

National Aeronautics and Space Administration

Impact of Lunar Gravity on Material Flammability

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Contents

- Material flammability in lunar gravity, or any gravity level other than earth, has received a limited amount of study
- We will discuss what we have learned so far and how we are planning to prepare for exploration missions to the Moon and Mars

- The objectives of this presentation are to discuss:
  1. How do we expect flame spread to be different in lunar-g than in normal-g?
  2. What are the methods we can use to investigate lunar-g flammability?

How is flame spread affected by Lunar-g?

- $g_{lunar} = 0.16\, g_{earth}$
- The primary parameter affected by the environmental changes is the buoyancy driving force

$$dP/dx = g(\rho - \rho_a)$$

that affects the buoyant flow velocity and in turn other flame parameters

- Buoyant velocity
  - Boussinesq approximation, small density variations, length scales are equal; β = coefficient of volumetric thermal expansion
    - Boussinesq approximation ignores density differences except where they appear in terms multiplied by *g*
  - Assume T_f (flame temperature) not affected by gravity changes

$$U_b = \sqrt{gL(\rho - \rho_a)/\rho_a} = \sqrt{gL\beta\,(T_f - T_a)}$$

$$U_b]_{lunar} = \sqrt{g_{lunar}L\beta\,(T_f - T_a)} = \sqrt{0.16\, g_{earth}L\beta\,(T_f - T_a)} = 0.4\, U_b]_{earth}$$

Flame spread parameters*

- **Flame stand-off distance**

$$y_f]_{lunar} \sim \delta_{lunar} = L\,Re^{-1/2} = L^{0.5}\frac{\mu^{0.5}}{(U_b]_{lunar}\,\rho_{lunar})^{0.5}} \sim (0.4U_b]_{earth})^{-0.5} P_{lunar}{}^{-0.5}$$

- **Heat flux from flame to solid** (convection)

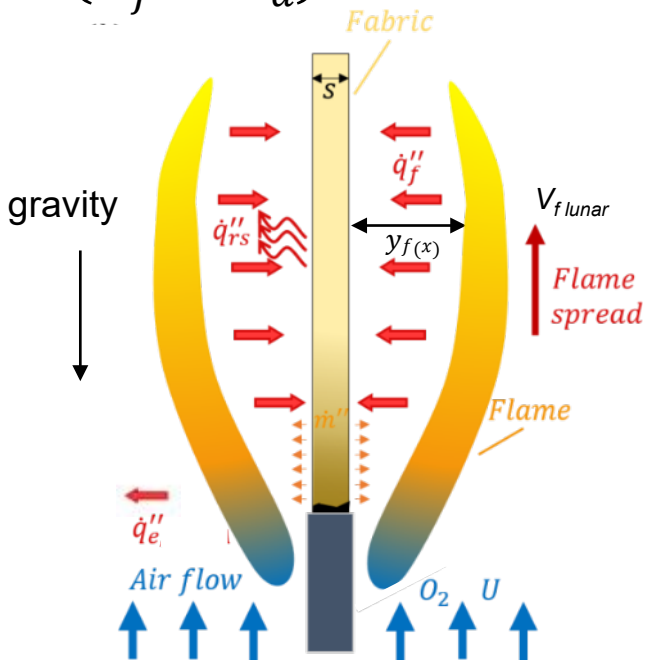
$$q''_f]_{lunar} = h(T_f - T_a) = k(T_f - T_a)/y_f \sim (0.4U_b]_{earth})^{0.5} P_{lunar}{}^{0.5}(T_f - T_a)$$

- **Concurrent flame spread**

$$V_f]_{lunar} \sim q''_f]_{lunar}\, L_f]_{lunar} \sim (0.4U_b]_{earth})^{0.5} P_{lunar}{}^{0.5}(T_f - T_a)$$

- **Convective heat transfer coefficient**

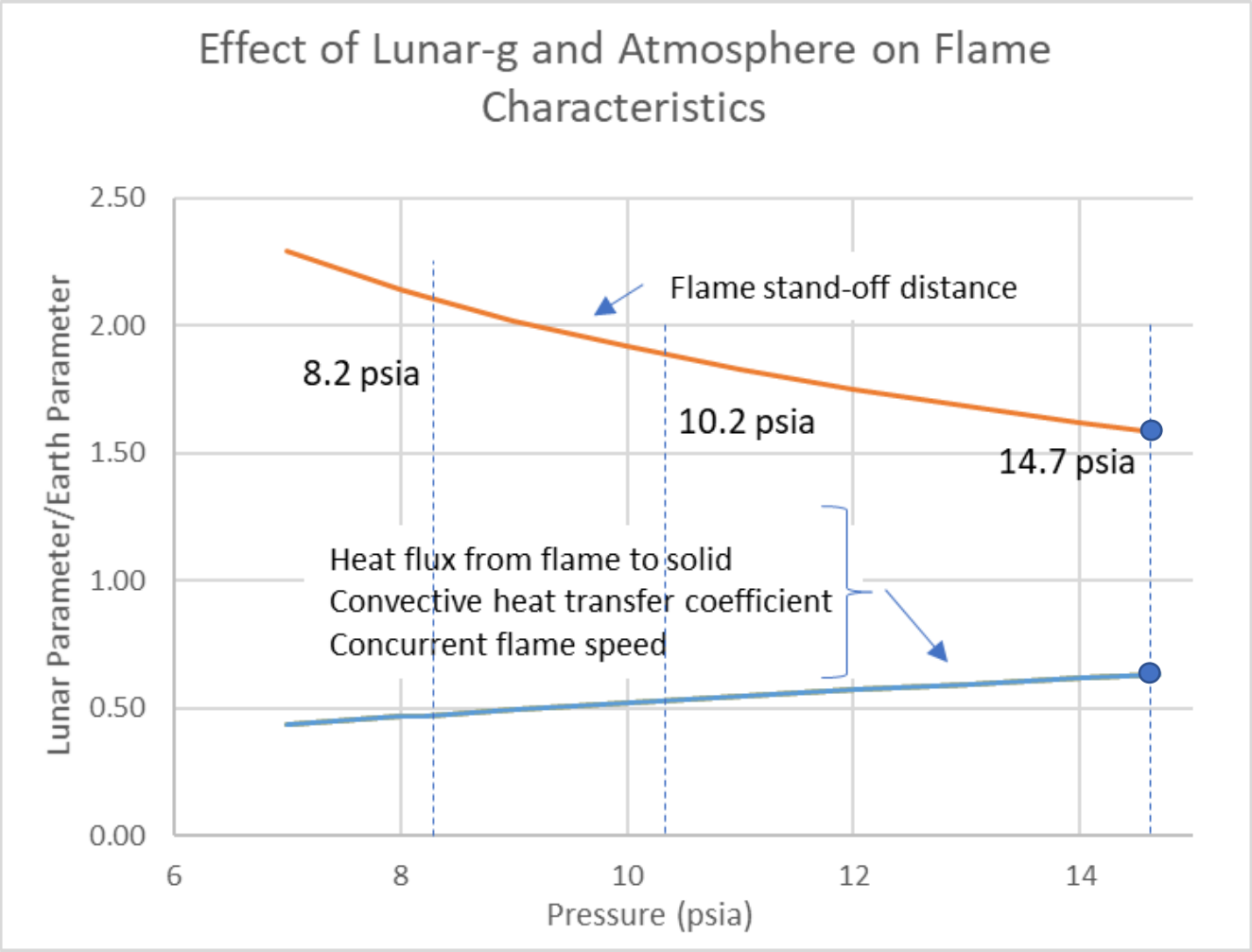
$$h_{lunar} \sim k/\,y_f]_{lunar} \sim k\,(U_b]_{lunar})^{0.5}(P_{lunar})^{0.5}$$



*Various references identified in Backup

NASA's Lunar Lander/Habitat Environment-Summary

- Buoyant velocity: $U_b]_{lunar} \sim \ 0.4\ U_b]_{earth} \sim 0.4\ \ (0.5\ \mathrm{m/s}) \sim 0.2\ \mathrm{m/s}$

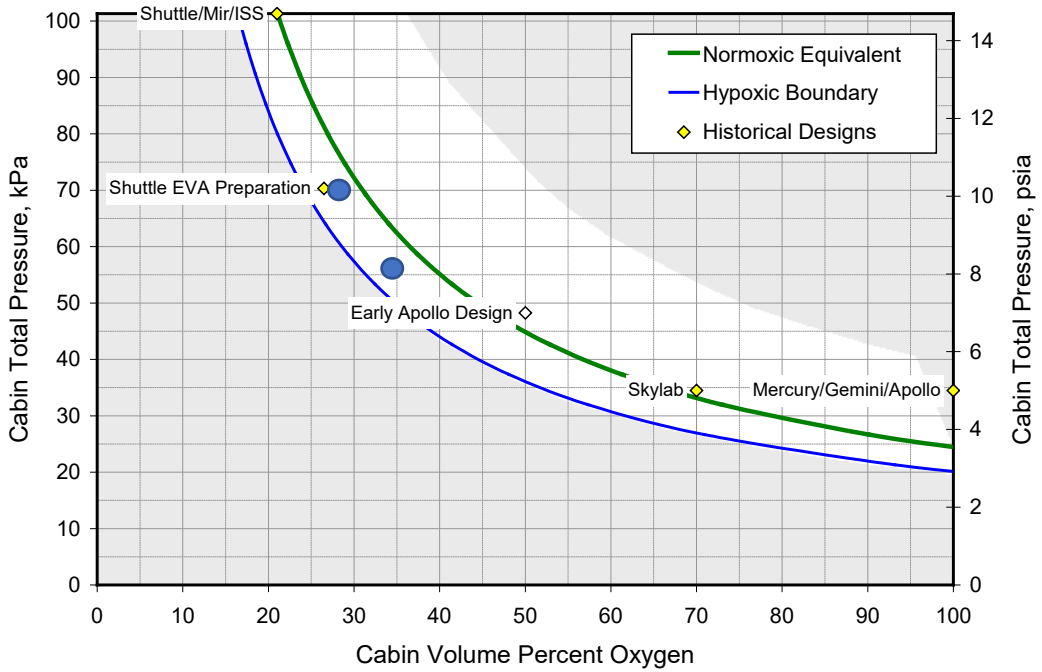


Assume $\%O_2$ is constant:

- As pressure decreases, flame stand-off distance increases
- As a result, other flame parameters decrease with decreasing pressure
- ➢ Normoxic conditions complicate this behavior

Impact of Normoxic Atmosphere in Lunar Landers/Habitats

- Operations on the moon in either landers, rovers, or habitats will present unique operating conditions
  - The purpose of being on the Moon is to conduct frequent extravehicular activities to explore, conduct experiments, etc.
    - EVA suit: 4.3 psia, 100% O_2 by volume (U.S. suits on ISS)



Recommendations for Exploration Spacecraft Internal Atmospheres: The Final Report of the NASA Exploration Atmospheres Working Group", JSC-63309, January 2006.

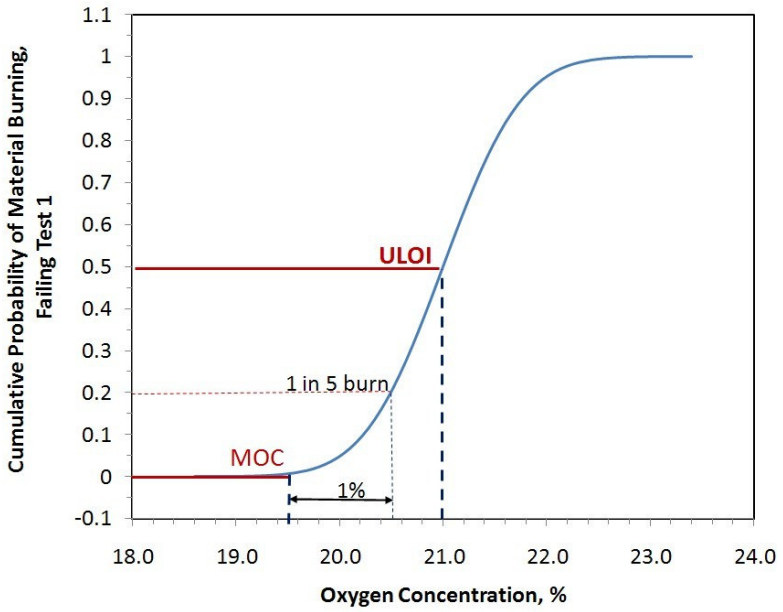
- It is undesirable to require long pre-breathe times prior to every EVA

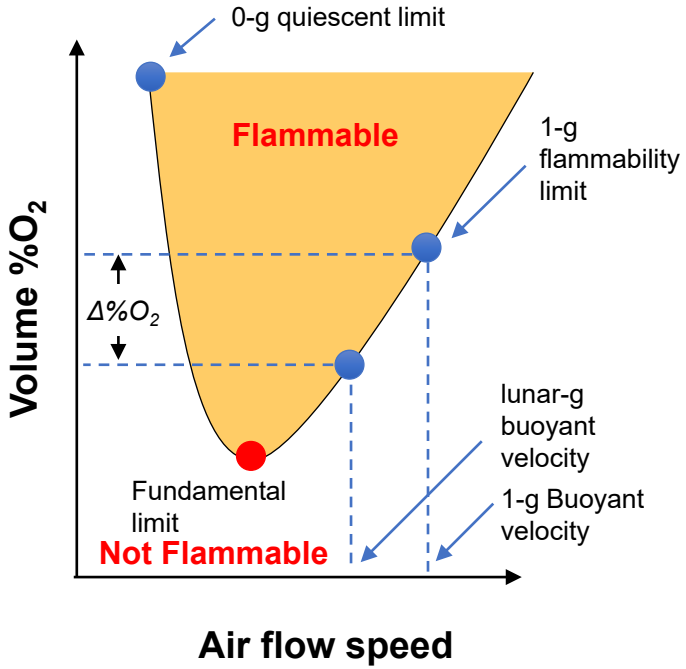
Atmosphere	Pre-breathe Times (hours)
10.2 psia, 28%O_2	3.5
8.2 psia, 34%O_2	0.5

- Using normoxic atmospheres:
  - Helps prevent decompression sickness
  - Increases flame spread rate
- Effects of partial gravity on the previous slide are coupled with the changes in flame characteristics at elevated O_2
- Flammability limits are even more important that flame spread for spacecraft fire safety

Flammability Limit Definitions

- Differences in the flammability limit are even more important for spacecraft fire safety
  - Upward Limiting Oxygen Index (ULOI)
    - Oxygen concentration where half of the samples will pass NASA-STD-6001 Test 1
  - Maximum Oxygen Concentration (MOC)
    - Oxygen concentration where at least five samples pass Test 1 and were at least one sample failed in the environment that contained 1 percent more oxygen by volume





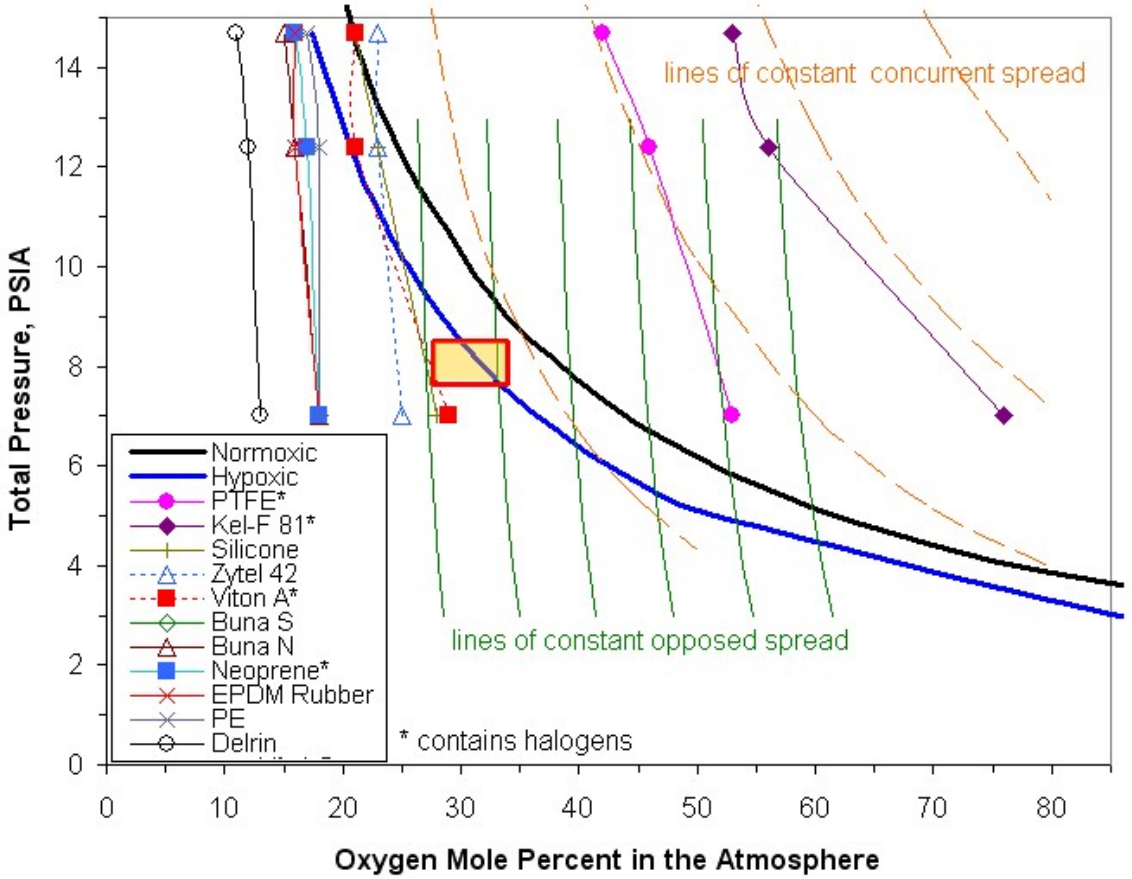
- The shape of the flammability curve on the left depends on the material properties
- In both 1-g and lunar conditions, extinction is by blow-off
- The reduced buoyant velocity (compared to 1-g) impacts limits by:
  - Reducing the oxygen flux to weaken the flame
  - Strengthening the flame by reducing the heat loss by convection

Sacksteder, K. R. and T'ien, J. S., Buoyant Downward Diffusion Flame Spread and Extinction in Partial-Gravity Accelerations, *Proc. Combust. Inst.* 25:1685-1692 (1994).

Osorio, A. F., Mizutani, K., Fernandex-Pello, C., and Fujita, O., Microgravity flammability limits of ETFE insulated wires exposed to external radiation," *Proc. Combust. Inst.* 35: 2683-2689 (2015)

Flammability Limits for Various Materials

- Normoxic conditions complicate flame spread and flammability limits
  - Reduced pressure decreases the flame spread rate
  - Increasing the $\%O_2$ increases flame spread rate



- Concurrent flame spread rate: $V_f \sim O_2$* flow velocity* $P^{0.5}$
- Opposed flame spread rate: $V_f \sim O_2^{0.9} * P^{0.05}$
- The nearly vertical lines for the pressure vs. MOC show that increasing oxygen has a significantly greater effect than increasing pressure
  - Similar for different materials
- MOC of many materials follow the trend of the microgravity opposed flow flame spread correlation
- The previous slides have shown the compounding impacts of gravity level and normoxic atmospheres

Olson, S.L., Ruff, G. A. and Miller, F.J. "Microgravity Flame Spread in Exploration Atmospheres," Paper No. Paper No. 2008-01-2055, 38th International Conference on Environmental Systems, San Francisco, CA, July 2008.

Hirsch, D.B, Williams, J., and Beeson, H.; "Pressure Effects on Oxygen Concentration Flammability Thresholds of Polymeric Materials for Aerospace Applications" Journal of Testing and Evaluation, V.36, Issue 1, (pp. 69-72). NASA Document ID 20070018178, (2008).

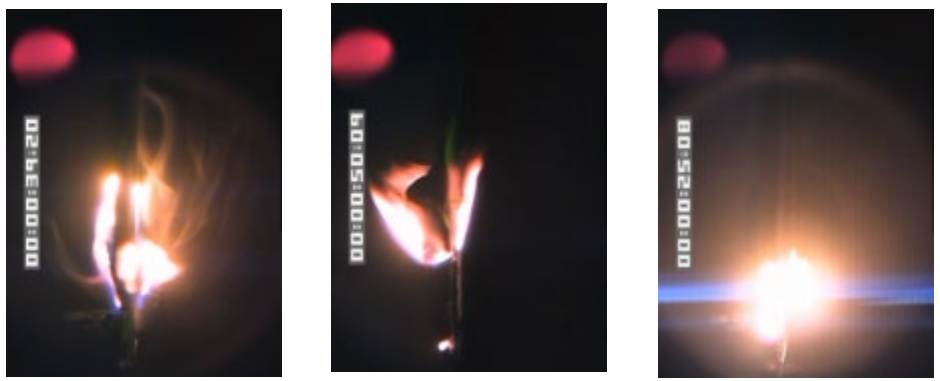
Reduced Gravity Flammability Threshold Tests

Objective

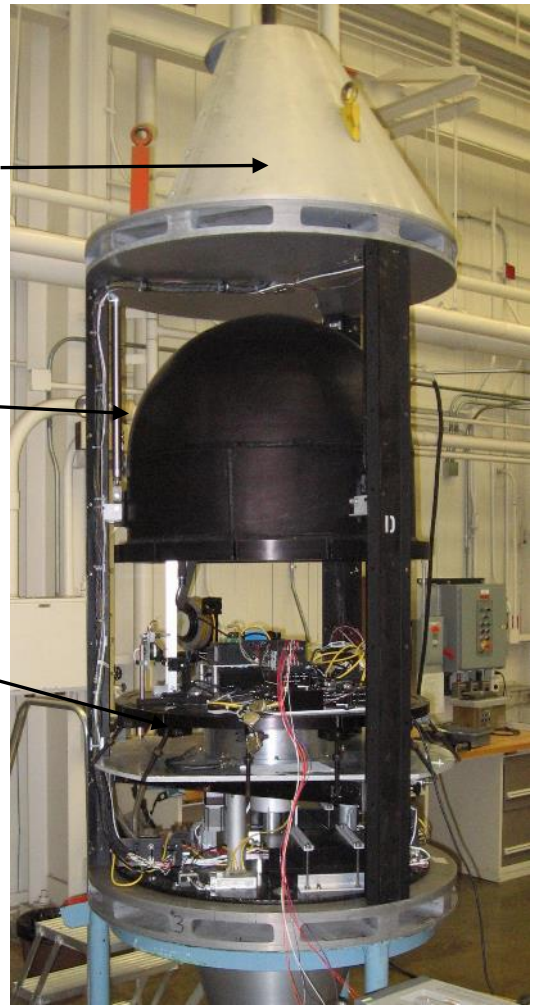
- **Quantify the low-g oxygen upward flammability thresholds for typical spacecraft materials and compare results with thresholds determined in normal gravity**

gravity

Ultem 1000 *Nomex* *Mylar*



Right: Centrifuge test rig for the Zero Gravity Facility

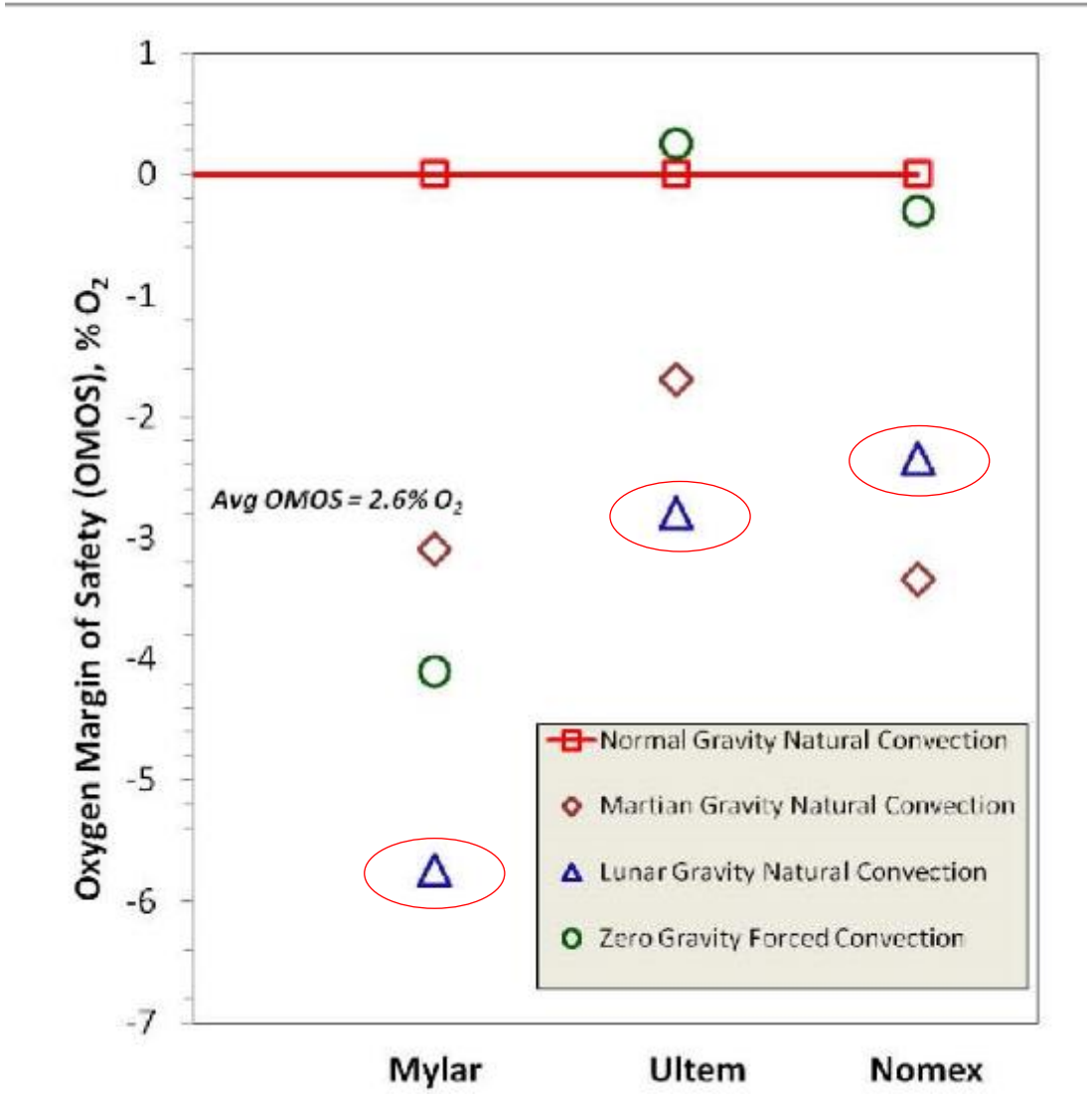


- **Tests were conducted in Zero Gravity Facility at NASA-GRC for Ultem 1000, Nomex, and Mylar**
  - 5.2-sec limits samples to thin materials
- **Modified test technique to determine the extinguishment limit (Maximum Oxygen Concentration)**

Ferkul, P. V. and Olson, S.L., Zero-Gravity Centrifuge Used for the Evaluation of Material Flammability in Lunar-Gravity, AIAA 2010-6260, 40th Int. Conf. Env. Syst, (2010).

Maximum Oxygen Concentration (MOC) at 0-g, Martian-g, and Lunar-g

- Tests were conducted at WSTF (normal-g) and GRC (partial-g) to quantify changes in the MOC for Nomex, Mylar, and Ultem
- Data for normal-, Martian-, Lunar- and zero-g has been obtained
  - Partial-g flames propagated at the normal-g MOC for all materials (charring and non-charring)
  - Lunar-g MOC can be lower than either zero- or Martian-g levels
  - Variation of MOC with gravity level is dependent on the material



Partial-Gravity Assessment Tools

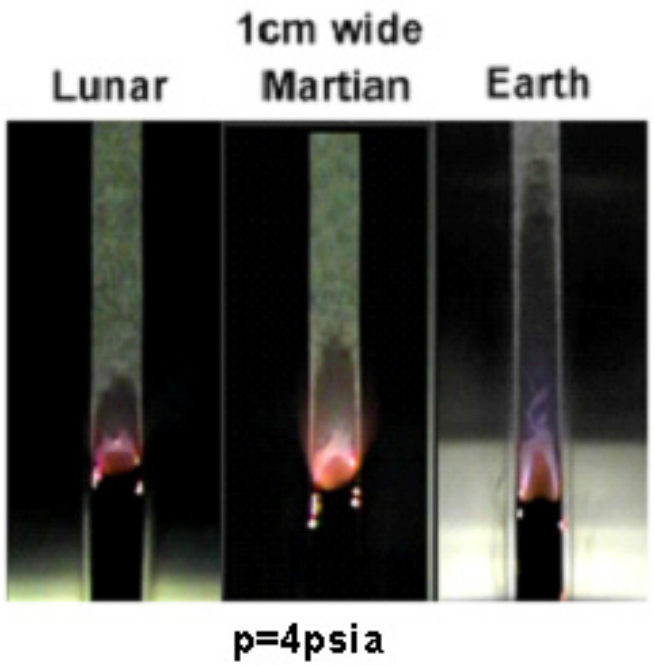
Platform/Activity	Duration	Comments
ZGF Centrifuge Rig	5 sec	Direct partial-g burn – flammability limits
P^2-g Scaling	Full burn	Evaluated for flame propagation rather than flammability limits
Modeling	Full burn	Status of model; Data for comparison of model is limited
Parabolic Aircraft	20 sec	Direct partial-g burn
Electromotive Drop Tower (EMDT)	10 sec	Partial-gravity drop tower being designed and planned to be operational no earlier than FY28
Blue Origin Rotating Capsule	120 sec	Need to assess capability prior to full commitment to test campaign starting in mid-2023
Commercial Lunar Payload Services (CLPS) Expt	Full burn	Provides a “Lunar truth” but tests are very limited in size and number

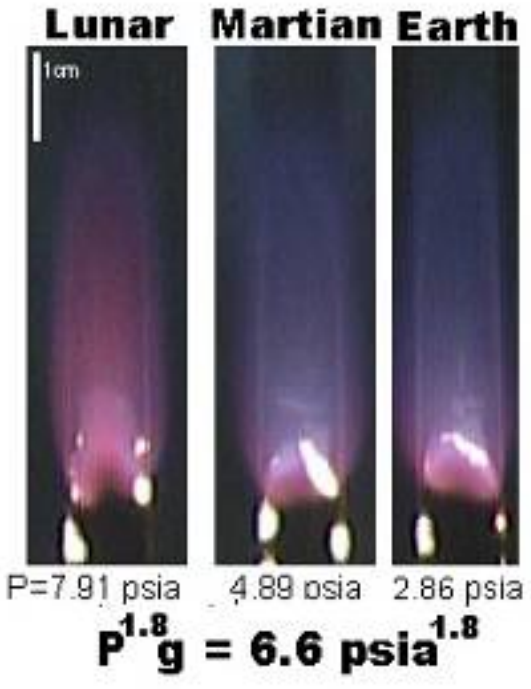
- A plan to assess lunar-g flammability most likely contains a combination of these activities
- Flights in a parabolic aircraft have been used to obtain information about material flammability in partial-g in the references
- We have discussed data from the Zero-Gravity Facility Centrifuge Rig

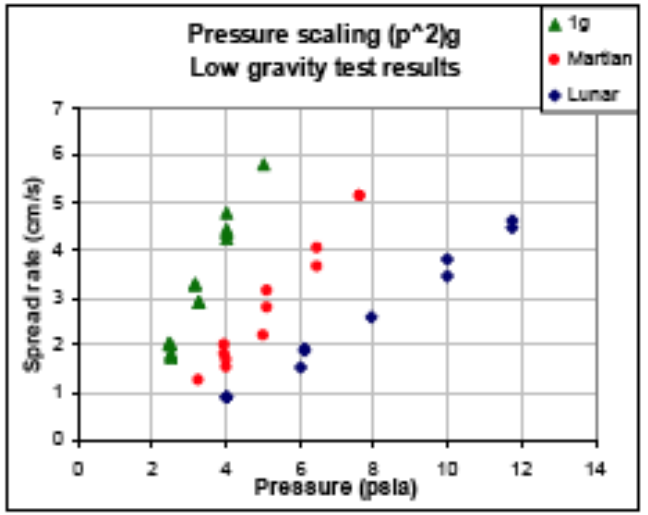
P^2-g Scaling

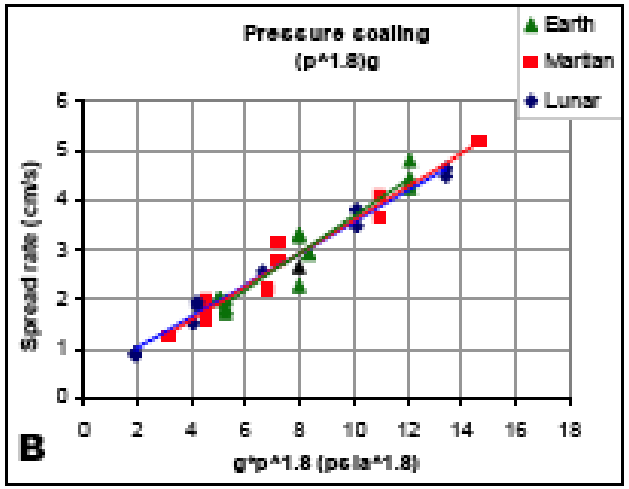
- Use Grashof number scaling to conduct flammability tests at reduced pressure to simulate partial-gravity combustion

$$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2} \propto gP^2$$









Kleinhenz, J., Feier, I. I., Hsu, S.-Y., T'ien, J. S., Ferkul, P. V. and Sacksteder, K. R.: Pressure modeling of upward flame spread and burning rates over solids in partial gravity, *Combustion and Flame* 154: 637-643 (2008).

Electromotive Drop Tower

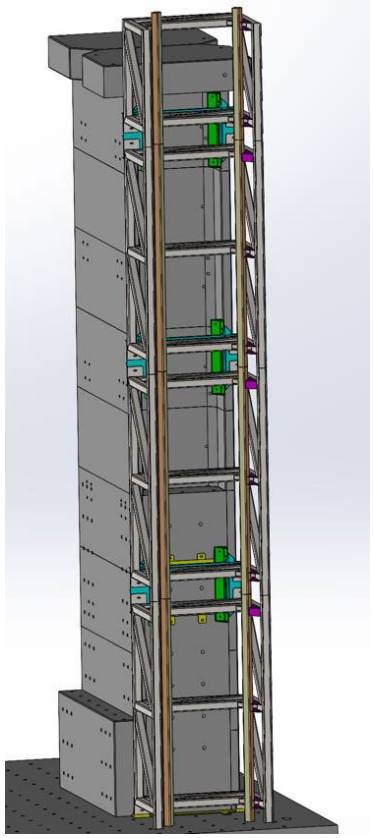
- **Motivation**
  - Provide inexpensive, reliable and flexible access to 10 s of zero-g or partial-g to facilitate fundamental research, technology development, and flight hardware risk mitigation testing.
- **Concept**
  - Convert the existing 5.2-second GRC Zero Gravity Research Facility to a state-of-the-art ~10-second, 0 to 0.5g test facility using a vertical rail and linear synchronous motor system to provide a revolutionary capability in testing at low and partial gravity at a significantly lower operating cost.
- **Target Metrics**
  - 10 s duration
  - 10^{-5} g below 20 Hz
  - Launch/landing 4 g avg 6 g max
  - Payload size 1 m x 1 m x 1.8 m
  - Payload mass 455 kg
  - 20 tests / day (1 OOM increase)
  - $300 / test (1 OOM reduction)
- **Draft Plan**
  - Engineering Model build and testing (FY22-23)
  - EMDT Design and Assembly (FY24-27)
  - Commissioning FY28
- **Applications**
  - Physical Sciences
    - Fundamental Physics
    - Combustion
    - Fluid Physics
  - Life Support
    - Fire Safety
    - Thermal Control
    - Fluid Acquisition/Control
    - Dust Behavior
  - Life Science
    - Gravitropism
    - Plant Thermal Model
  - ISRU
    - Reactor Design
    - Regolith Acquisition/ Handling

    Science

    Asteroid Sampling

    Soil Physics





Blue Origin New Shepard Partial-g Concept

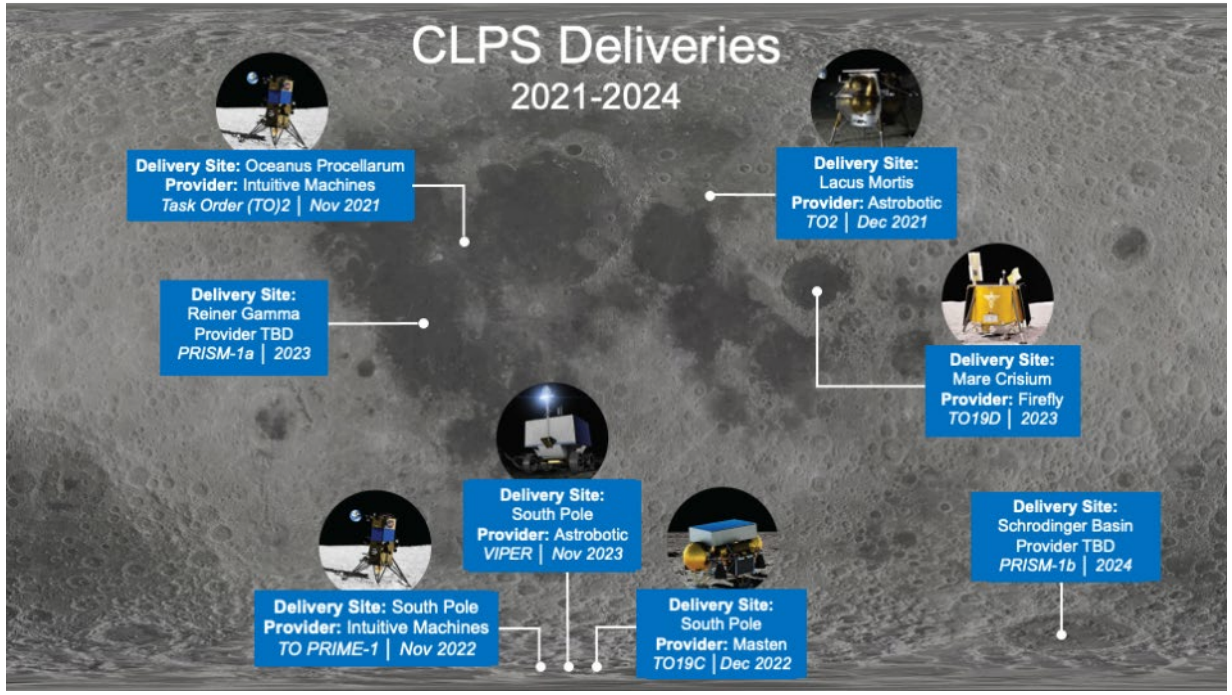
- Blue Origin's New Shepard vehicle is being upgraded to enable rotation about it's vertical axis during the low gravity portion of the flight
- Flight Opportunities Program purchased payload space on New Shepard for the initial flight
- Concept of Operations
  - Capsule is spin-stabilized at apogee using its reaction control system
  - Up to 2 minutes of lunar-g at steady state
  - Lunar-g ~11 rpm at 1.25 m
- Capabilities
  - Individual payloads up to 150 lbm
  - Single, double, and full stack lockers
    - 20.6' x 16.3" x 9.5"; 20.6" x 16.3" x 18"; 28" x 32" x19", respectively
  - Greater that 800 W available
  - Total payload capacity up to 900 lbm
- Proof-of-concept partial-g flight planned for early 2023



Blue Origin, used with Permission (Erika Wagner)

Commercial Lunar Payload Services (CLPS)

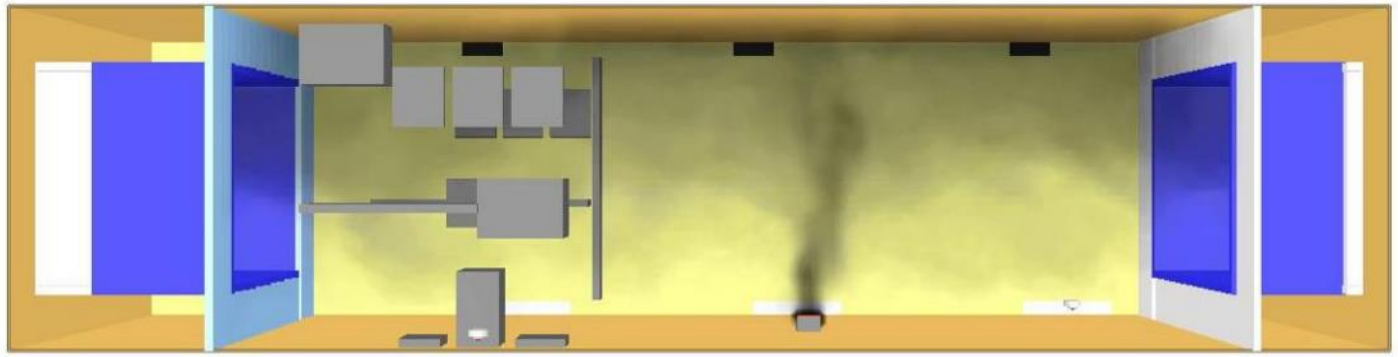
- Utilize commercial end-to-end delivery services to enable access to the lunar surface
  - Deliveries initiated using a Task Order (TO)
    - Any of the 14 companies on the catalog can respond to a task order
    - Expected Task Order cadence of 2 per year
  - Task Orders list what NASA wants delivered, and any constraints, *e.g.* landing site, specific needs of instruments
  - First 6 lunar surface deliveries awarded with deliveries commencing in 2021
    - 2021: Non-polar delivery (Astrobotic and Intuitive Machines) – TO 2A & 2B
    - 2022: Polar delivery (Masten) – TO 19C
    - 2022: PRIME-1 (Intuitive Machines)
    - 2022: Crisium delivery (Firefly Aerospace) – TO 19D
    - 2023: Volatiles Investigating Polar Exploration Rover (VIPER) to Moon's south polar region (Astrobotic) – TO 20A



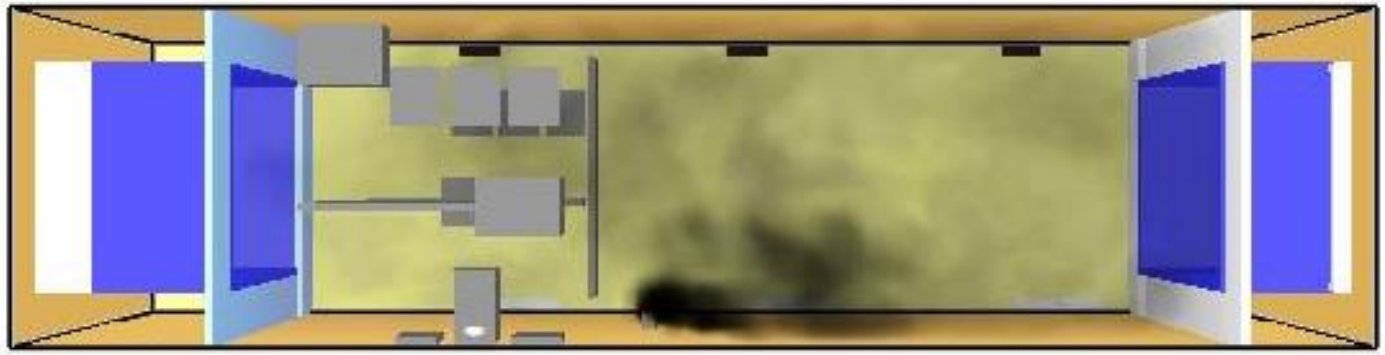
- We are making plans for a flammability experiment on a future CLPS mission
  - CLPS 2a: late 2024; 2b: early 2025

Fire Detection in Zero-Gravity

Normal gravity (ISS Destiny Module with ECLSS circulation)



Zero gravity (ISS Destiny Module with ECLSS circulation)

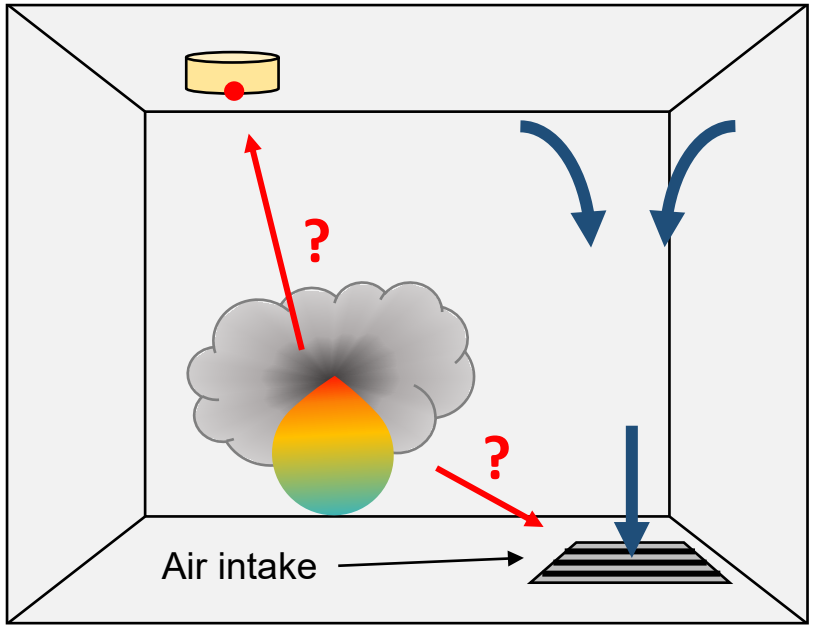


Brooker, J.E., Urban, D.L. and Ruff, G.A. "ISS Destiny Laboratory Smoke Detection Model," Paper No. 2007-01-3076, 37th International Conference on Environmental Systems, Chicago, Illinois, July 9-12, 2007.

- In partial-g, there will be a competition between rate of smoke production, buoyancy, and ECLSS air circulation
  - Where do you put the detector relative to the ECLSS air intake?

Urban, D.L., Dietrich, D. L., Brooker, J. E., Meyer, M.E., and Ruff, G.A. "Fire Detection Tradeoffs as a Function of Vehicle Parameters," Paper No. ICES-2016-318, 46th International Conference on Environmental Systems, July 10-14, Vienna, Austria.

- Modeling has shown that in zero-g with forced convection, the spacecraft volume must reach the alarm level before an alarm will sound
  - Unless the smoke production rate is large
  - If the smoke production rate is too low, smoke is scrubbed by air circulation before it can reach alarm levels



Partial gravity

Conclusions

- Owing to lack of access to partial gravity test platforms, the data set of lunar flammability tests is very small
- Theory and experimental results indicate that oxygen flammability limits in lunar-g are lower than those measured in 1-g
  - The magnitude of $\Delta\%O_2$ depends not only on the material but on the direction of burning (concurrent or opposed)
- Configurations that will not support a flame in low-gravity could support a flame in lunar-gravity
- The $\%O_2$ of planned habitat atmosphere exacerbates these issues by enhancing the flammability
- Additional work is needed to establish a partial gravity flammability acceptance criterion
- Lunar gravity can change fire detection strategy depending on vehicle design
- Turning the ECLSS flow off to extinguish a fire in lunar-g is not effective because the reduced gravity will still induce buoyant flow velocities
- We are developing a plan to quantify the magnitude of $\Delta\%O_2$ using a combination of modeling, low-gravity aircraft, drop tower centrifuge, and rotating capsule in a sub-orbital flight to be anchored by a lunar lander test

Back-up

References

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Special thanks to Professor Carlos Fernandez-Pello for supplying these references and his valuable insights.

Experimental Results:
Effects of pressure, oxygen concentration and gravity

1-g

Decreasing Ambient Pressure

100 kPa | 80 kPa | 60 kPa | 50 kPa | 40 kPa | 30 kPa | 25 kPa | 15 kPa

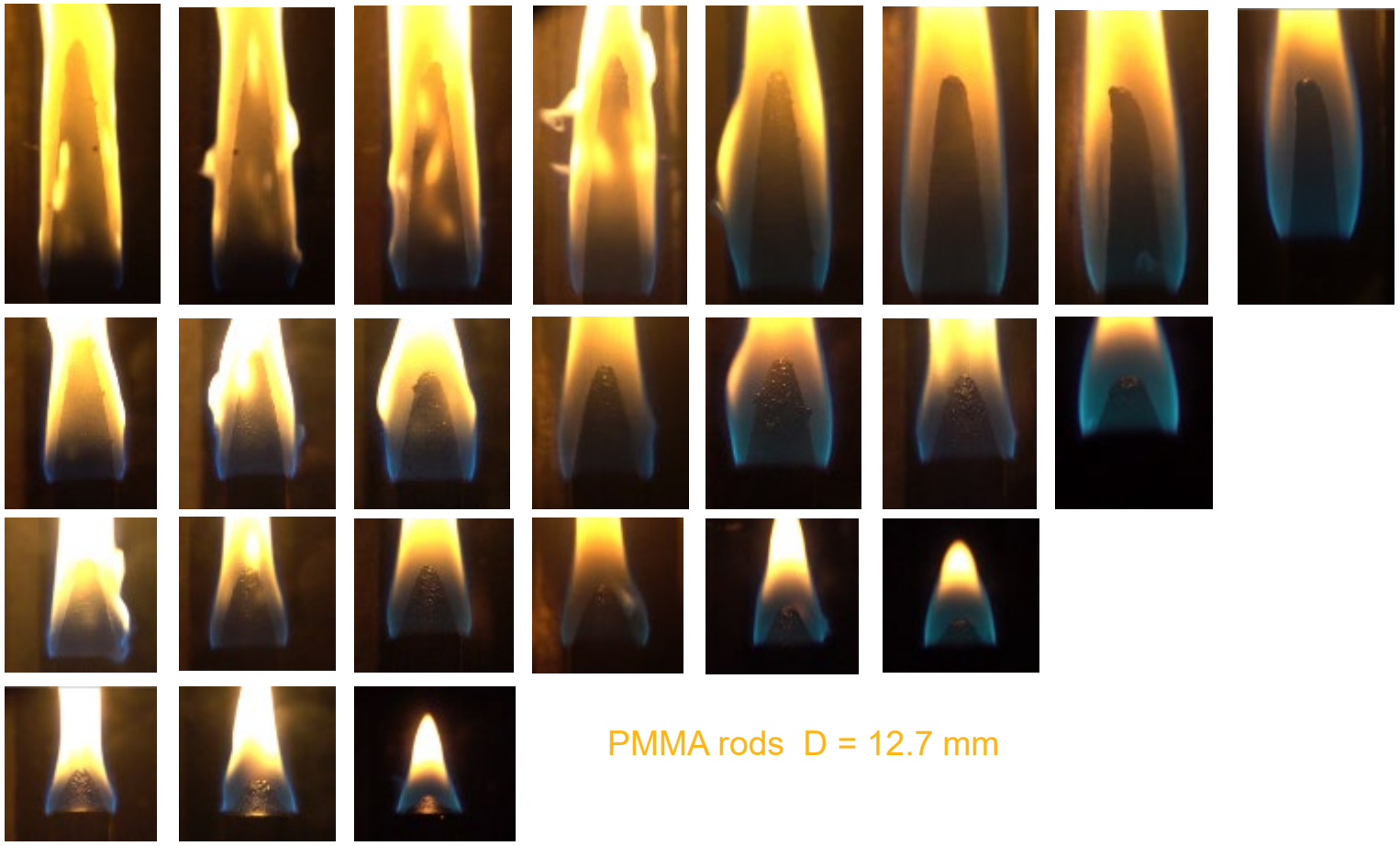
Decreasing Oxygen Concentration

23%

21%

20%

19%



PMMA rods D = 12.7 mm

μg

100 kPa

21%

19%

17%



Decreasing Oxygen Concentration

Micro-g images obtained from the Microgravity Science Glovebox on ISS

- **Increasing the oxygen concentration dominates the effect of reducing pressure**
- **The microgravity flame is weaker but can still propagate and at lower %O_2 than in 1-g**


NASA