Fire on the Moon: Solid Fuel Combustion Experiments

Paul Ferkul (USRA)

Ya-Ting Liao (CWRU)

Gary Ruff (NASA GRC)

Dan Gotti (USRA)

Jay Owens (USRA)

Luke Ogorzaly (HX5 Sierra)

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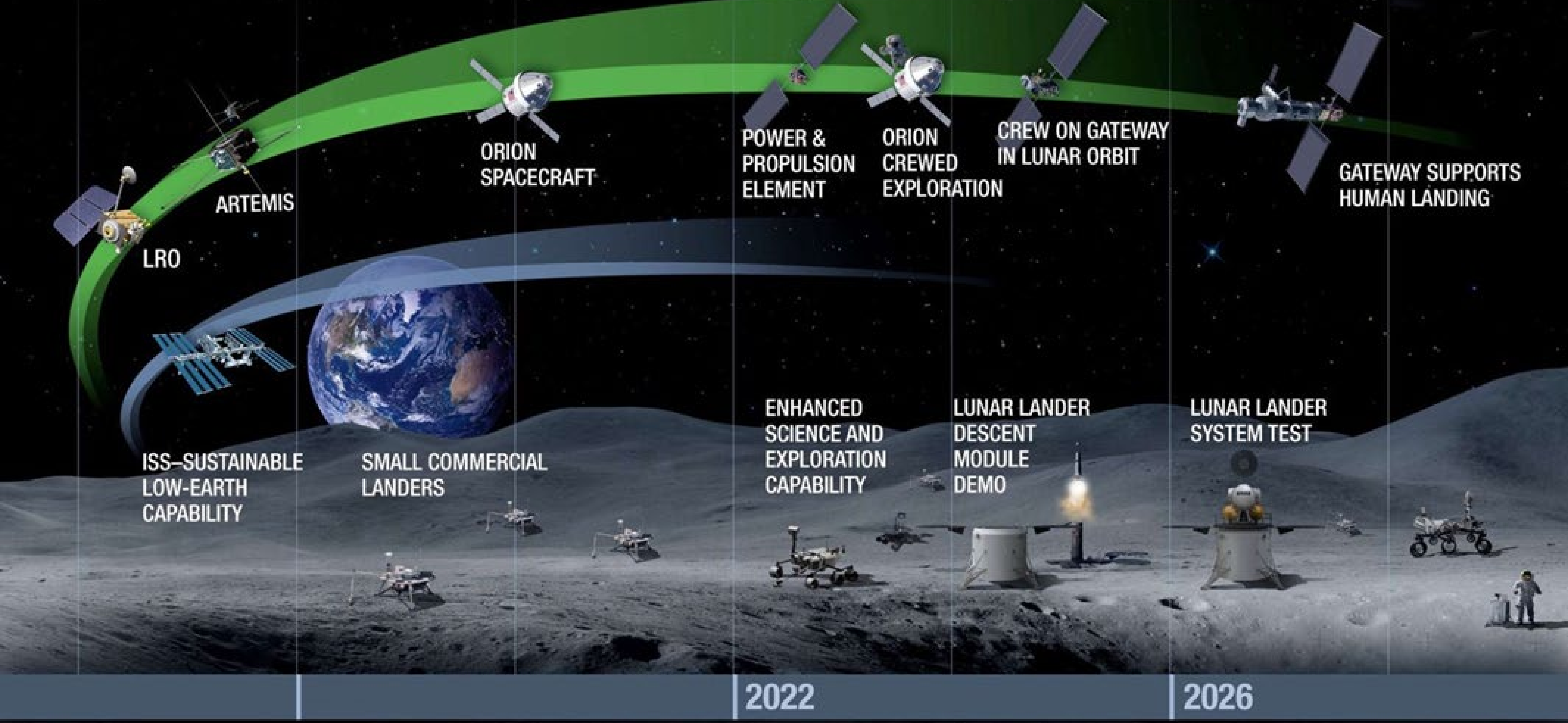
Path to Lunar Surface



*Slide borrowed from Steve Clarke, Deputy Associate Administrator for Exploration, NASA Science Mission Directorate

NASA Science and Technology Needs

-In the 2011 National Research Council (NRC) decadal survey report, "*Recapturing a Future for Space Exploration, Life and Physical Sciences Research for a New Era*," fire safety in space and more specifically material flammability received considerable emphasis. One of the highest-priority enabling recommendations made in Chapter 9: Applied Physical Sciences in Space was *"Fire safety research to improve methods for screening materials for flammability and fire suppression in space environments."*

-In 2018, the Committee on a Midterm Assessment of Implementation of the Decadal Survey on Life and Physical Sciences Research at NASA reaffirmed this need in their report "*A Midterm Assessment of Implementation of the Decadal Survey on Life and Physical Sciences Research at NASA*."

-NASA's 2018 Strategic plan calls out combustion research, the scientific backbone behind material flammability and spacecraft fire safety. Furthermore, in Strategic Goal 1 it was stated that "*[NASA GRC] is a global leader in the fields of microgravity combustion and fluid physics to understand the behavior of fire and fluids in space.*"

→ The proposed experiment is highly relevant to NASA's Strategic Plan and Exploration

→ NASA Glenn is best postured to provide the expertise to design and conduct this experiment and to apply the gained knowledge to future spacecraft systems.

NASA Science and Technology Needs

- Human Exploration and Operations (HEO) Systems Engineering and Integration Decision Memorandum titled Updated Exploration Atmospheres (HEO-DM-1006) and signed February 18, 2021 identifies the ambient pressures and oxygen concentrations to but used in various phases of exploration missions.
  - Identifies material flammability in low- and partial-gravity at these conditions to be a significant knowledge gap for exploration
- This gap is captured in the Integrated Exploration Capabilities Gap List (HEO-DM-1008) signed March 19, 2021 which is to be used by HEOMD Programs to plan exploration-forward investments.
  - The AES Enabling Capabilities program has directed the Spacecraft Fire Safety Demonstration Project to pursue opportunities to obtain material flammability data in partial-g including the Commercial Lander Payload Services concepts to be discussed in this presentation.

Science Background: Combustion at Reduced Gravity

For the last 40 years, NASA has recognized that studying combustion in reduced gravity is important for:

-Spacecraft/exploration fire safety

-Fundamental science

-Applying the knowledge gained to terrestrial problems

NASA Glenn Research Center has been at the forefront of microgravity research in Combustion Science and Fluids Physics

(In this presentation, the focus is on Solid Fuel Combustion)

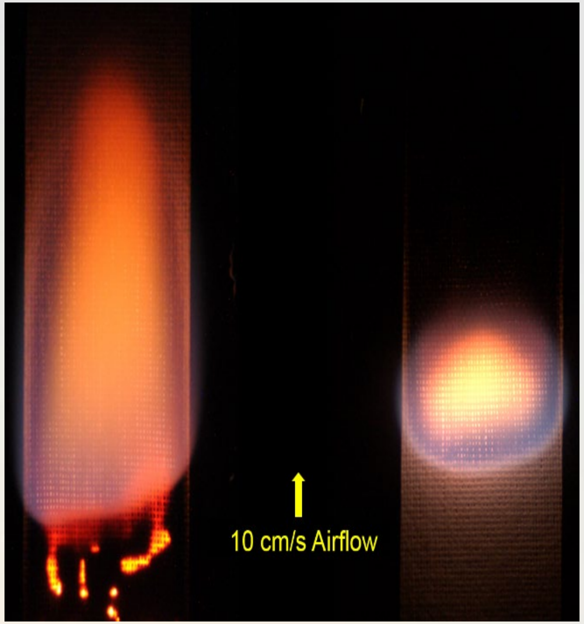
NASA relies on a 1-g test for screening material flammability for flight.

If a material passes this test, then it is considered safe for spaceflight.

This test has been a practical means to assess the great number of materials that have been screened.

However, microgravity research has suggested that normal gravity may not represent the most flammable condition for a material.

Theoretical and experimental results have demonstrated that some materials that will not burn in 1-g will burn in 0-g (with a low-speed flow) or in partial gravity (such as Lunar-g).



Flame Spread in Microgravity over 2.2-cm-wide SIBAL Fabric.

Left: Concurrent flow (comparable to 1-g upward spread).
Right: Opposed flow (comparable to 1-g downward spread).

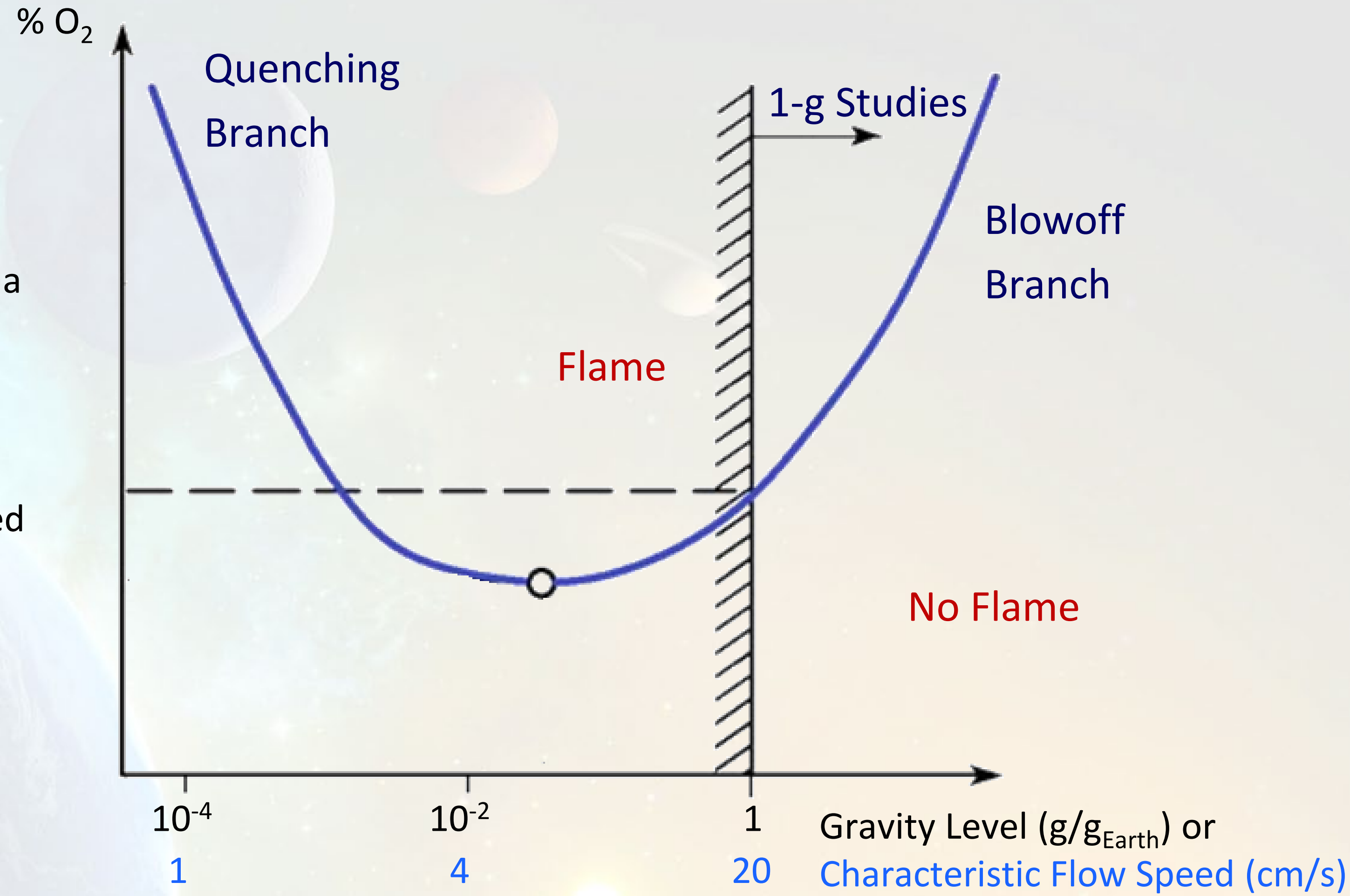
In microgravity, both concurrent and opposed-flow flame spread are possible, but on Earth, downward flame spread (opposed flow) cannot be achieved. This demonstrates enhanced flammability in microgravity, and suggests similar behavior at partial gravity.

Flammability Boundary

Flow can be generated by buoyancy, forced convection, or a combination of the two.

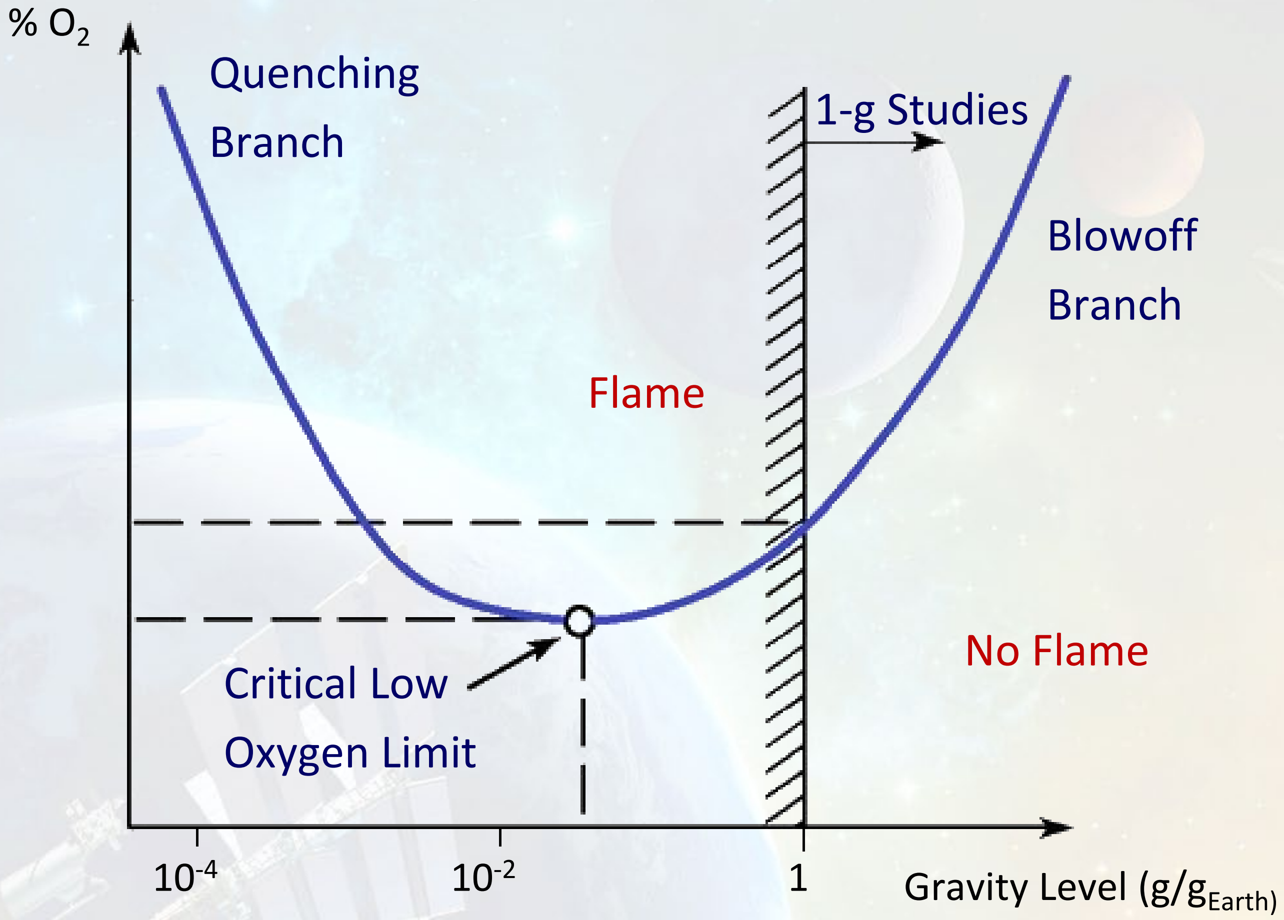
To date, in order to study the flammability boundary at low speed, we have mostly performed tests in microgravity but with imposed forced convection.

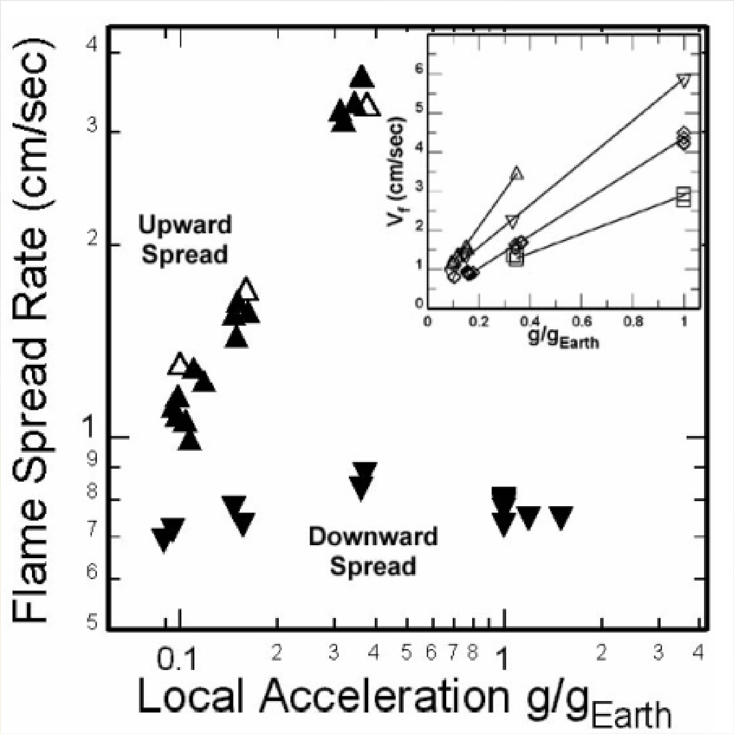
The lunar surface offers the unique environment of reduced gravity to study flame spread.



Reference: T'ien, J. S., Diffusion flame extinction at small stretch rates: the mechanism of radiative loss, *Combustion and Flame*, 1986.

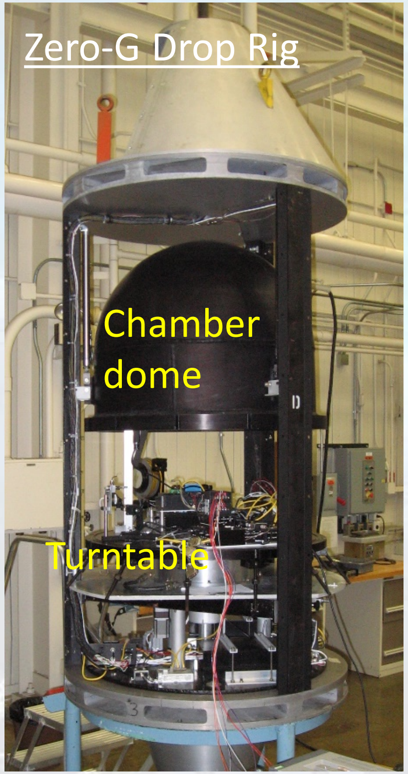
Flammability Boundary

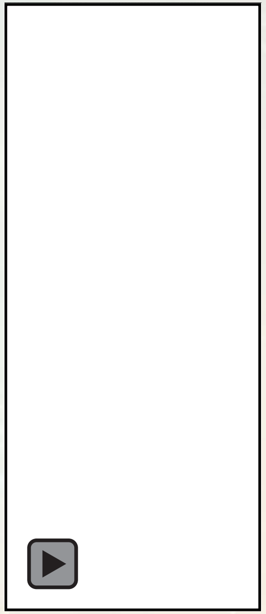


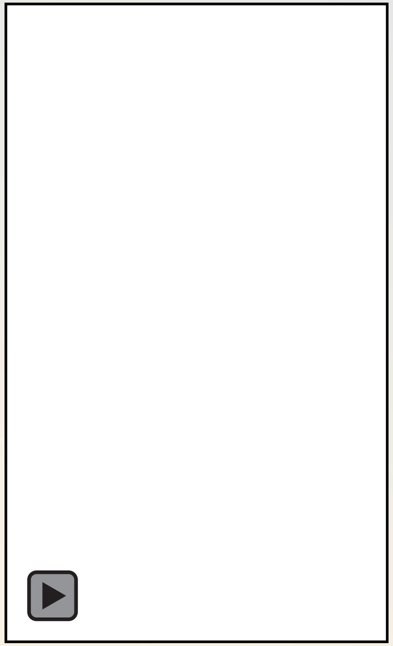


Numerical and experimental evidence suggests that Lunar gravity is nearly the most flammable condition.
Oxygen concentration for flammability reaches a minimum value in the vicinity of $g = g_{Moon}$ (left; model)
Downward flame spread rate peaks in partial-g [right, Sacksteder; KC-135 experiments].

5.2 second drop tower tests using a centrifuge to generate g







Comparison of a candle-like flame in Lunar g (left) and normal g (right)

Proposed Concept: Overview

We propose to use a small chamber to conduct the first-ever combustion tests on another world.

Hypothesis: some materials burning in Lunar-g are more flammable than on Earth. This has important implications for the current 1-g material screening method used by NASA.

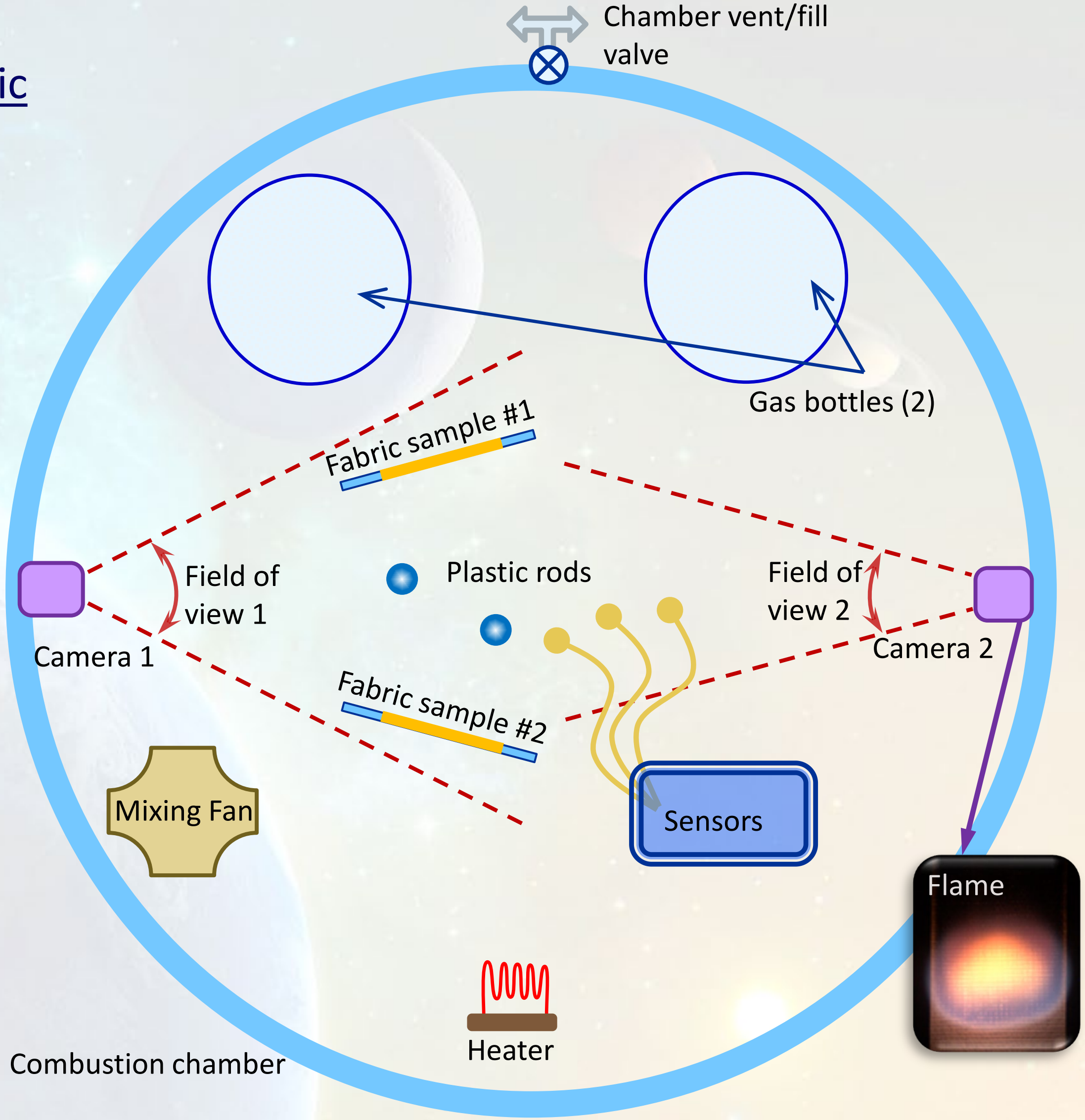
Four fuel samples individually burned in Lunar gravity; Cameras and other sensors record flame characteristics.

Oxygen limits for upward and downward spread on the Moon will be compared to 1-g values.

Measured flame characteristics in 1-g and Lunar-g will be compared to detailed model predictions. These comparisons will refine pressure-gravity scaling relations and will be applied to other g-levels.

The work directly addresses knowledge gaps in flammability and crew safety as defined in several NASA strategic documents.

Concept Schematic



Modes of Operation

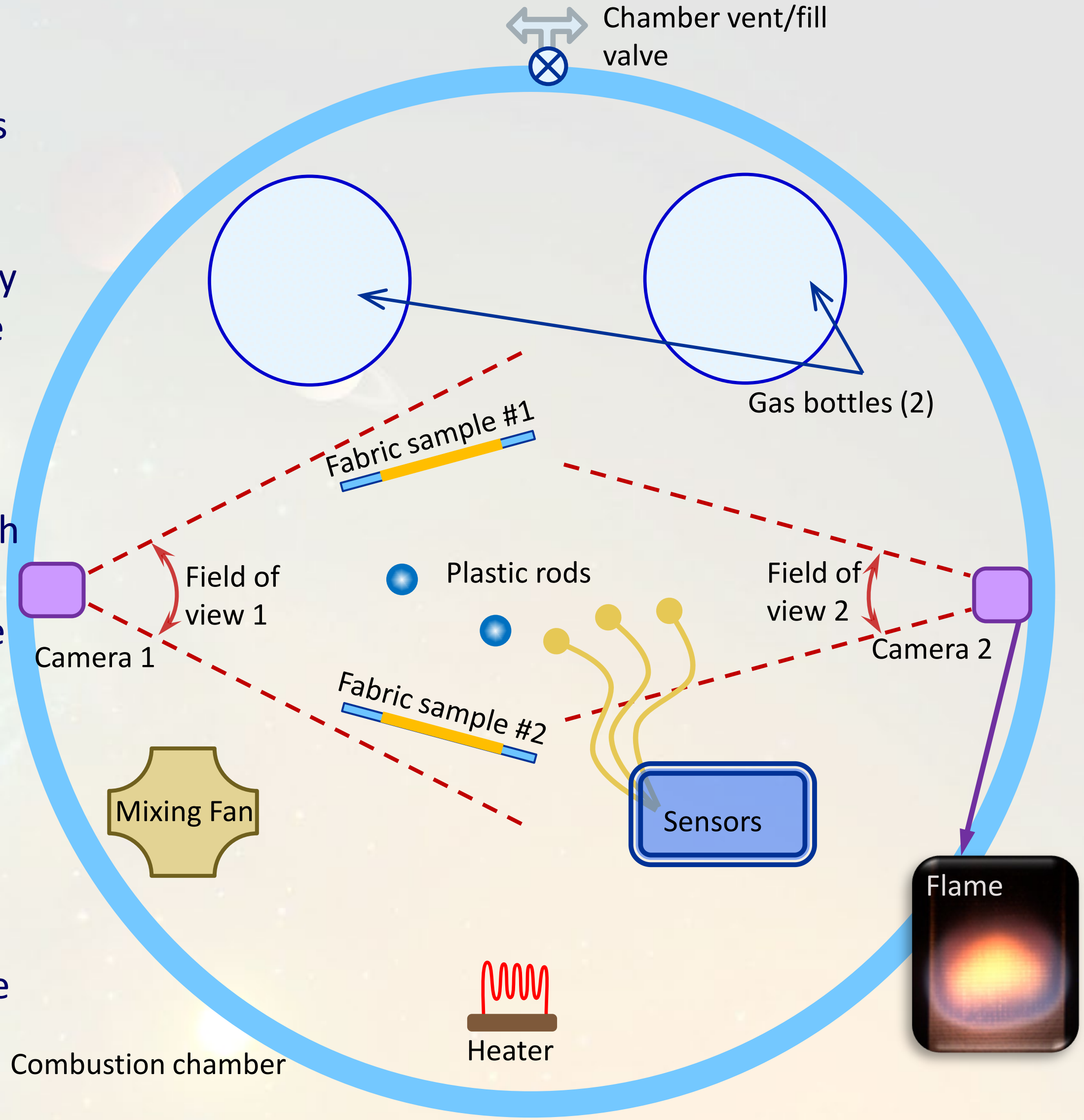
25 cm-DIA x 20 cm tall = 10 L; For 21% O_2/N_2 at 1 atm, this 10 liter volume contains 2.8 g O_2

Mode 1: To maintain O_2 approximately constant (necessary for a flammability test), assume 10% of this oxygen can be burned, namely 0.28 g. This is the amount of oxygen consumed by burning:

- 0.24 g cellulose (about 18 cm^2 SIBAL fabric) or
- 0.15 g PMMA (0.13 cm^3; 2-mm-DIA x 40 mm-length

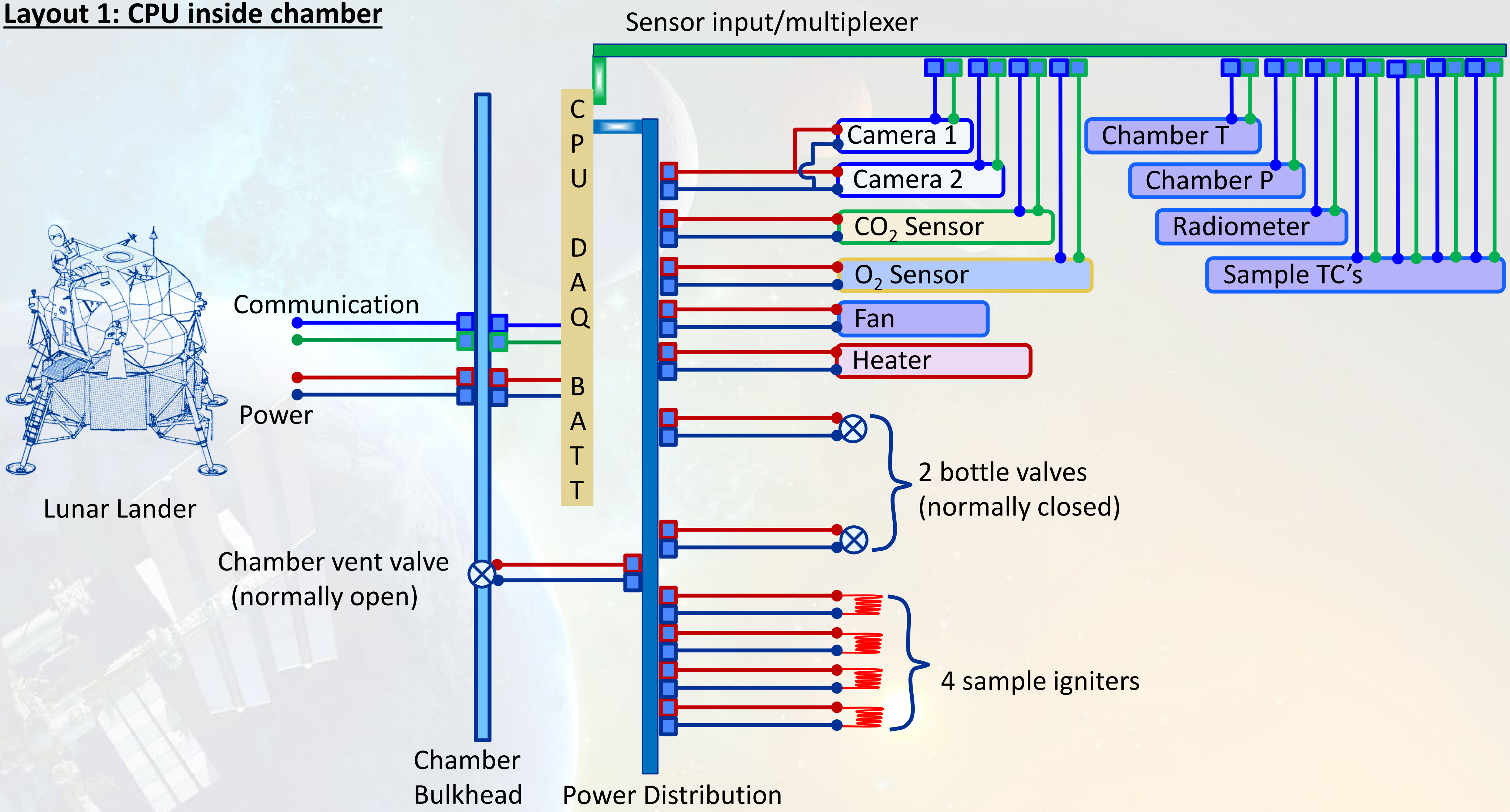
Mode 2: To determine oxygen depletion-to-extinction, the PMMA rods will be ignited and allowed to burn until the flammability limit is reached. Burn length, final O_2 concentration, and final CO_2 concentration will independently determine extinction limit.

Mode 3: To investigate a planned normoxic environment (for example 34% O_2 at 0.558 atm) on flame spread on the Moon compared to Earth. <u>34% + Lunar-g could be quite challenging from the point of view of fire safety.</u>

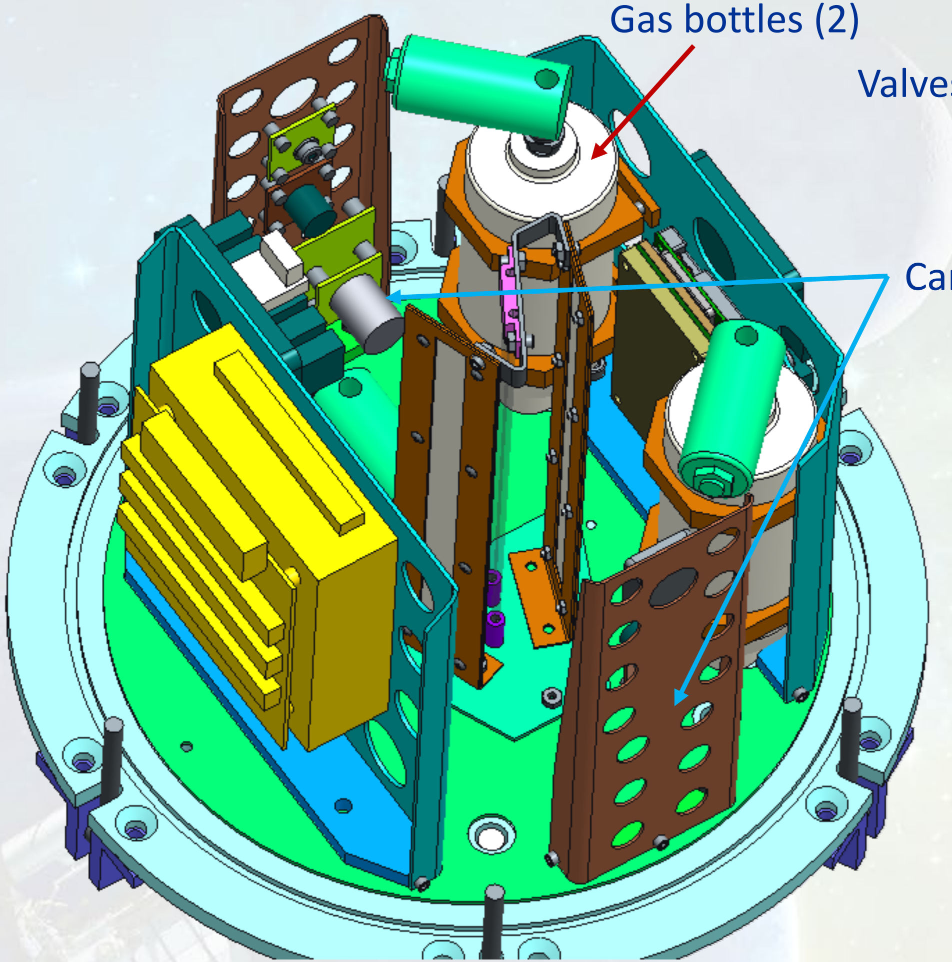


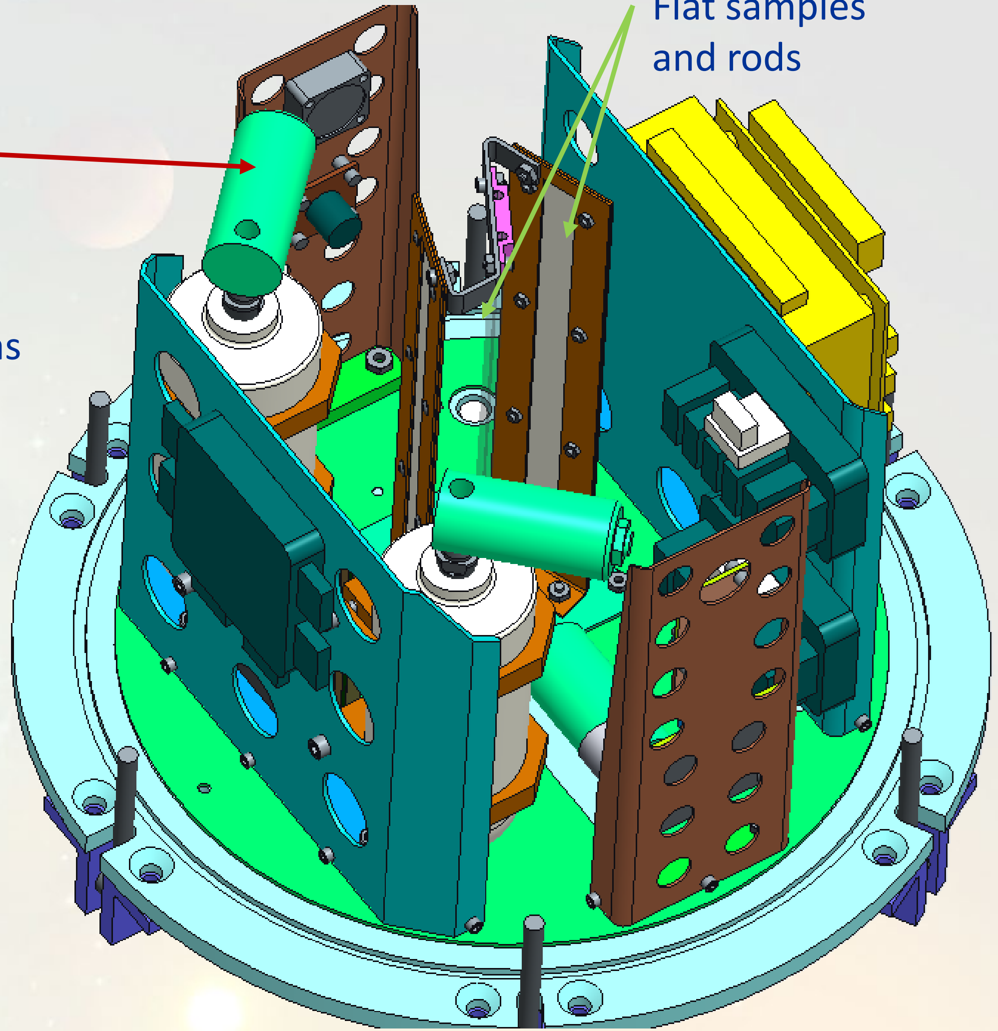
Electrical and Interface Concept

Layout 1: CPU inside chamber



Engineering Hardware is being built

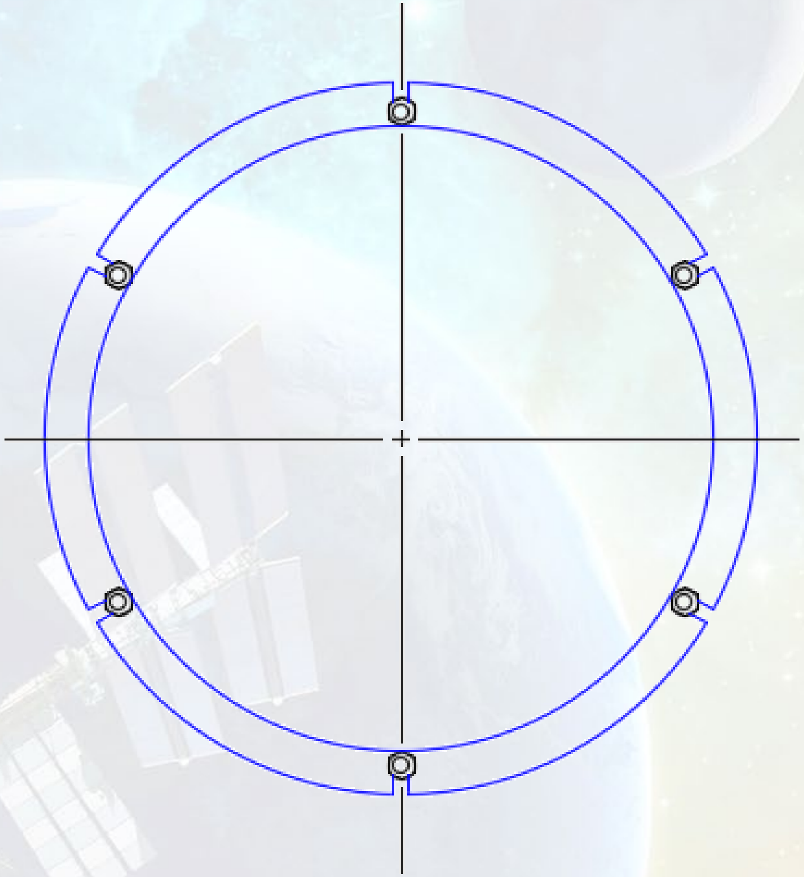


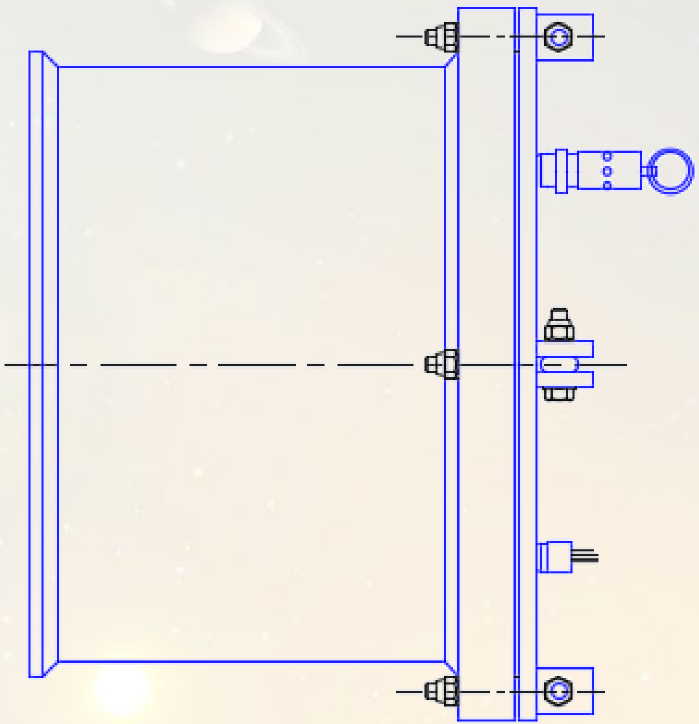


Design allows for height to be easily expanded, if the opportunity arises.

We will employ an image processing algorithm to mitigate distortion from wide-angle cameras.

Chamber is 8” tall x 9.75” ID; empty volume = 600 in.^{3} = 9.8 L





How large should the chamber be?

The answer goes jointly with fuel sample size to be burned.

Fuel consumption as a function of chamber volume:

Chamber open volume (L)	*Oxygen mass (g)*	*Mass of burned fabric for 10% drop in oxygen (g)*	*Equivalent area of fabric (cm^2)*	*Equivalent length of 2-mm-DIA PMMA rod (cm)*
1	0.28	0.024	1.75	0.39
2	0.56	0.047	3.50	0.79
5	1.40	0.118	8.74	1.96
10	2.80	0.236	17.5	3.93
20	5.60	0.472	35.0	7.86
50	14.0	1.18	87.4	19.6
100	28.0	2.36	175	39.3

Concept of Operations

During the launch, Lunar transit, and landing phases of the mission, the experiment would be dormant with the chamber valve open and the chamber evacuated.

After hardware power-up:

- -Close the chamber valve and release gas.
- -Run heater if needed to increase the temperature of the gas/chamber to ~ 20 deg C.
- -Initiate cameras and instruments.
- -Ignite and record data.
- -After burn, open the chamber valve to vent.
- -Repeat sequence for next burn.

Fire on the Moon Summary

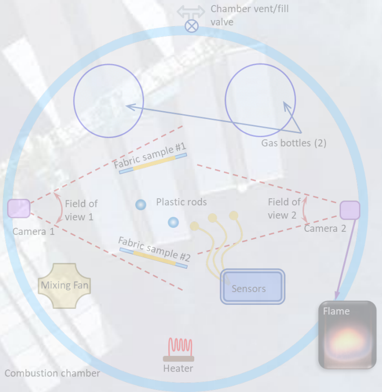
Objective: Burn solid fuels in Lunar-G, compare to 1-g, and refine material flammability screening tests.

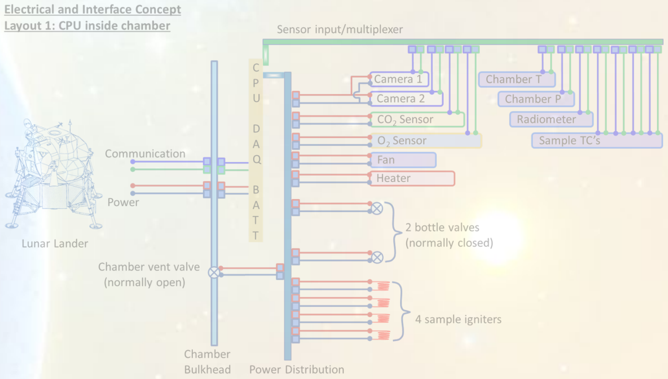
NASA Value: Material flammability called out in National Research Council decadal survey reports.

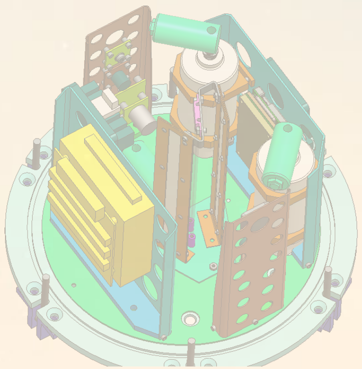
NASA's 2018 Strategic plan calls out combustion research, and states "*[NASA GRC] is a global leader in the fields of microgravity combustion and fluid physics.*"

Payload Approach: Burn fuel samples in upward and downward configuration, record flame images and sensor data, and determine flammability limits

Payload Properties: Chamber free-volume 10 liters, small air bottles provide air, camera and sensors record tests, computer used for control and data storage/transfer.







Backups

Characteristic Buoyant Convective speed as a function of gravity level

Consider a balance of convection and gravitational body force in the Navier-Stokes equation:

$$\rho u \frac{\partial u}{\partial x} \approx g\, \Delta\rho$$

The characteristic buoyant flow speed (U) can be defined in two ways from this relation

I.) $U_1 \sim g^{(1/2)}$; when there is a fixed characteristic length for the system for example

For example, if a small (1-cm), engulfed, burning sample on Earth has $U_1 \approx 100$ cm/s, then on the Moon the same sample would have $U_1 \approx 40$ cm/s

II.) $U_2 \sim g^{(1/3)}$; when the characteristic length is the “thermal length” (which implicitly depends on U)

For example, in the stabilization zone of a flame, the flame standoff distance is on the order of the thermal length. For a representative flame on Earth having $U_2 \approx 20$ cm/s, the corresponding value on the moon would be $U_2 \approx 10$ cm/s

Estimate of Payload Accommodation Properties

Mechanical	
Surface Delivery Mass	Although it is expected that some landers can handle significantly larger payloads, NASA limited payloads to less than approximately 15 kg
Radiation	Not expected to exceed 1 krad (over duration?)
Surface Communication	
R/F Communication Capability	Up to 3.0 kbps per kg of payload
Wired Interface	Serial RS-422
Wireless Interface	2.4 GHz IEEE 801.11n compliant Wi-Fi
Power	
Continuous Power Level	Up to approximately 8 Watts
Peak Power Level	Potentially up to 25 Watts for one minute
Power Conditioning	Regulated and switched 28 VDC

*No pressurized volume or thermal protection or conditioning could be assumed for payload accommodations.