_f / V_{f,th}$$

$$R_{rad} \sim \frac{\varepsilon(1-a_{abs})\sigma\left(T_v^4 - T_\infty^4\right)}{\rho_g c_g V_r \left(T_f - T_v\right)} \quad \text{(Radiative effect)}$$

$$Da \equiv \frac{L_g / V_r}{\rho_g / \dot{\omega}} \sim \frac{\alpha_g}{V_r^2} \rho_g Y_O A \exp(-E/RT_f) = \frac{L_g^2 \dot{\omega} \Delta h_r}{L_g \lambda_g (T_f - T_v)/L_g} \quad \text{(Finite kinetic effect)}$$

Combustion heat in the preheat zone (numerator); Required heat to keep gas-phase temperature gradient (denominator)

Effect of boundary layer for blow-off model

$V_{g,eff} \sim \dfrac{V_g}{\Pr \mathrm{Re}_x^{1/2}}$ BL model (Lg is determined by bulk V_g; $Lg \sim \alpha/V_g$)

$V_{g,eff} \sim \dfrac{V_g}{\sqrt{\Pr}\, \mathrm{Re}_x^{1/4}}$ EPL model (Lg is determined by $V_{g,eff}$; $Lg \sim \alpha/V_{g,eff}$)

$V_{g,eff} \sim \dfrac{V_g}{\sqrt{\Pr}\, \mathrm{Re}_x^{1/3}}$ 1/3 model (Empirical model by Bhattacharjee et al.)

Solid phase

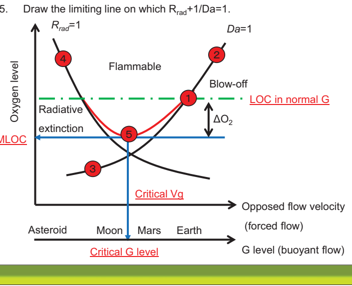
	PMMA
Dimensions	8cm x 2cm x 0.125mm
Density, ρ_s (kg/m³)	1190
Specific heat, c_s (kJ/Kg K)	1.465
Vaporization temperature, T_v (K)	670
Enthalpy of reaction, ΔHr (kJ/kg)	25900
Surface emissivity, ε	1.0
Pre-exponential factor, A (m³/kg s)	1.36×10^9
Activation energy, E (J/mol)	1.50×10^5

A.C. Fernandez-Pello, S.R. Ray, I. Glassman, Flame spread in an opposed forced flow: the effect of ambient oxygen concentration, Proc. Combust. Inst., 18 (1981), p. 579-589.

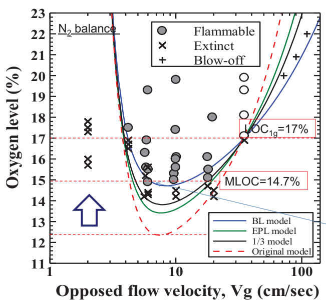
Gas phase at T=670K

	Cp [J/mol K]	λ_g [W/m K]	a_g [mm²/s]	a_{abs}
N_2	30.47	0.0444	80.1	0.0

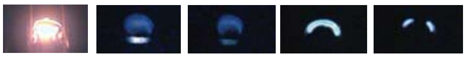
1. Measure the LOC of the downward spread. (OI may be used.)
2. Measure the LOC at a certain high opposed velocity, Vg=80cm/s.
3. Draw blow-off limiting line. (Empirical A and E are obtained.)
4. Draw radiative extinction line with Tv and other gas properties.
5. Draw the limiting line on which R_{rad}+1/Da=1.



Comparison with flight experimental results (PMMA sheet)



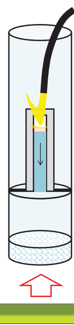
- The BL model leads to reasonable agreement with the flight experimental results. **The predicted ΔO_2 was quantitative.**
- The limiting line can be drawn by the values which can be obtained **by ground-based experiments only.**



Ignition — Steady spread below LOC_{1g} — Extinction due to recovery of G

Issues and potential of the proposed method

- **Accurate and proper A and E** for blow-off extinction are required to predict the limiting line.
- **Adding blow-off test with high upward flow** to the existing ISO 4589-2 is one of possible solutions.
- **The flammability of other materials can be checked easily.**



The example of blow-off test

For NOMEX HT90-40

E_{emp}=3.5x10⁵ (J/mol)
A_{emp}=5x10¹⁵ (m³/kgs)
Tv=750 (K)

The flammability of NOMEX can be predicted!

The similar configuration of ISO 4589-2
High upward flow: 50 ~ 140 cm/s
(beyond the buoyant flow)