Lunar Combustion Investigation: Flammability Results from a Rotating Sounding Rocket

Paul V. Ferkul[1], Michael C. Johnston[2], Nathan Kralik[3], and Ya-Ting Liao[3]
Universities Space Research Association[1]
NASA Johnson Space Center [2]
Case Western Reserve University [3]

2025 Annual Meeting
Phoenix, Arizona
December 3-6, 2025

Lunar Combustion Investigation: Flammability Results from a Rotating Sounding Rocket

Objectives

Demonstrate the feasibility of conducting material flammability experiments in partial-g on the spinning Blue Origin New Shepard vehicle which simulates Lunar gravity with centrifugal force

Obtain data from the flight that will support other simulated Lunar-g experiments in drop towers and parabolic flight, actual Lunar-g experiments, and computer models.

Outcome

The LUCI scientific objectives were achieved. Material flammability testing at partial-g is feasible using a spinning vehicle. Conducting large scale flammability testing would require additional programmatic support. This might be considered should more Lunar-g flights become available using New Shepard.

Overview

Conduct partial-g fire tests on the Blue Origin sounding rocket.

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

Fuel samples burned in pairs; cameras and other sensors record flame characteristics.

Oxygen limits for upward and downward spread at partial-g will be compared to 1-g values.

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

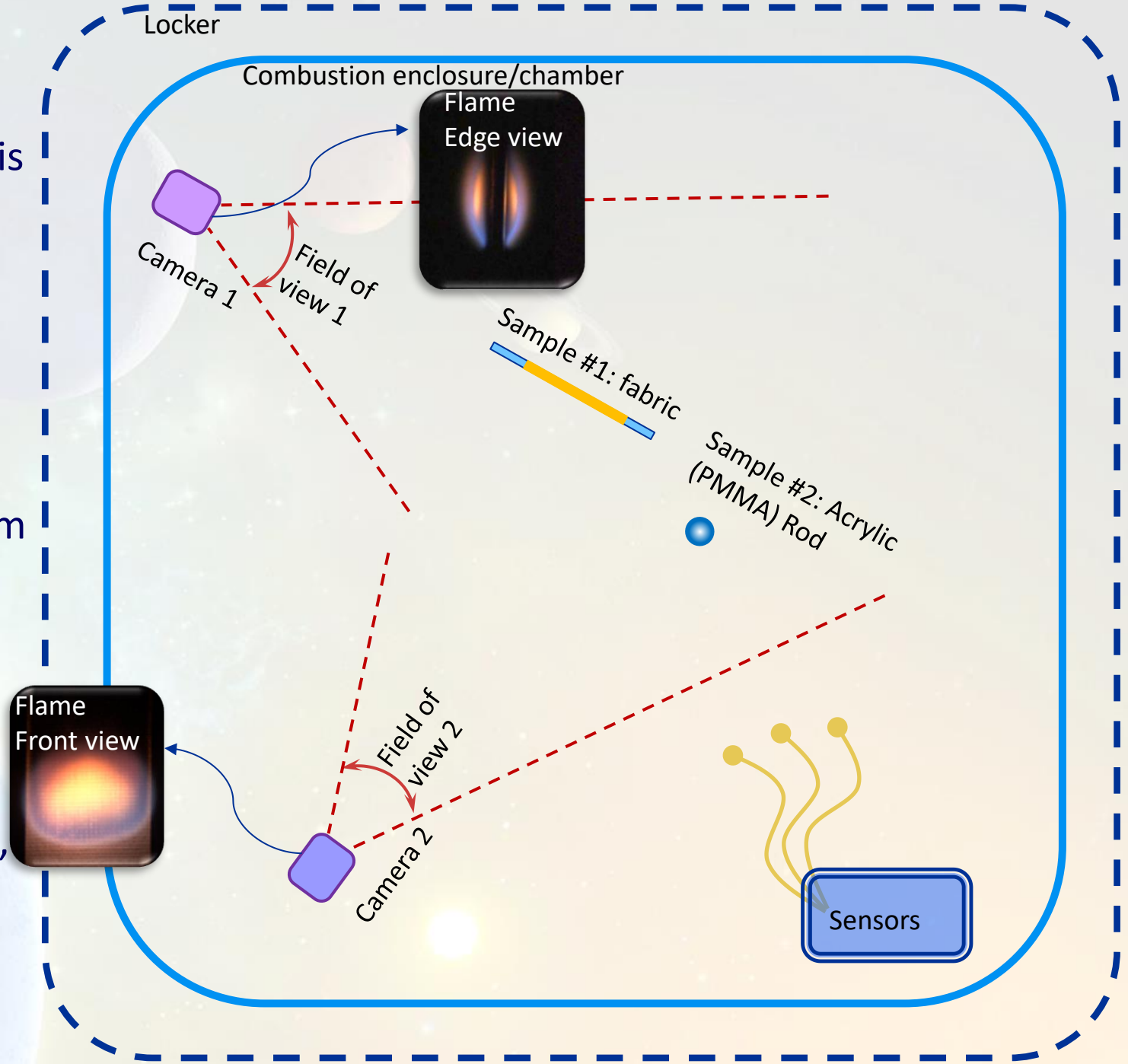
The work directly addresses knowledge gaps in flammability and crew safety as defined in several NASA strategic documents.

Schematic

Centrifugal gravity is into the page; this would be looking outward from the axis of rotation of the vehicle toward the cylindrical hull of the rocket. The flames would generally rise out of the page, or towards the axis of rotation.

Two samples: Fabric 5 cm wide x 30 cm long and 4-mm-DIA acrylic, (PMMA); ignited with slight pause between them.

Sensors: Chamber oxygen concentration, pressure, temperature, and centrifugal acceleration.

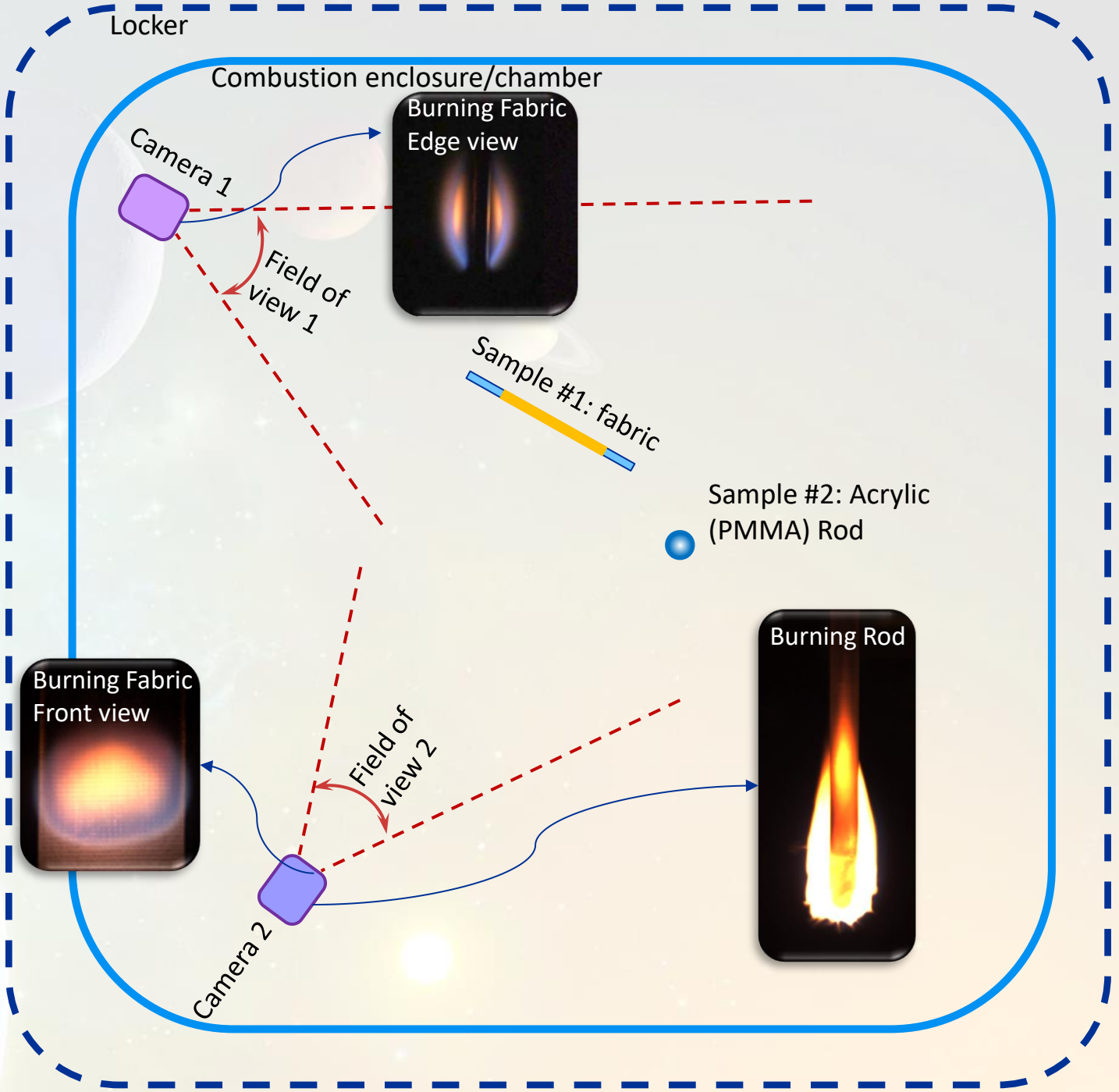


Schematic

Centrifugal gravity is into the page; this would be looking outward from the axis of rotation of the vehicle toward the cylindrical hull of the rocket. The flames would generally rise out of the page, or towards the axis of rotation.

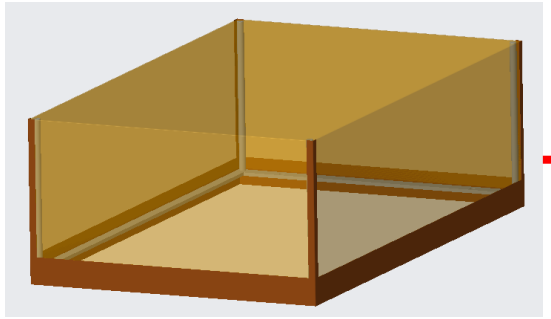
Two samples: Fabric 5 cm wide x 30 cm long and 4-mm-DIA acrylic, (PMMA); ignited with slight pause between them.

Sensors: Chamber oxygen concentration, pressure, temperature, and centrifugal acceleration.

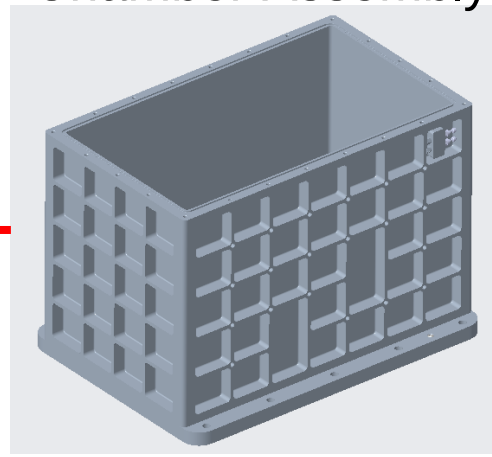


Hardware

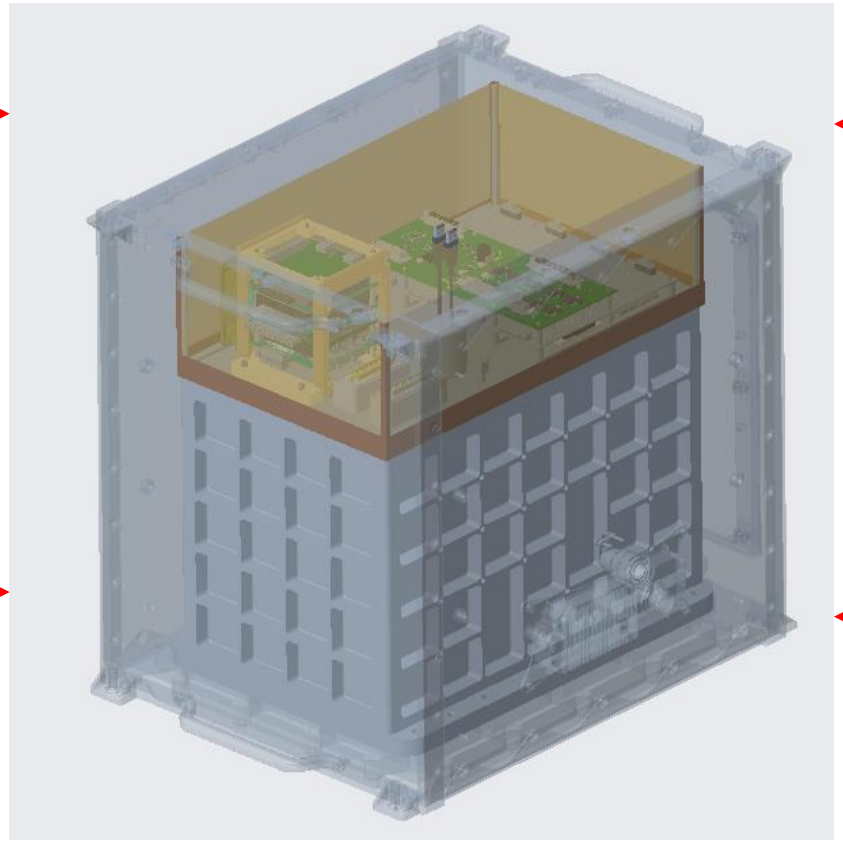
EMI Shielding

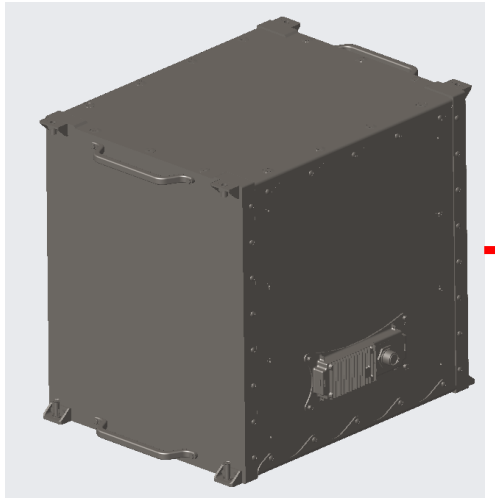


Chamber Assembly

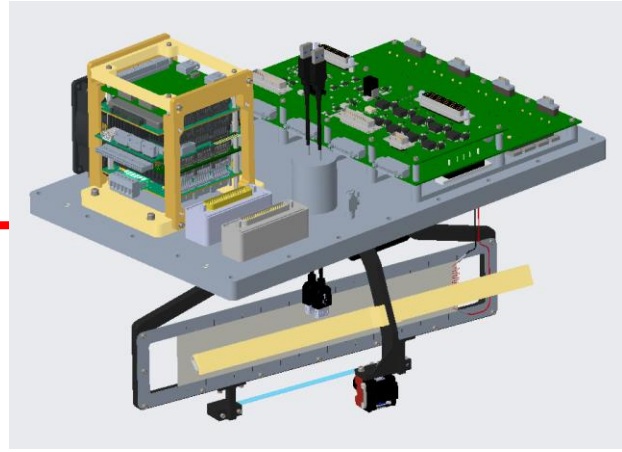


Top Level Assembly



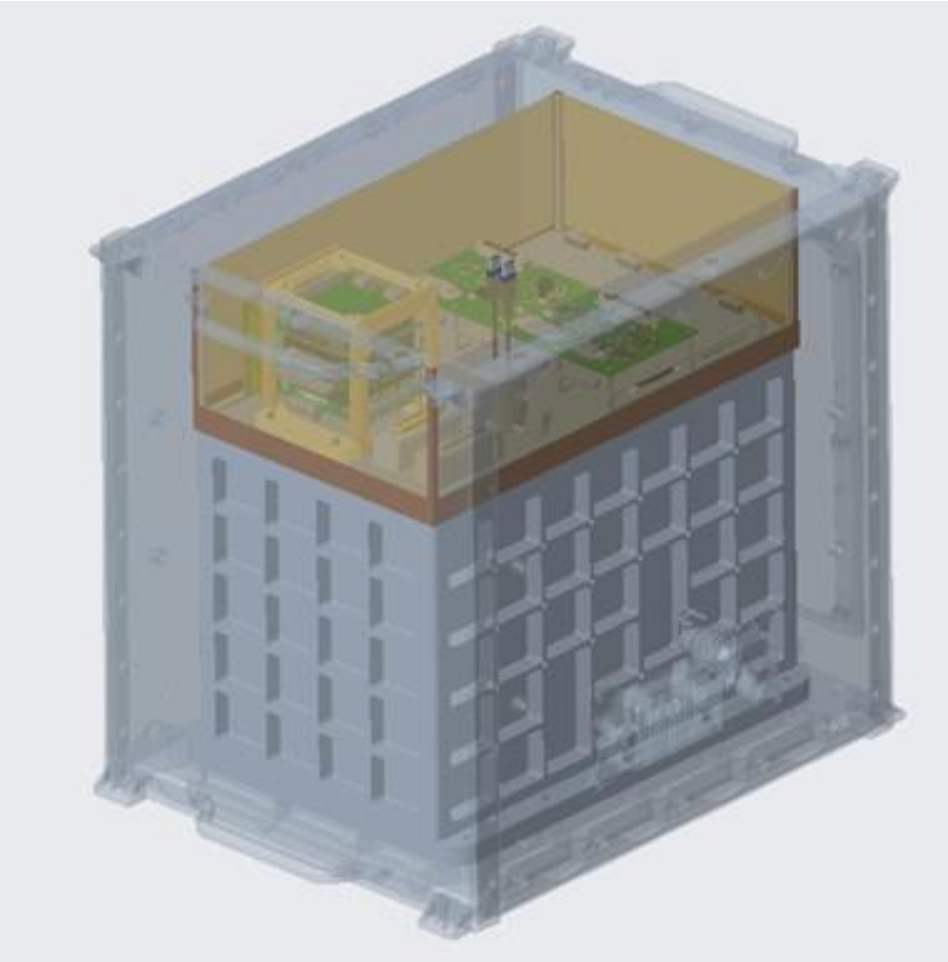


Blue Origin Locker

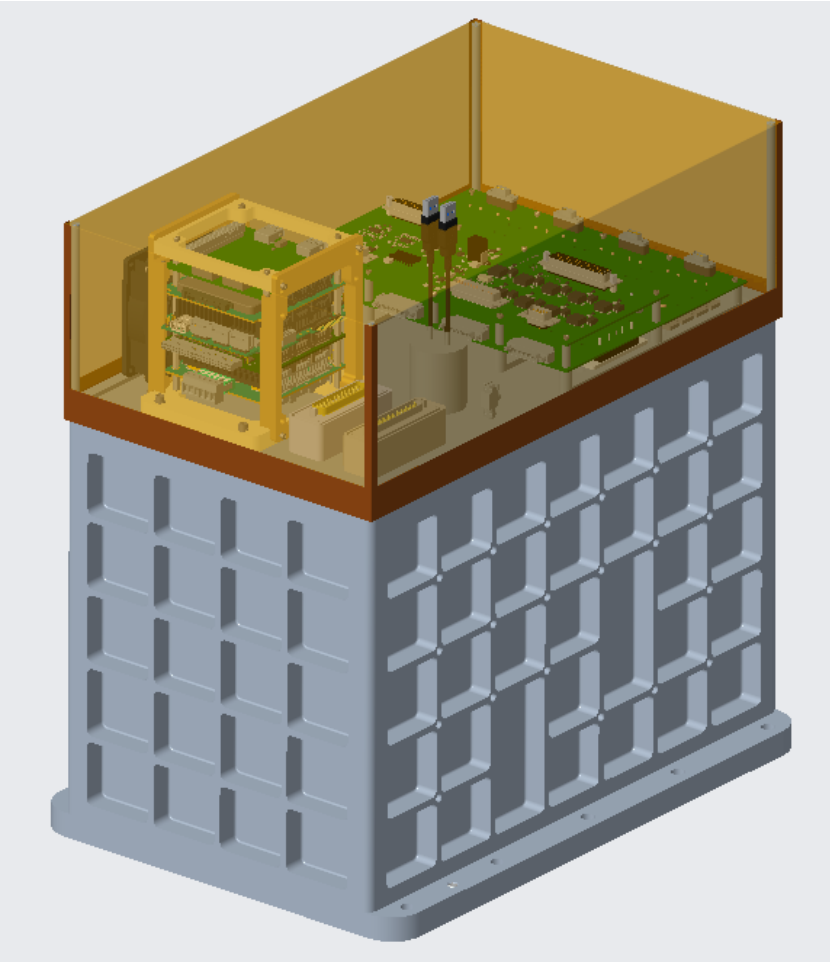


Lid Assembly

Top Level Assembly



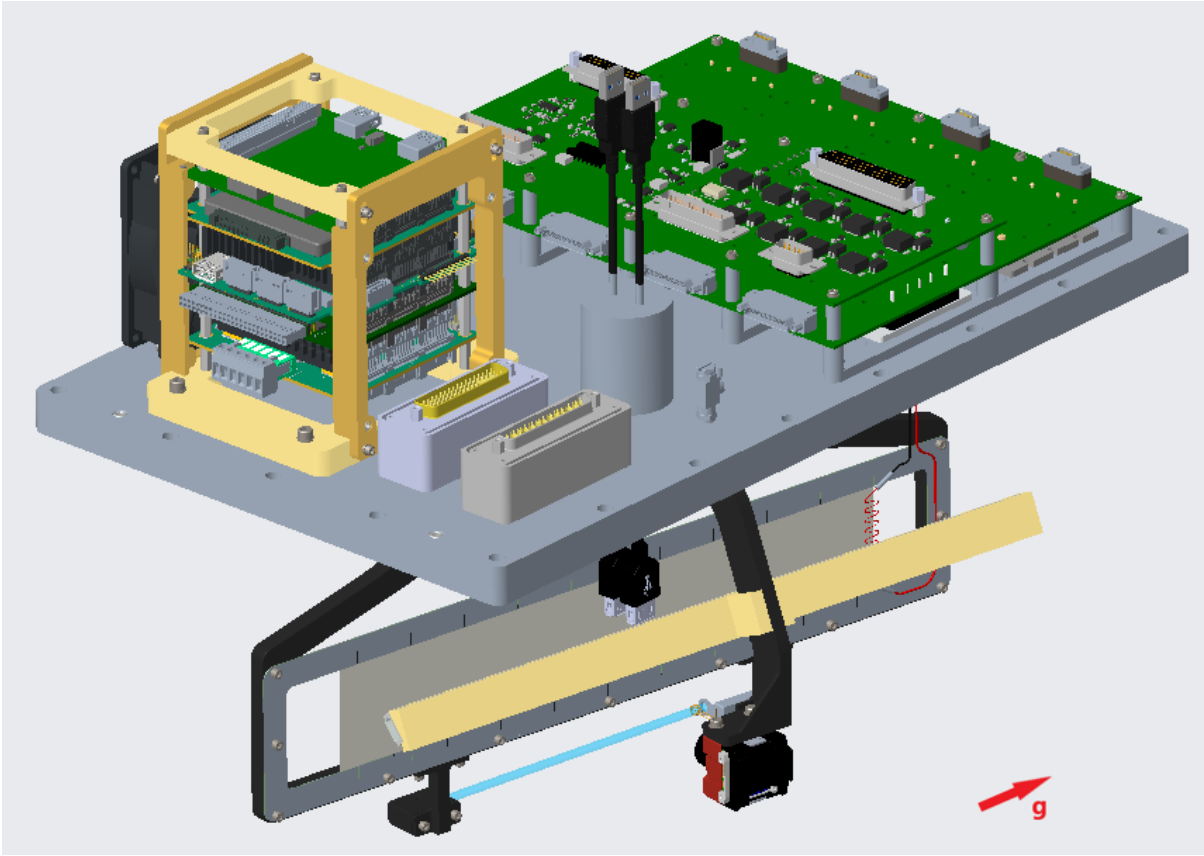
In Payload Locker

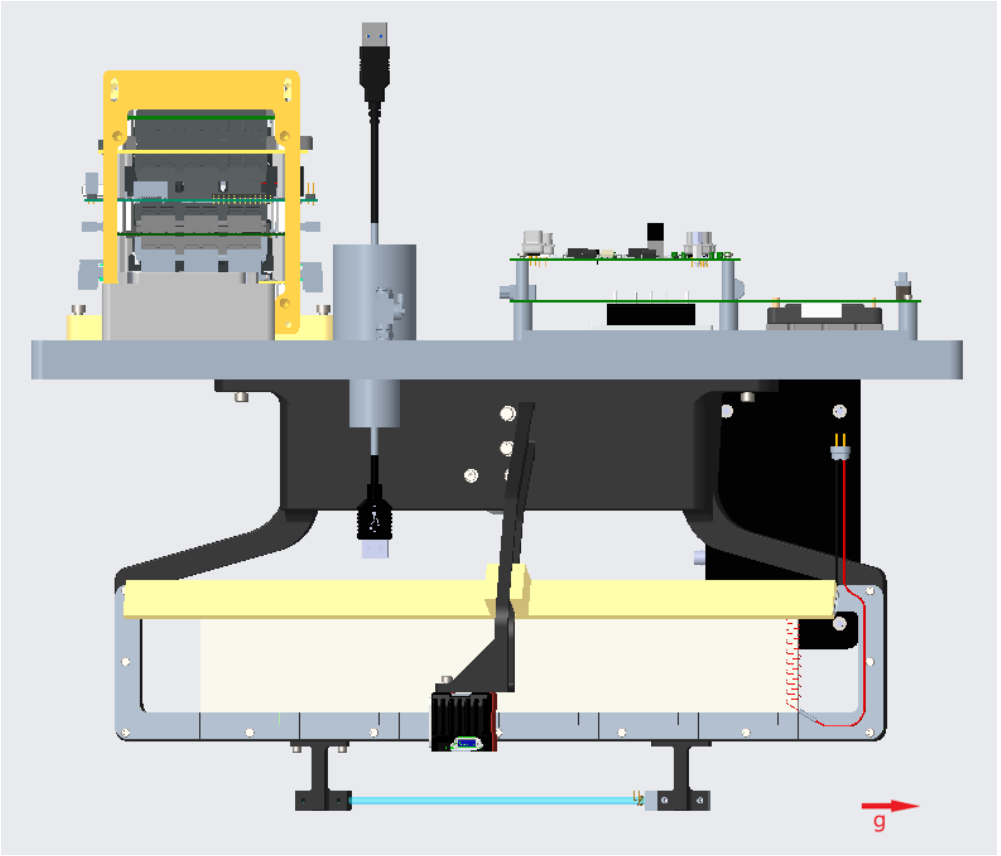


Out of Payload Locker

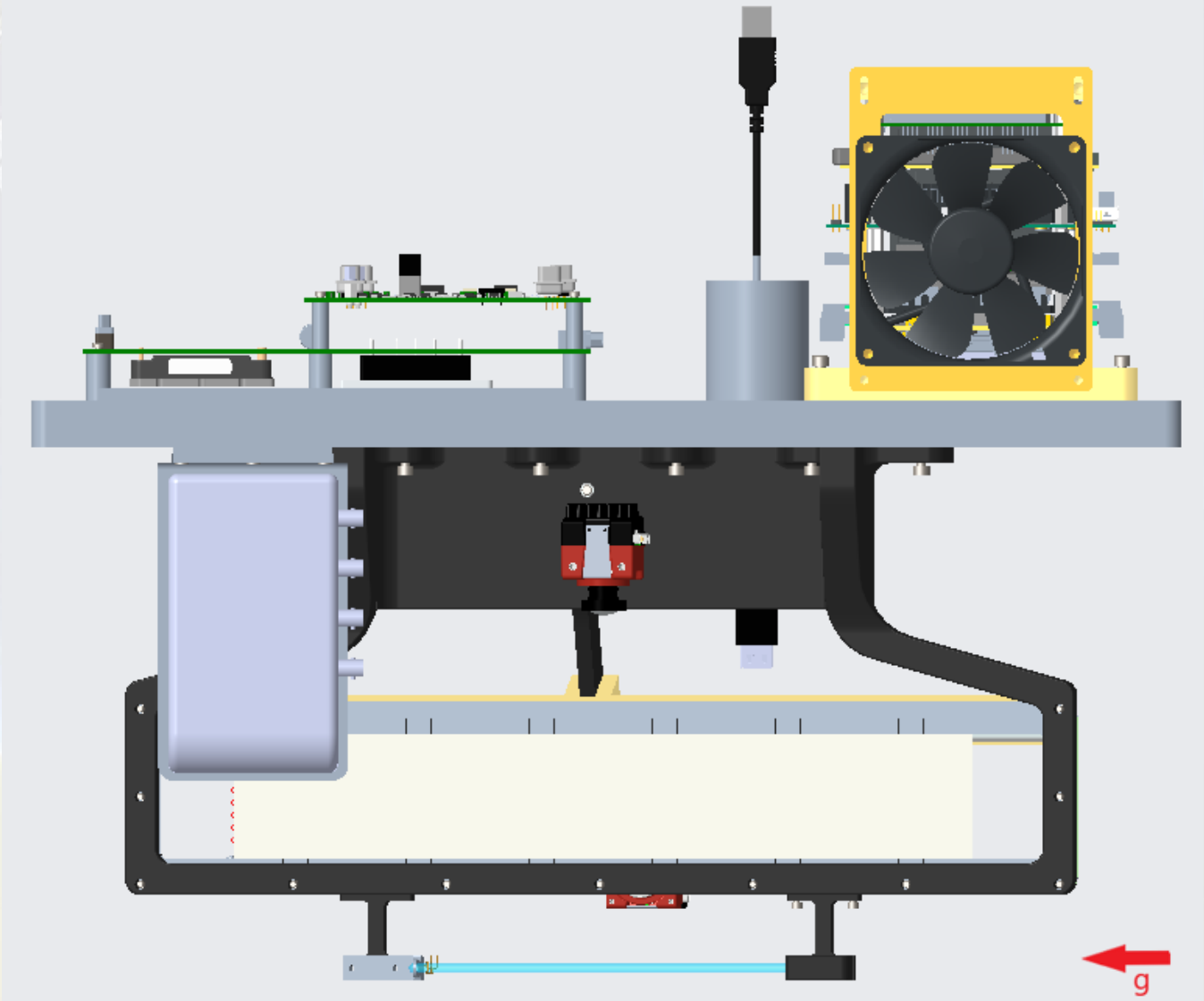
Combustion Chamber Lid Assembly

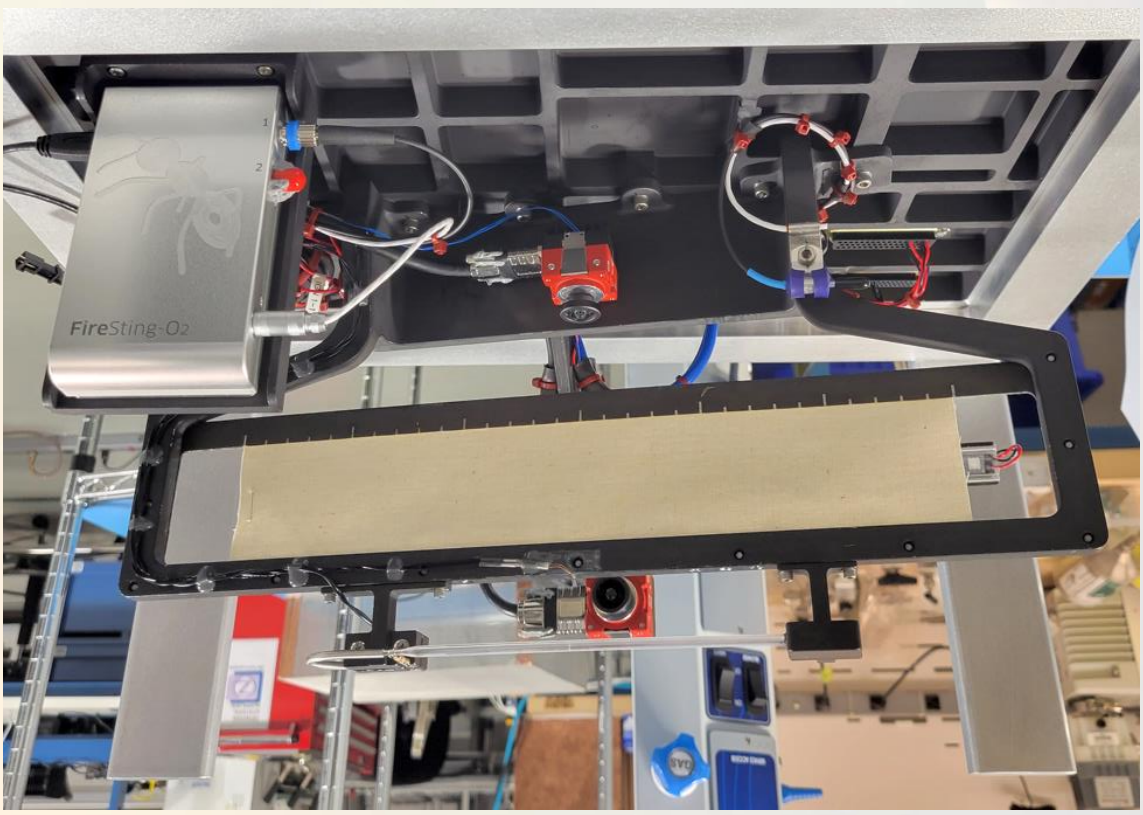
Glenn Research Center





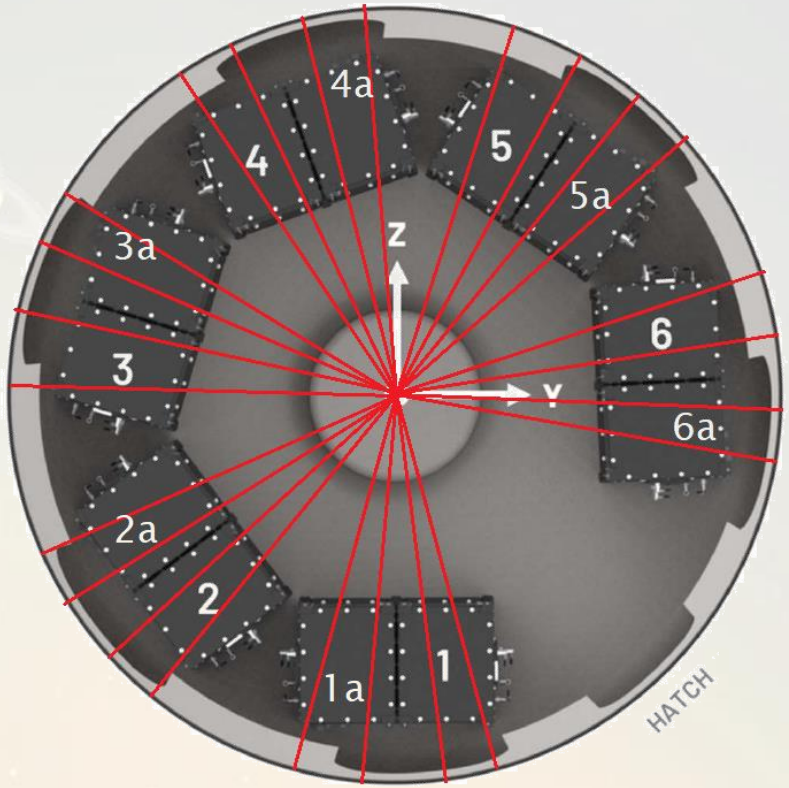
Lid is the main attachment point for
All Payload Avionics and Diagnostics


g


FireSting-O2

The effective floor of our hardware (orientated so that the centrifugal g-vector points downward toward the floor) measures about 41 cm x 48 cm. The available height in the g-direction is about 53 cm.

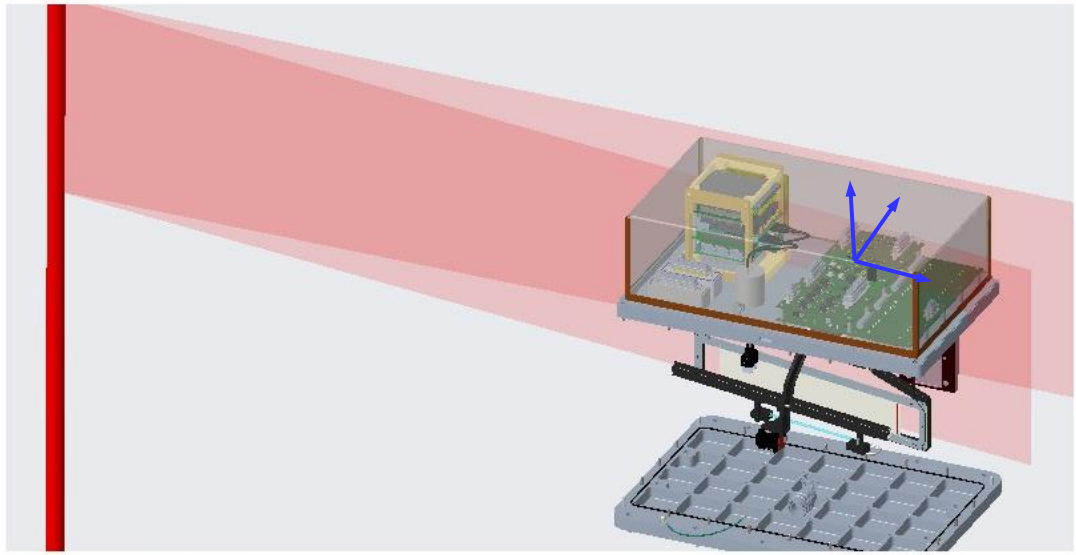
NOTE: How we orient our samples depends on the specific locker location. It is required that the principle vertical axes of the burn samples be aligned with the radial lines.

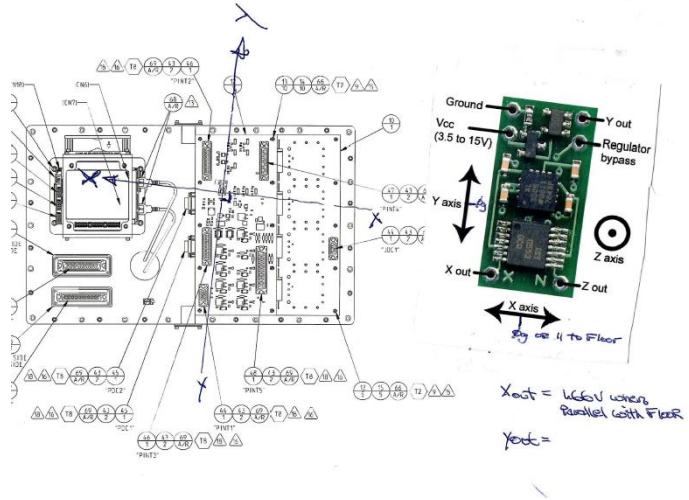


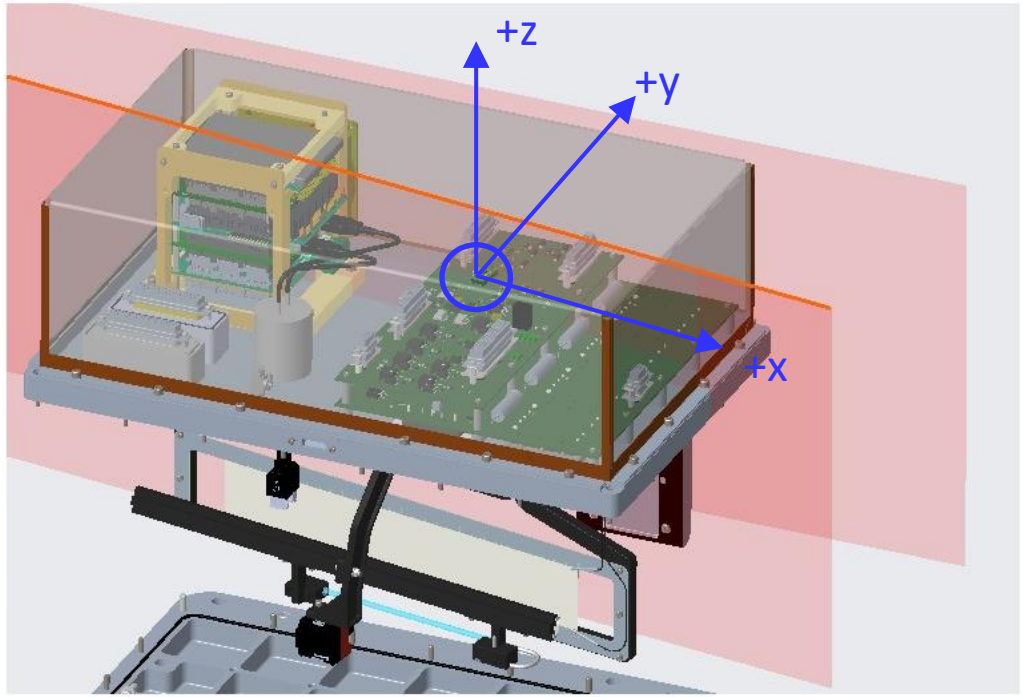
(From Blue Origin Payload Users Guide, fig. 3.3)

Top-Down View of Payload Stack Layout Within CC


Launch
Rocket sense of rotation

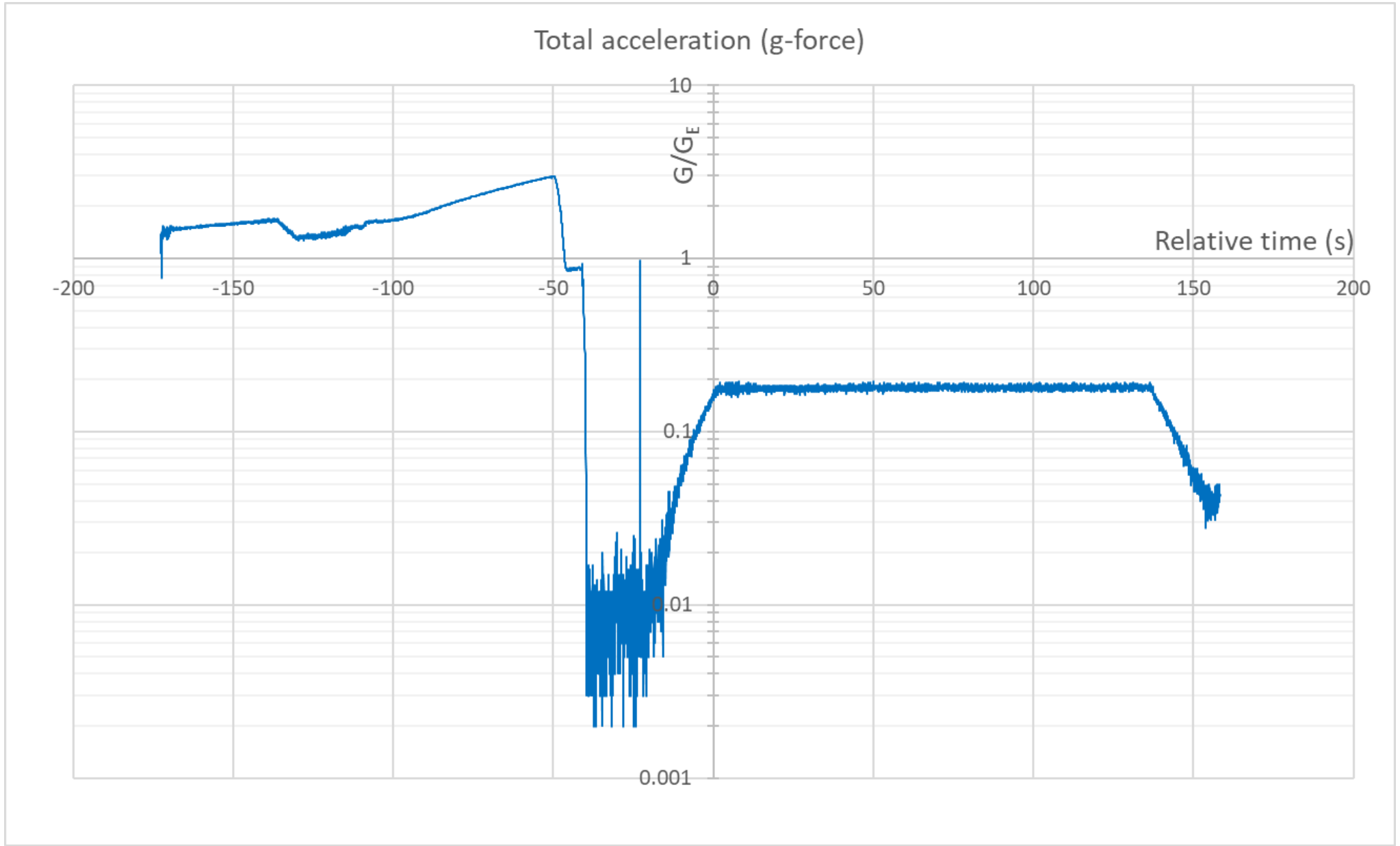


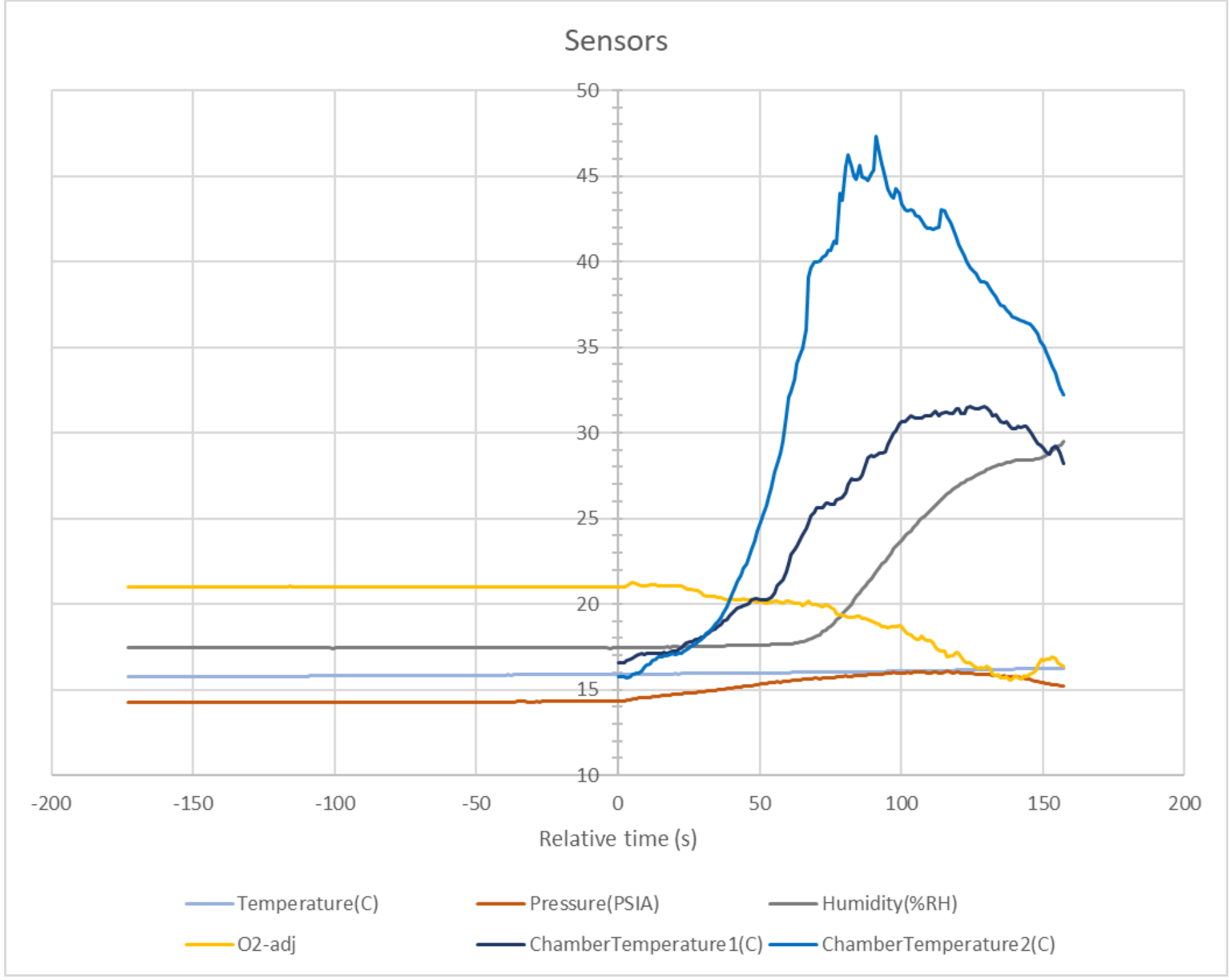

Ground
Vcc
(3.5 to 15V)
Y out
Regulator
bypass
Y axis
Z axis
X out
Z out
X axis
Xout = when parallel with floor
Yout =


+z
+y
+x

- Blue Origin New Shepard sounding rocket yields Lunar gravity by using centrifugal acceleration.
- These are the first-ever, extended-duration (greater than 25 seconds) combustion tests performed in simulated Lunar gravity.
- A steady vehicle rotation of 11 RPM is established, with an effective radius of rotation of 1.22 m at the experiment location.
- Two samples are burned simultaneously in air at normal pressure: Cotton-fiberglass composite fabric sheet and a 4-mm diameter rod of acrylic plastic (polymethyl methacrylate).
- Flame images from two orthogonal cameras are used to determine flame spread and growth rates, and the burn lasts for over two and a half minutes.
- The oxygen concentration in the chamber is measured. As the burns progress, the oxygen concentration drops, enabling a limiting value for extinction to be defined.
- The effect of Coriolis force is discussed.
- Results from this experiment are compared to related 1-g work, drop tower tests, aircraft experiments, and modeling.
- The results are applicable to NASA's exploration efforts in that they guide the selection of fire-safe materials and environments and ensure safety of future spacecraft and Lunar habitats. The data also provides fundamental understanding of fires.
- Finally, the experiment is a steppingstone to the ultimate goal of performing burn tests on the Lunar surface in the Flammability of Materials on the Moon (FM^2) experiment which is planned to launch in late 2026.

- History
  - ZIN technologies brought on board October 2021
  - Initial Planned launch was Spring 2023, Launch provider delay initially delayed launch into late Summer early Fall 2024, until it finally launched Feb 4 2025
  - First mission sequence test was performed in July 2023
    - Due to launch slip some improvements were made and last mission sequence test was ran in February 2024 before being shelved prior to flight.
- Objectives
  - Burn SIBAL fabric & PMMA
  - Conduct first-ever, long duration observation and measurement of flame spread in a partial-g environment
    - Verify this platform is a viable means to obtain material flammability data in Lunar-g and will include an assessment of the Coriolis force on results
    - Provide guidance for sample selection and test definition for a Lunar in-situ experiment
- Data
  - First Flight
    - Measurements of flame spread rate and output of other diagnostics, including g-level vs. time for the two samples
    - Sample closeout photos and photos before and after each test
    - Data from 1-g burns


Total acceleration (g-force)
10
1
0.1
0.01
0.001
G/G_E
Relative time (s)
-200
-150
-100
-50
0
50
100
150
200

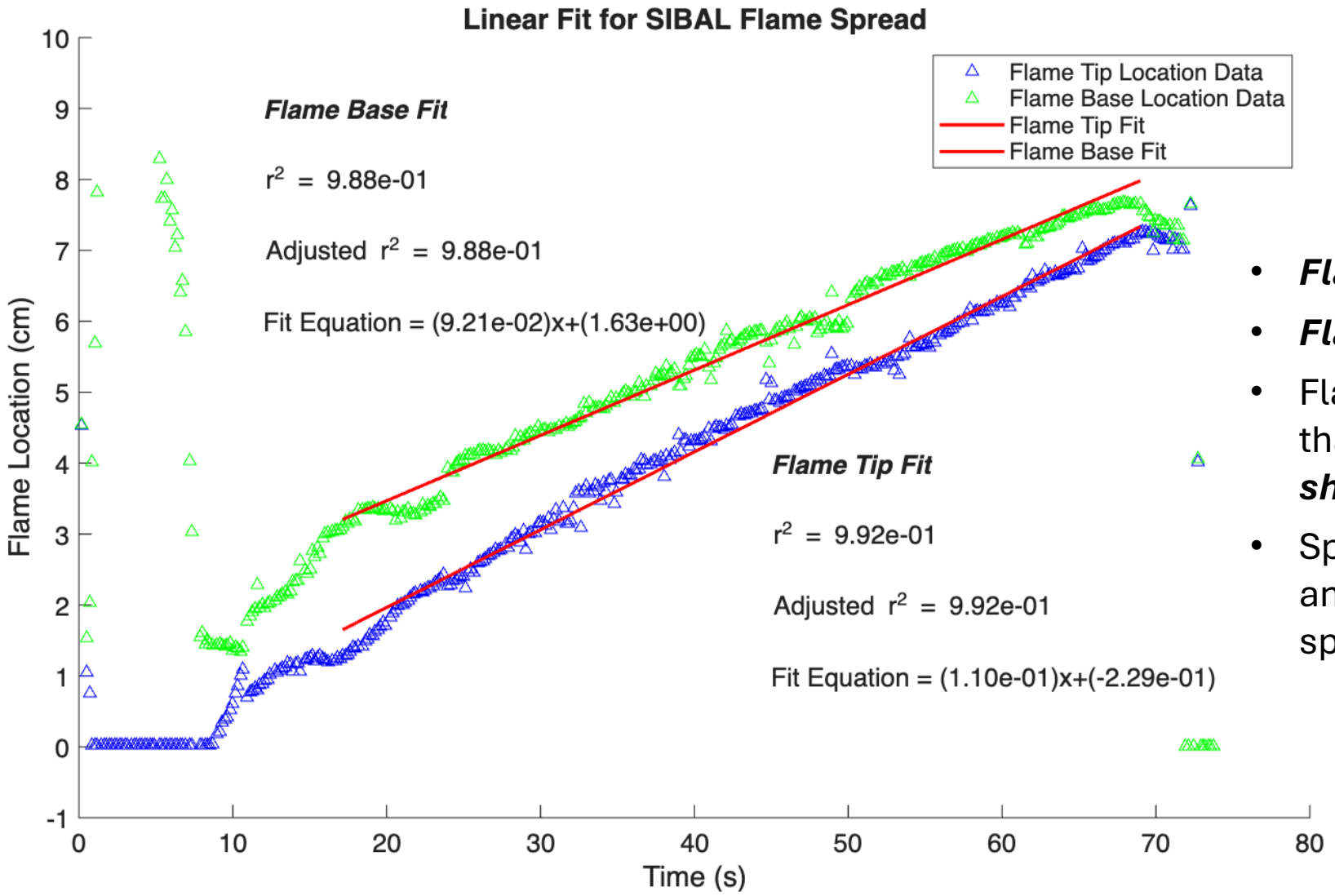

Sensors
50
45
40
35
30
25
20
15
10
-200
-150
-100
-50
0
50
100
150
200
Relative time (s)
Temperature(C)
Pressure(PSIA)
Humidity(%RH)
O2-adj
ChamberTemperature1(C)
ChamberTemperature2(C)

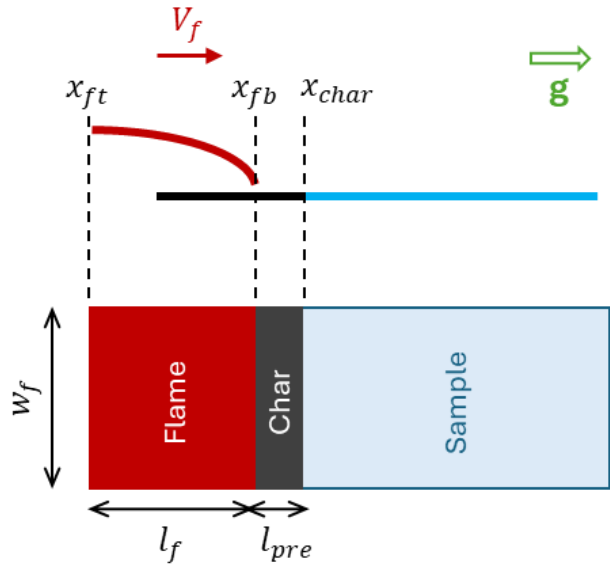
LUCI samples 30 s after ignition. Left: Edge view of SIBAL fabric (cotton-fiberglass blend) burning downward in Lunar-g 30 s after ignition. The flame spread for over a minute. Right:4-mm-diameter PMMA rod burning upward in air in Lunar-g, 30 s after ignition. The flame eventually grows to engulf the entire rod.

PMMA rod after 90 seconds of burning in Lunar g. Two orthogonal camera views are shown. The one on the right demonstrates how the Coriolis force pulls the flame away from the axis of the fuel, which is aligned with the direction of the centrifugal acceleration.

- Potential Follow-on Objectives
  - Evaluate the hypothesis that some materials burning in partial-g environments may be more flammable compared to 1-g.
    - Compare upward and downward oxygen limits to 1-g values
    - Evaluate flame size, strength, intensity, and spread compared to 1-g
  - Develop a numerical model
    - Assess the applicability of the model by comparing to the test data obtained.
    - Determine applicability of the pressure-gravity scaling relations for upward spread rates.
    - Refine model using experiment results
  - Provide a bridge between current 1-g material screen method and actual behavior in reduced gravity.
- Data
  - Flammability limits (%O_2) for a subset of materials in Lunar-g
  - Measurements of the flame spread rate over materials in exploration atmospheres
  - Sample closeout photos, and photos before and after each test
  - Data from 1-g burns

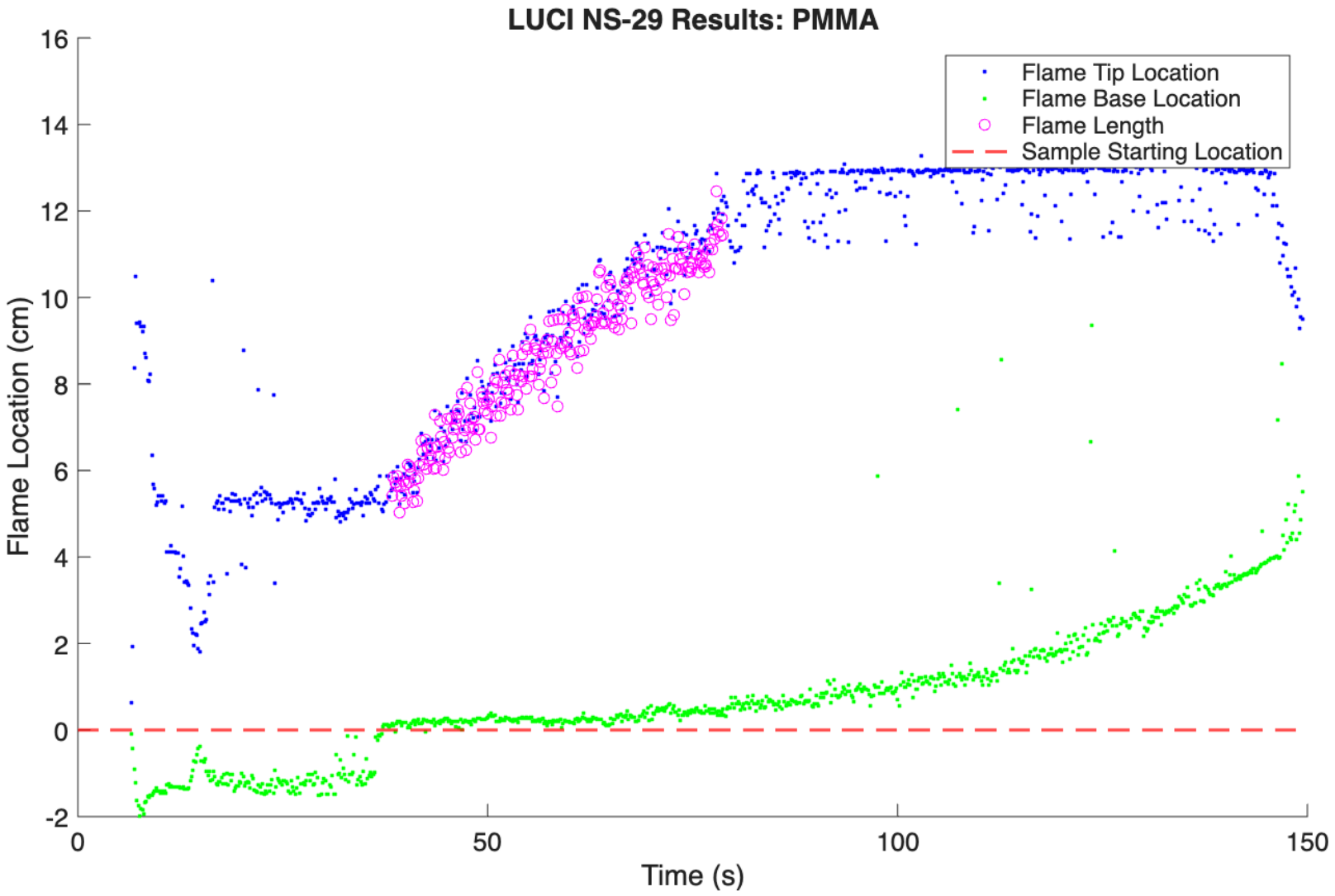
LUCI: SIBAL fabric

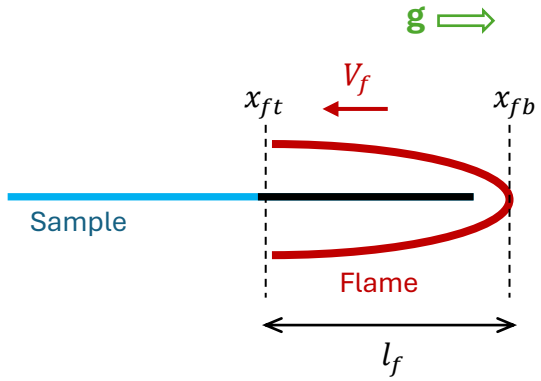




- ***Flame base spread rate*** = .92 mm/s.
- ***Flame tip spread rate*** = 1.1 mm/s
- Flame tip spreads very slightly faster than flame base, indicating a ***slowly shrinking flame length***.
- Spread rates for char front, flame base, and flame tip are all linear (steady state spread).

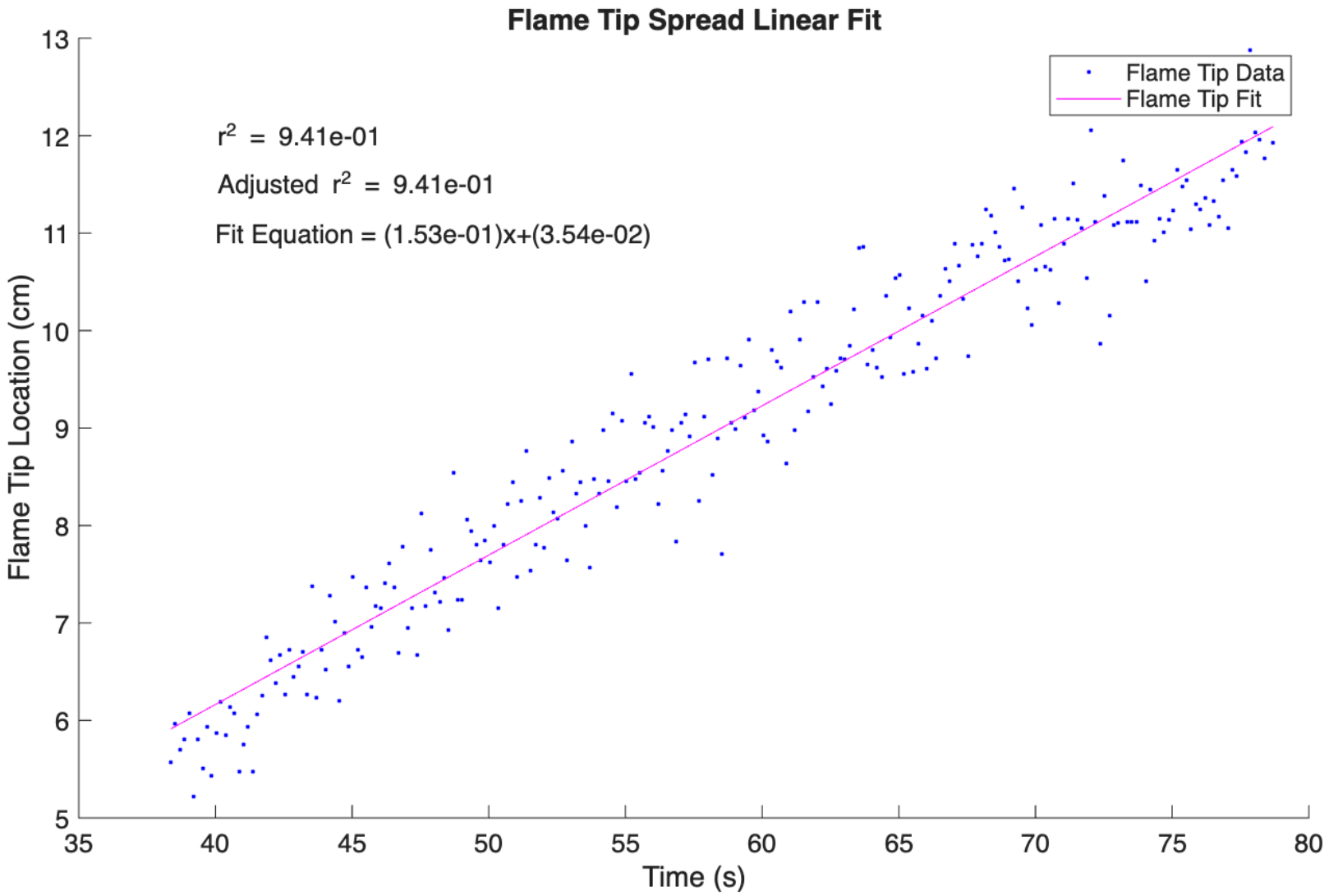
LUCI: PMMA

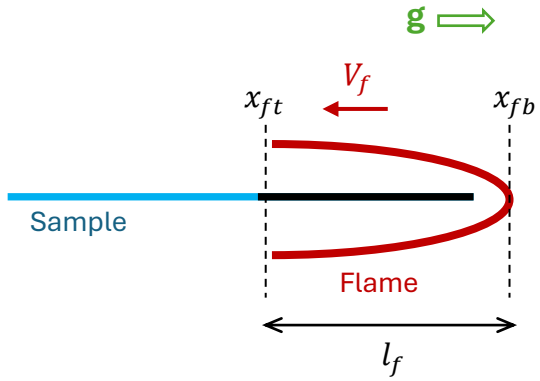




- ***Flame length increases ~linearly*** until flame tip becomes obscured by sample holder (could not measure flame length accurately beyond this point).
- Total base spread of ***~6cm*** until extinction.
- Flame base spread rate is ***not constant***; steady spread was not achieved.

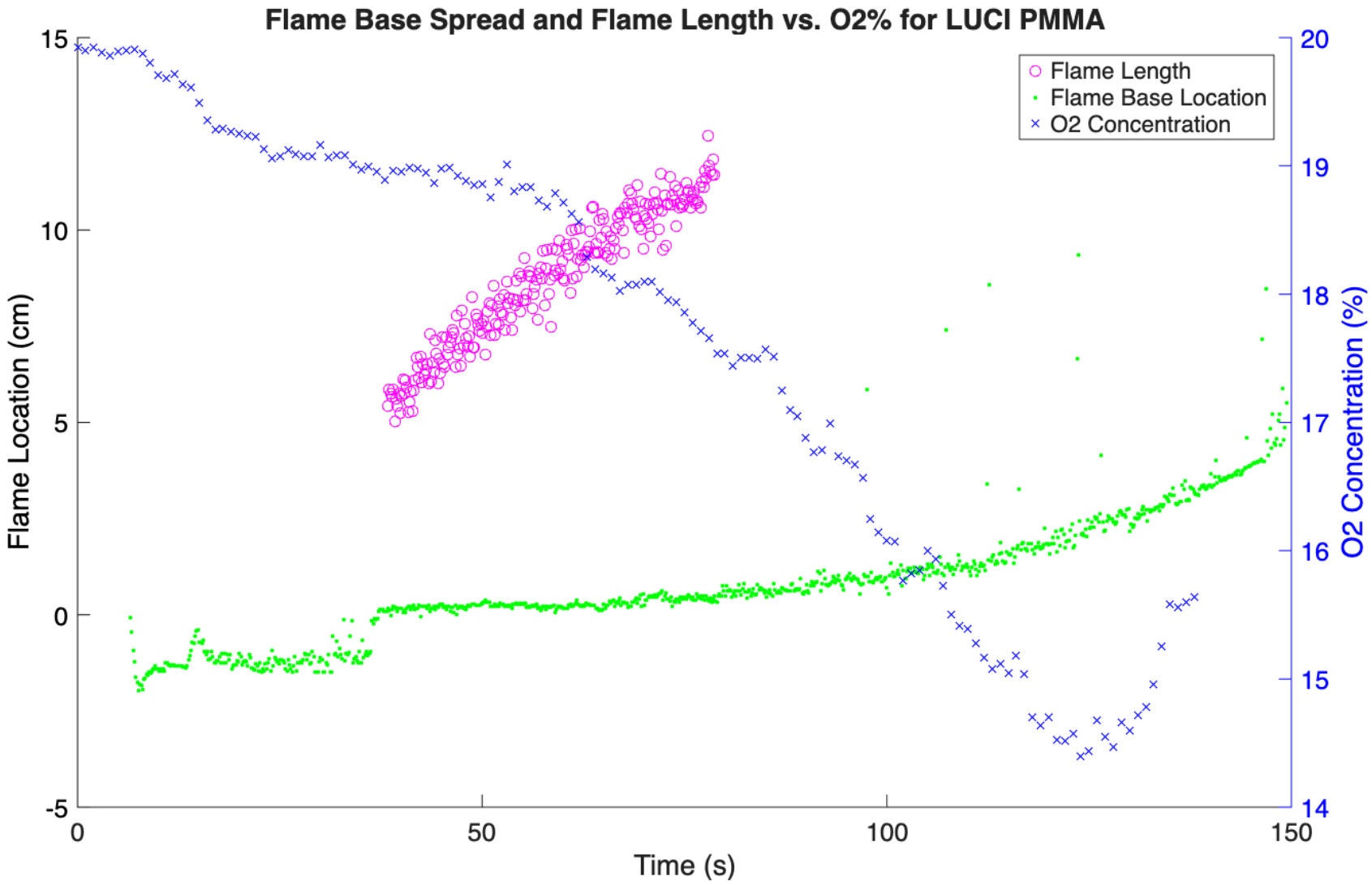
LUCI: PMMA

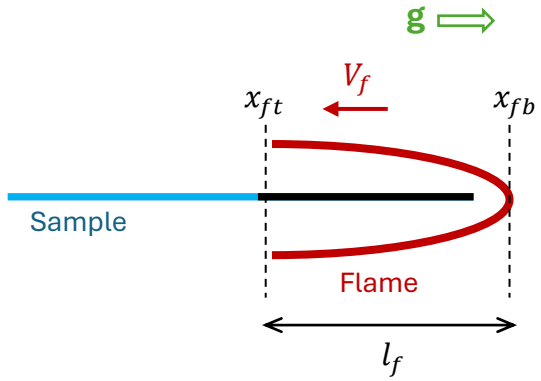




- Flame tip spread is approximately linear.
- Flame spread rate = 1.5 mm/s.

LUCI: PMMA



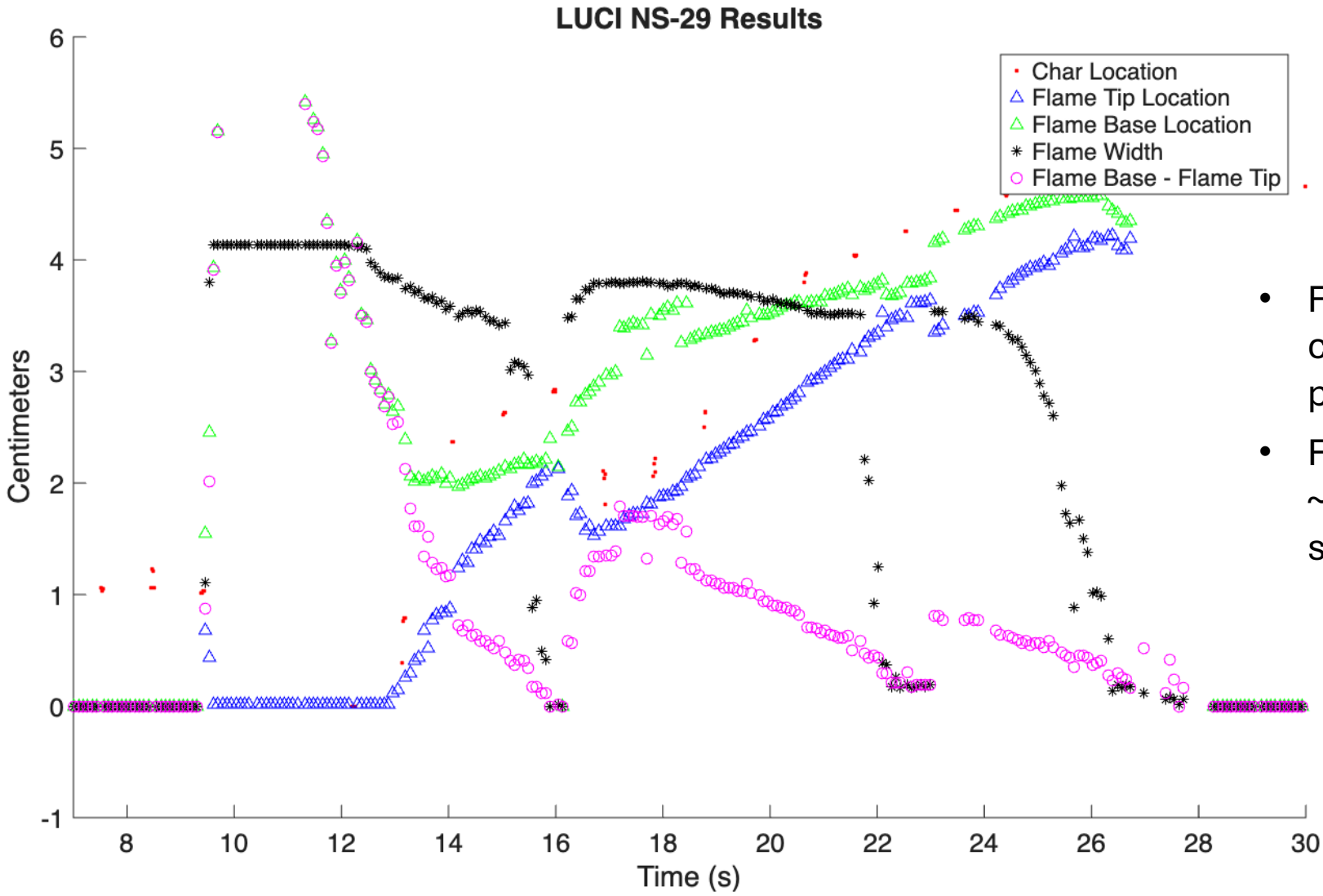


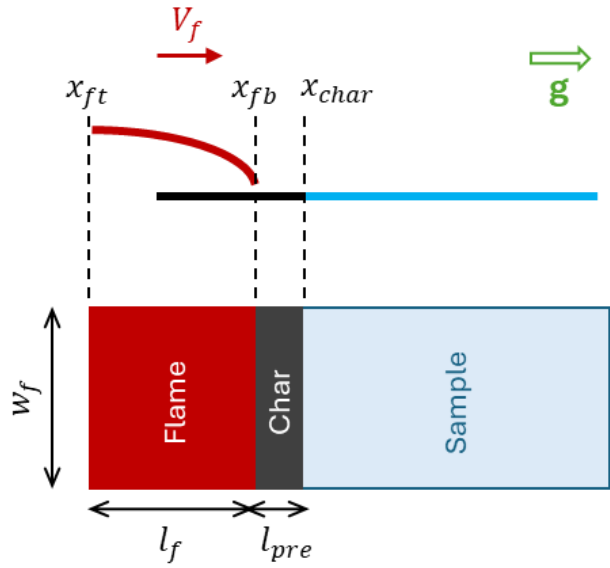
- O2% decreases from 20% to 14.3%.
- O2% rises back to 15.8% likely due to the decrease in gravity (and thus buoyant flow) which occurred at 125s.

LUCI 1-G Updates

- Results have been obtained and plotted with partial-g results for comparison.
- Fits of the data were created where possible and useful, and more fits can be created in the future if necessary.
- Results are not as clean as partial-g, the program does not read the flame spread as cleanly, and the flame burns out much quicker, resulting in fewer total data points.

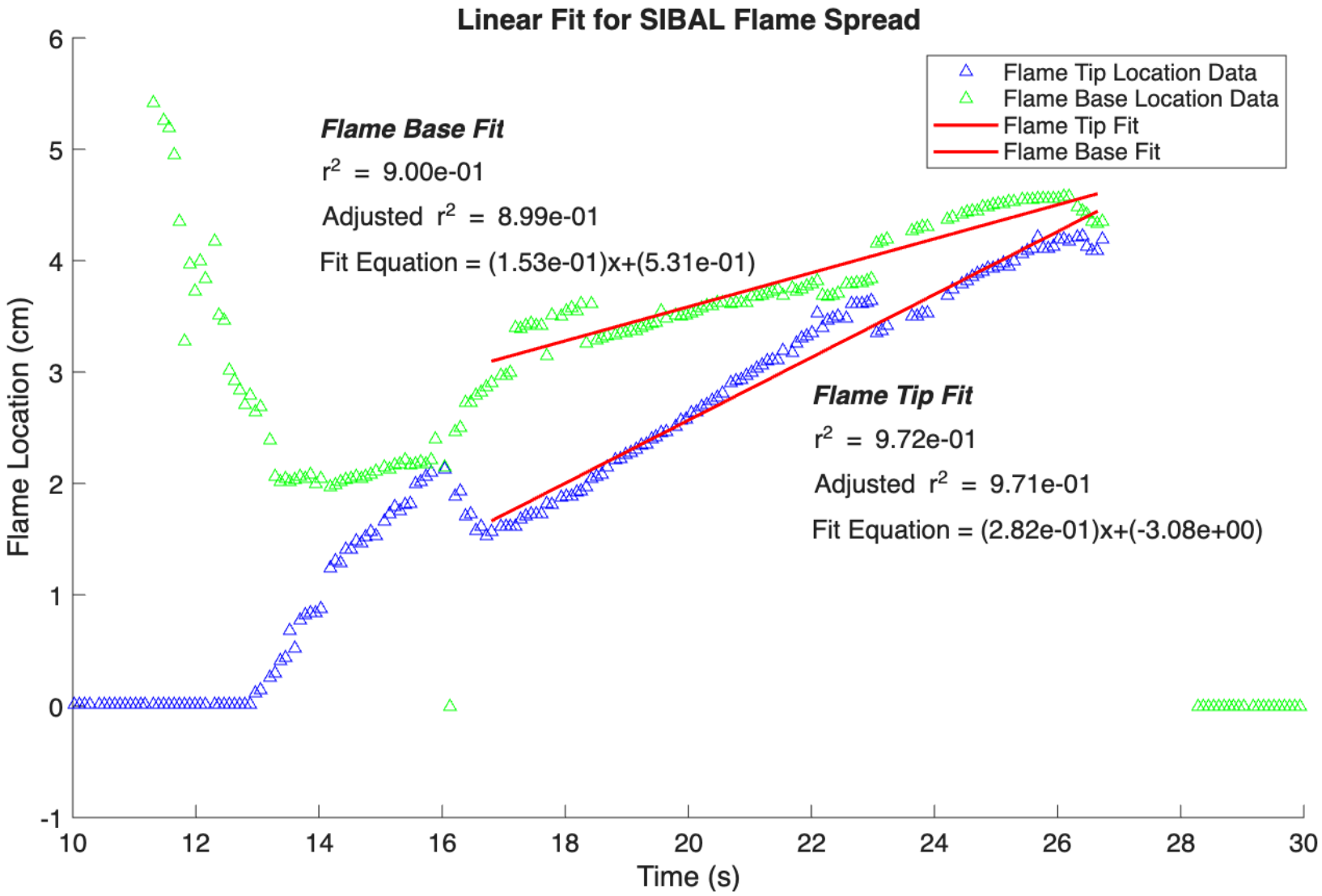
1-G Results: SIBAL fabric

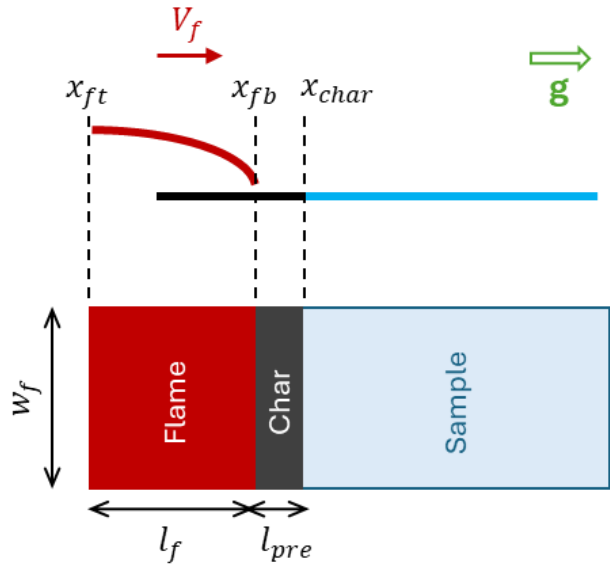




- Flame length is not completely constant; **flame shrinks** more than partial-g burn.
- Flame width decreases suddenly at ~24 seconds, and goes to 0 within 4 seconds.

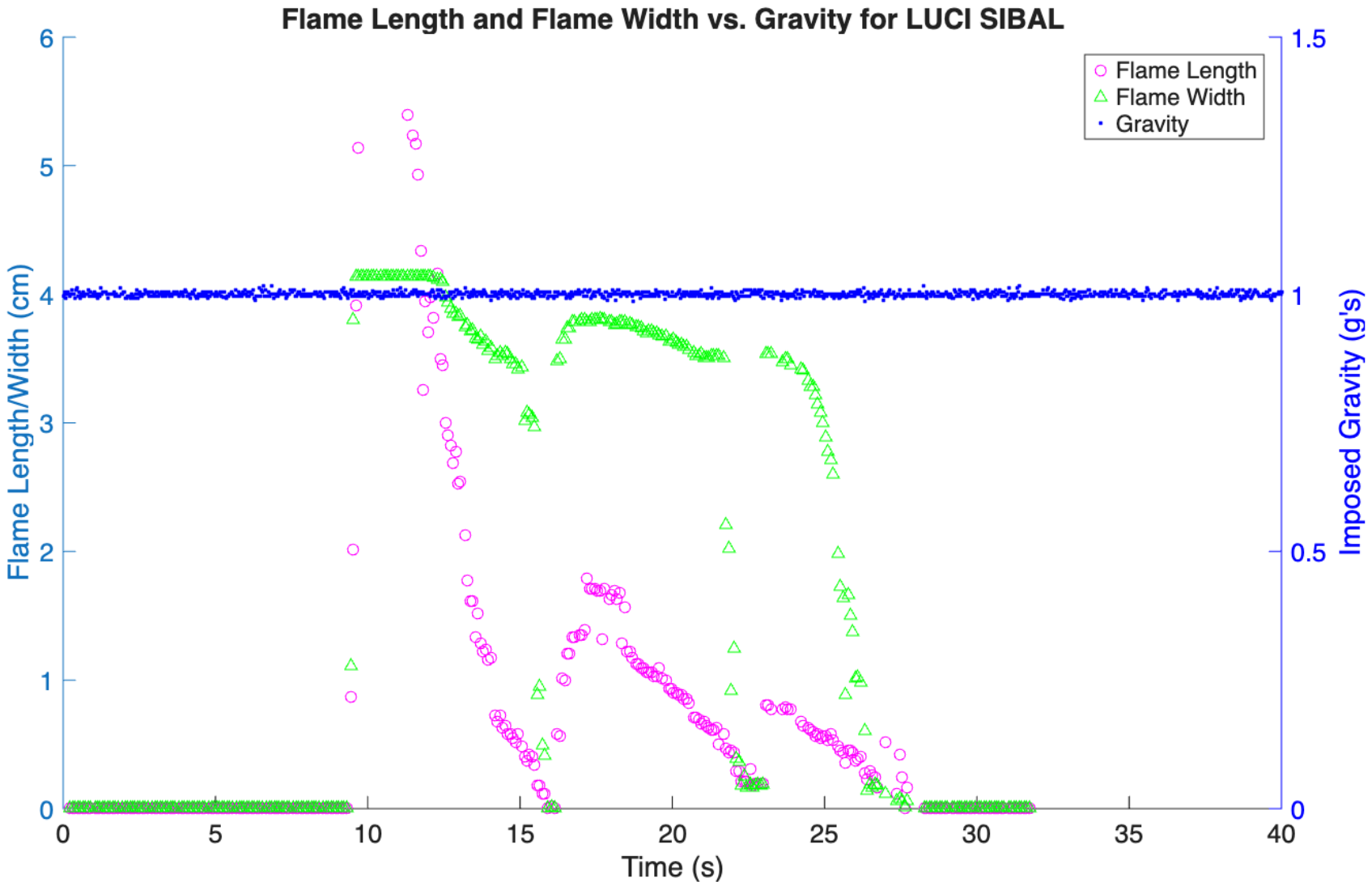
1-G Results: SIBAL fabric

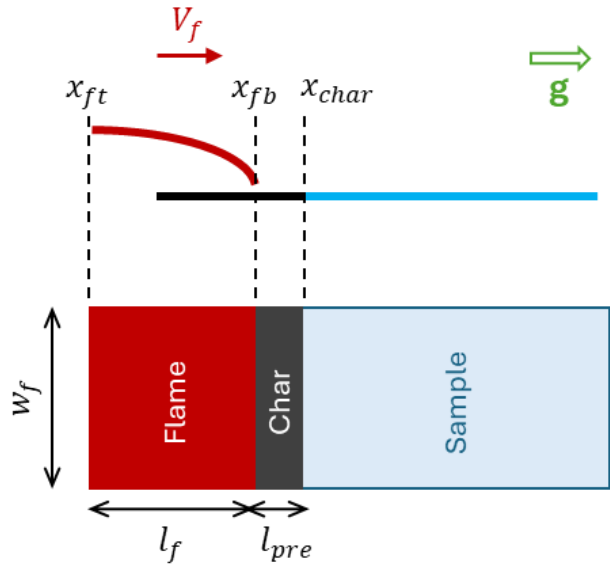




- Flame tip spread rate is ~double flame base spread rate.
- Small fluctuations in the tracking result in inexact fits for the spread data, therefore this is only an approximate relationship.

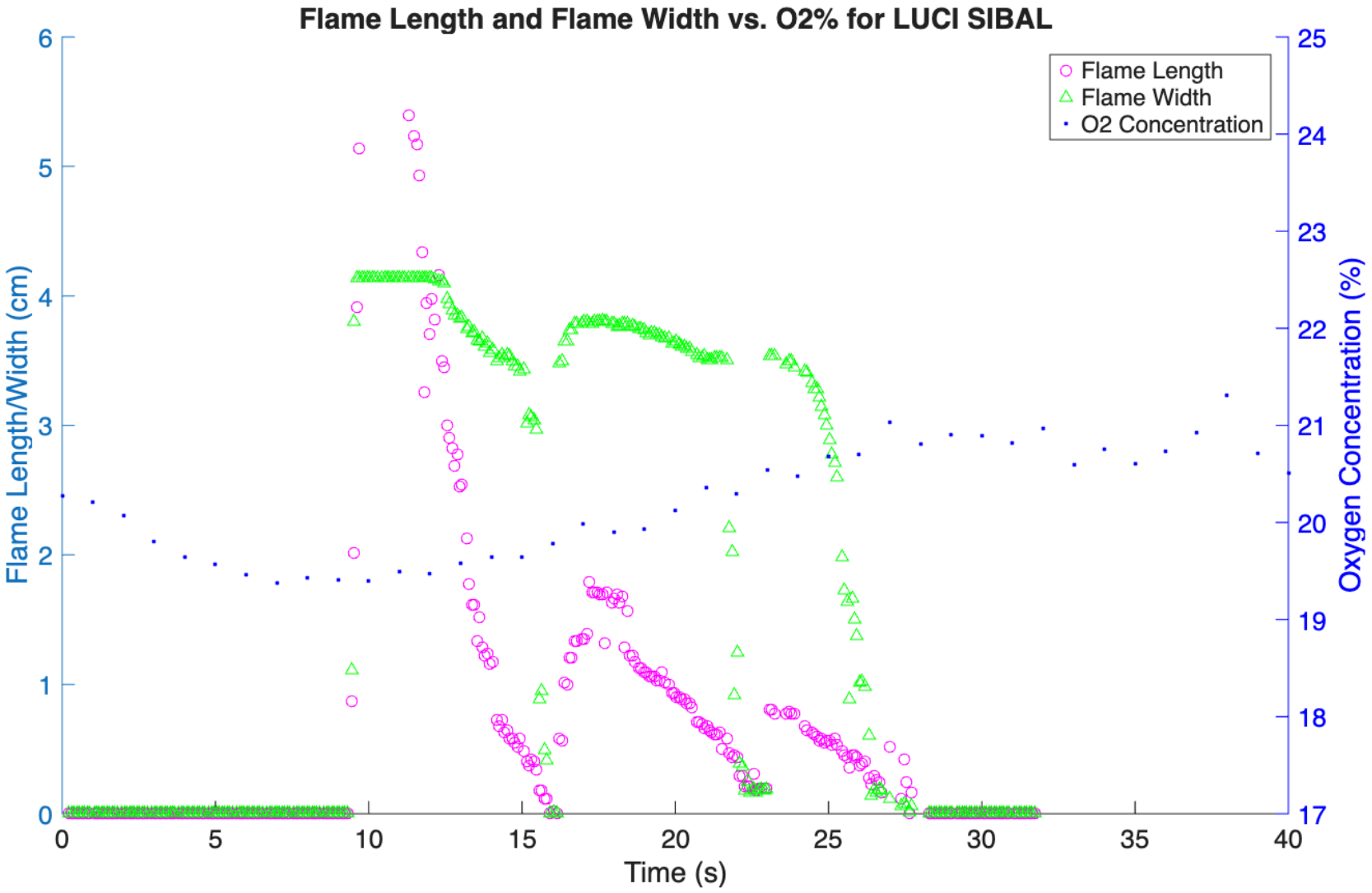
1-G Results: SIBAL

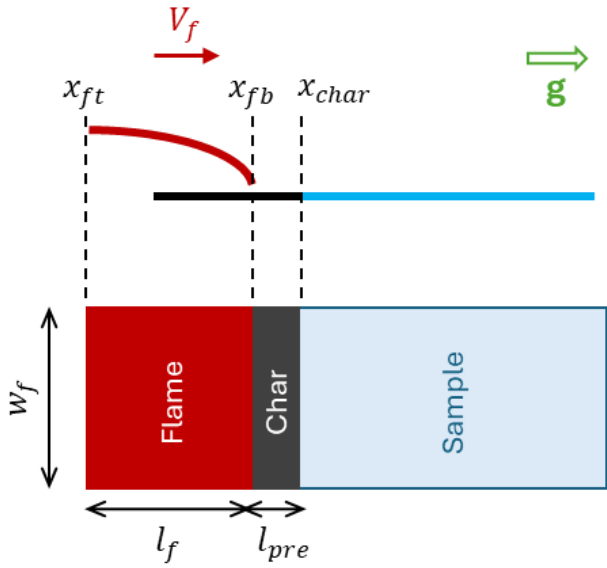




- Gravity (in g's) remains constant at Earth's gravity.

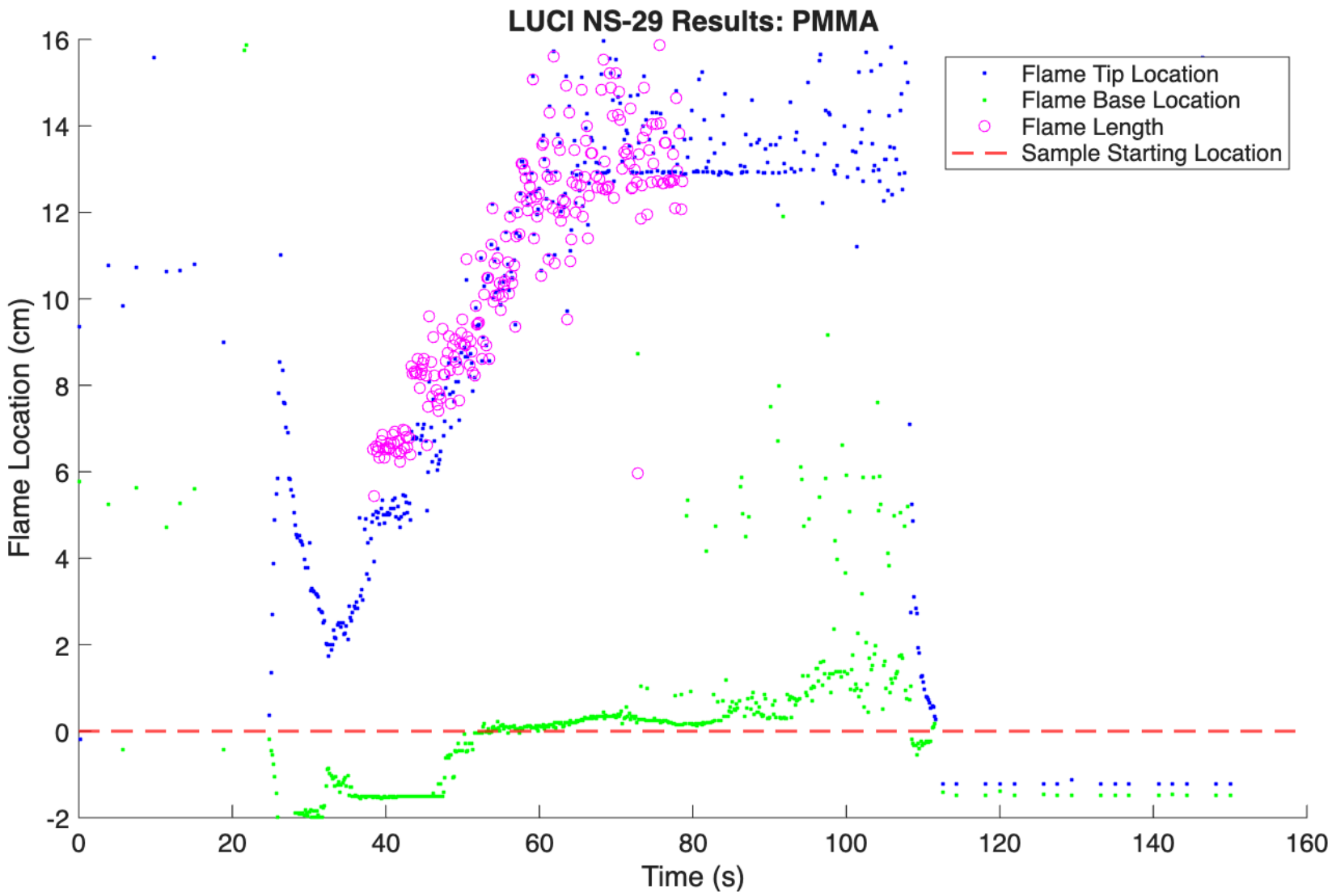
1-G Results: SIBAL

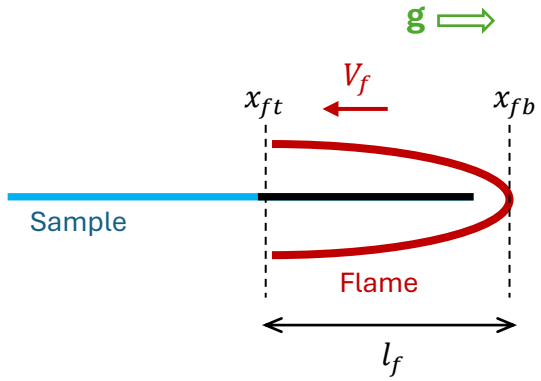




- O2% varies slightly but is roughly constant at 20%.

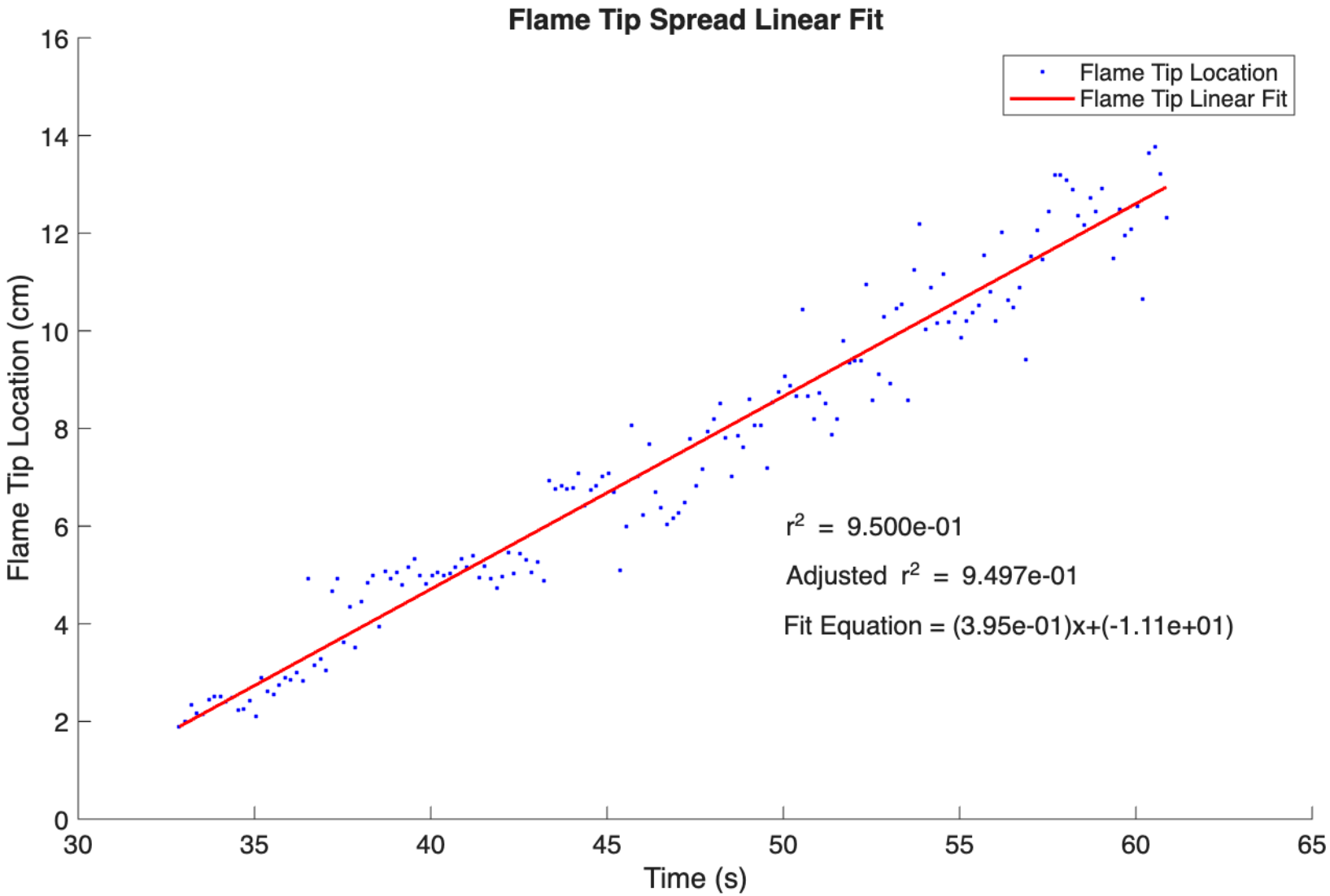
1-G Results: PMMA

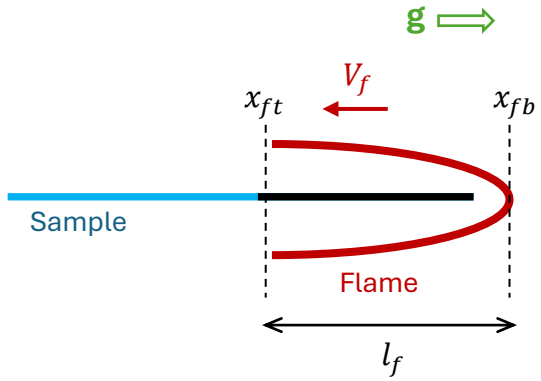




- Base was not accurately tracked towards the end of the experiment; from observation it remained at a ~constant location.
- Flame tip spread was ~linear until tip becomes obscured by sample holder.

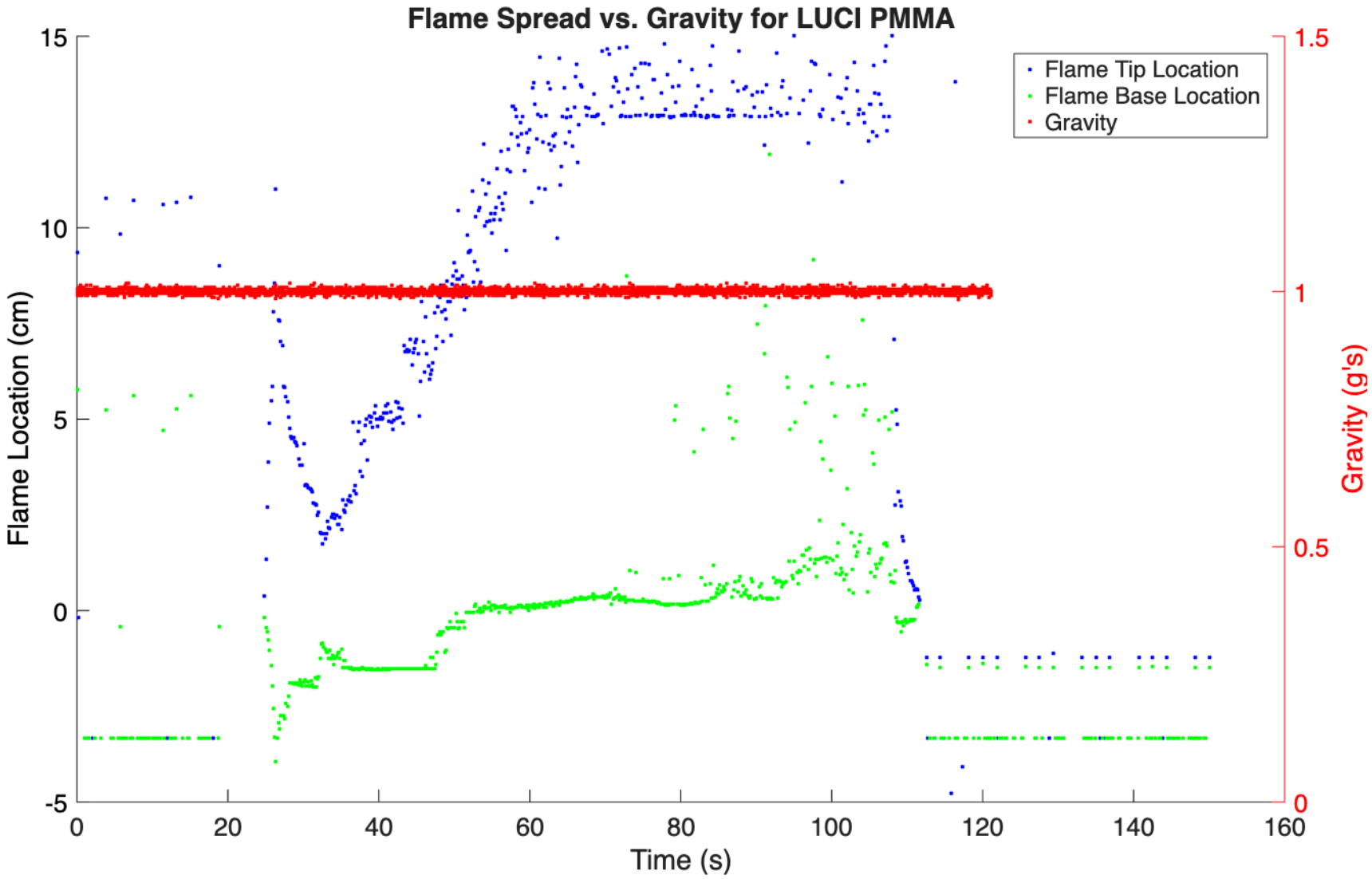
1-G Results: PMMA

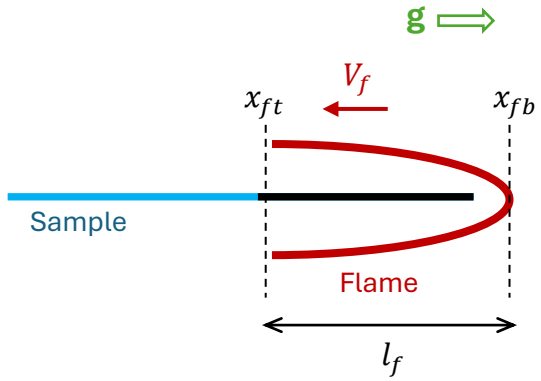




- Flame tip grows at a rate of ~ **3.95 mm/s** at the beginning of the burn.
- Flame base location is ~constant, so this can be approximated as flame growth rate (flame length).

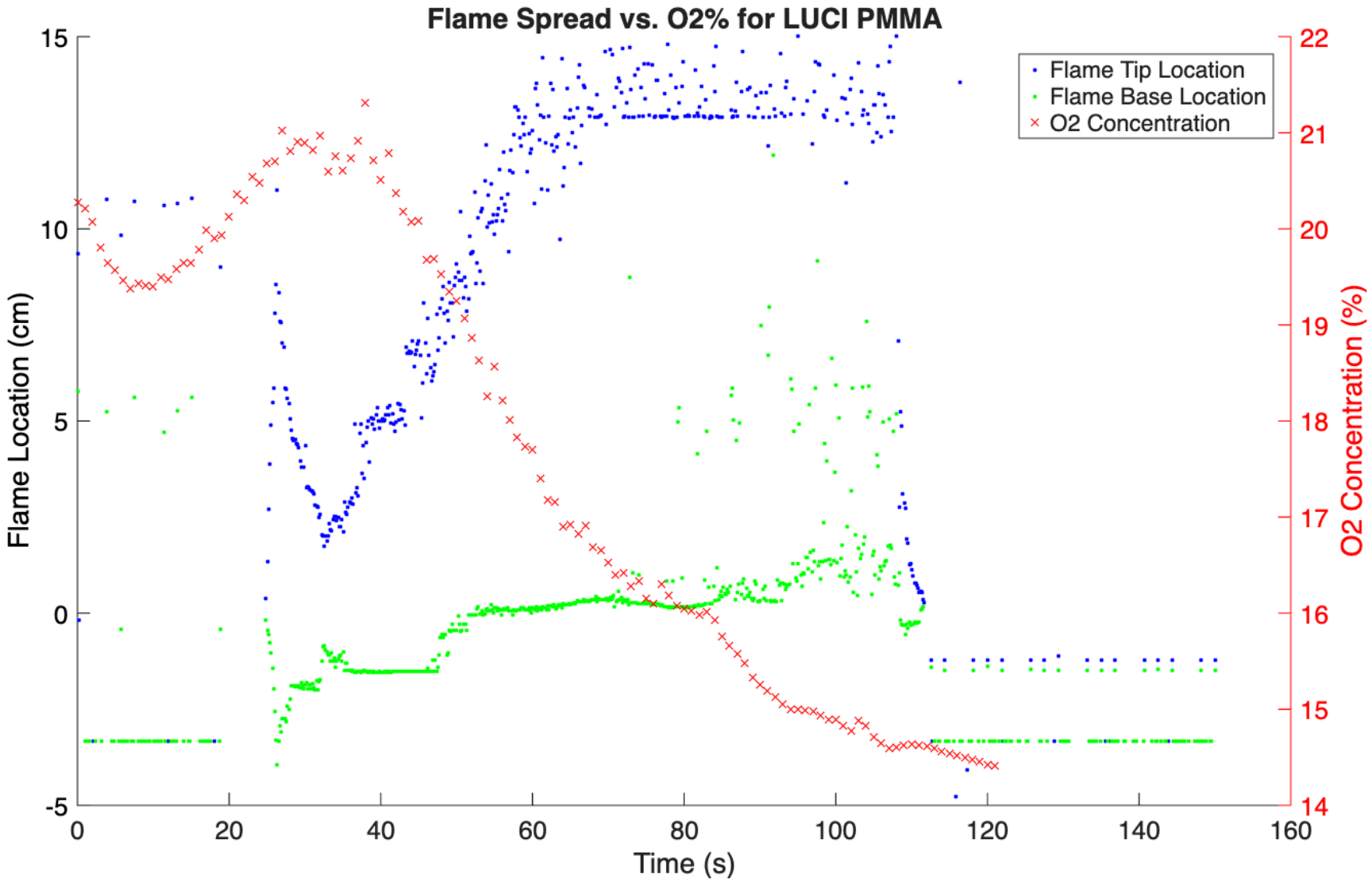
1-G Results: PMMA

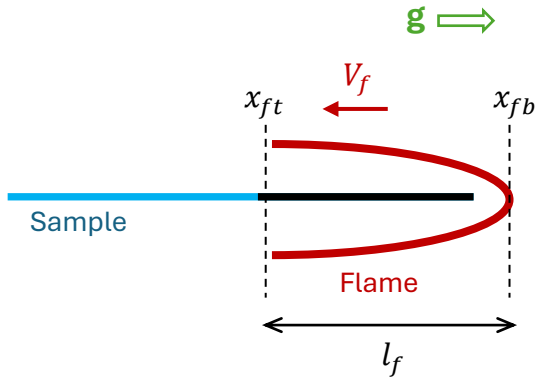




- Gravity remains constant at Earth's gravity for duration of burn.

Results: PMMA

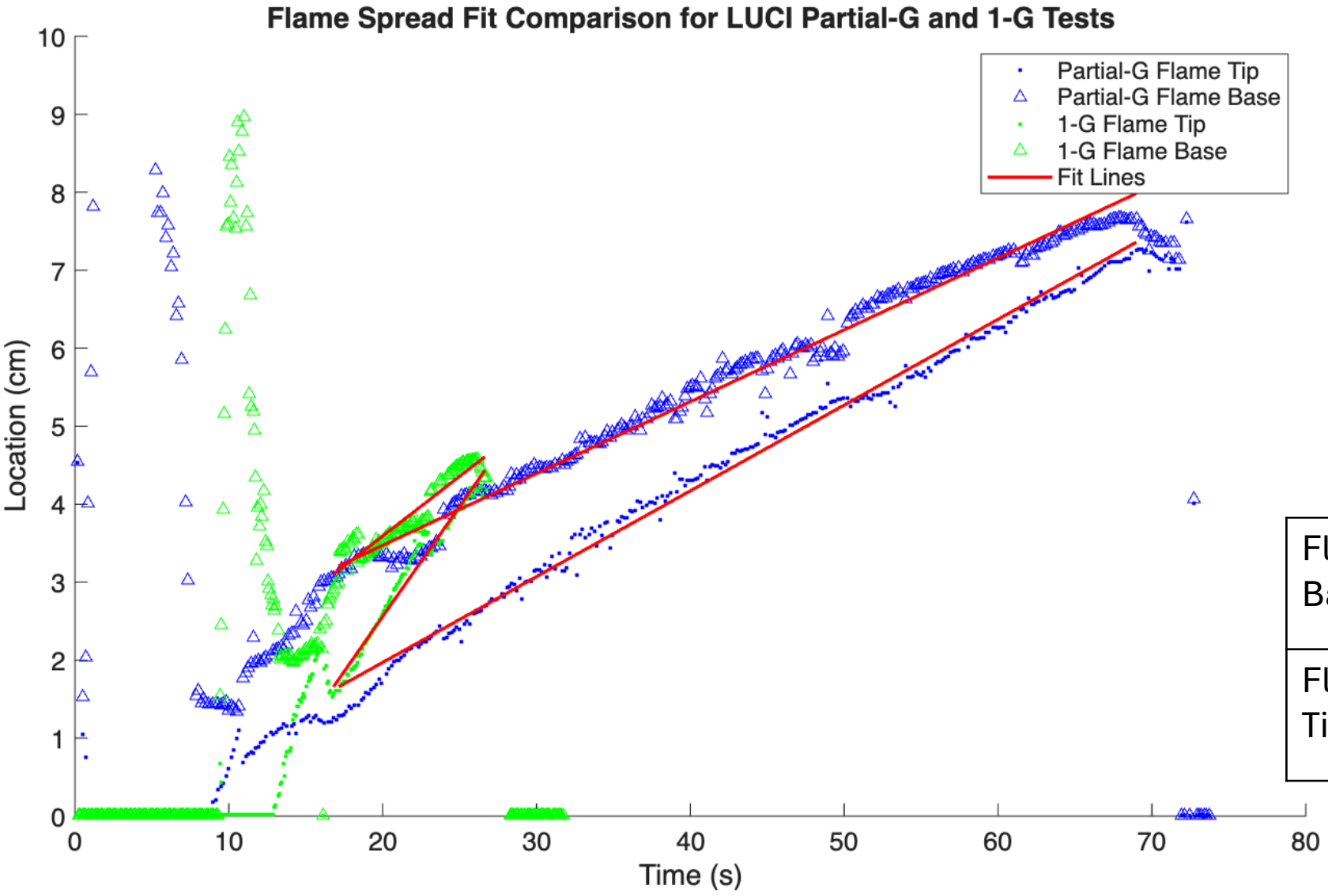


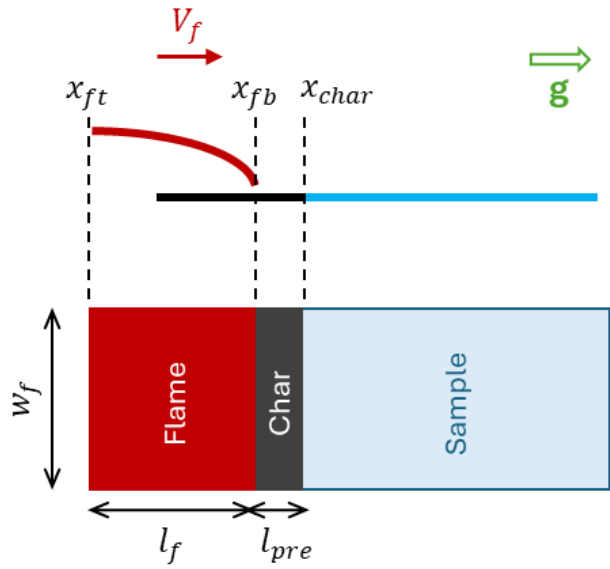


- O2% rises quickly in the beginning, then decreases ~linearly from 21% to 14.5%.

Combined Results: SIBAL

SIBAL Flame Spread Fit Comparison

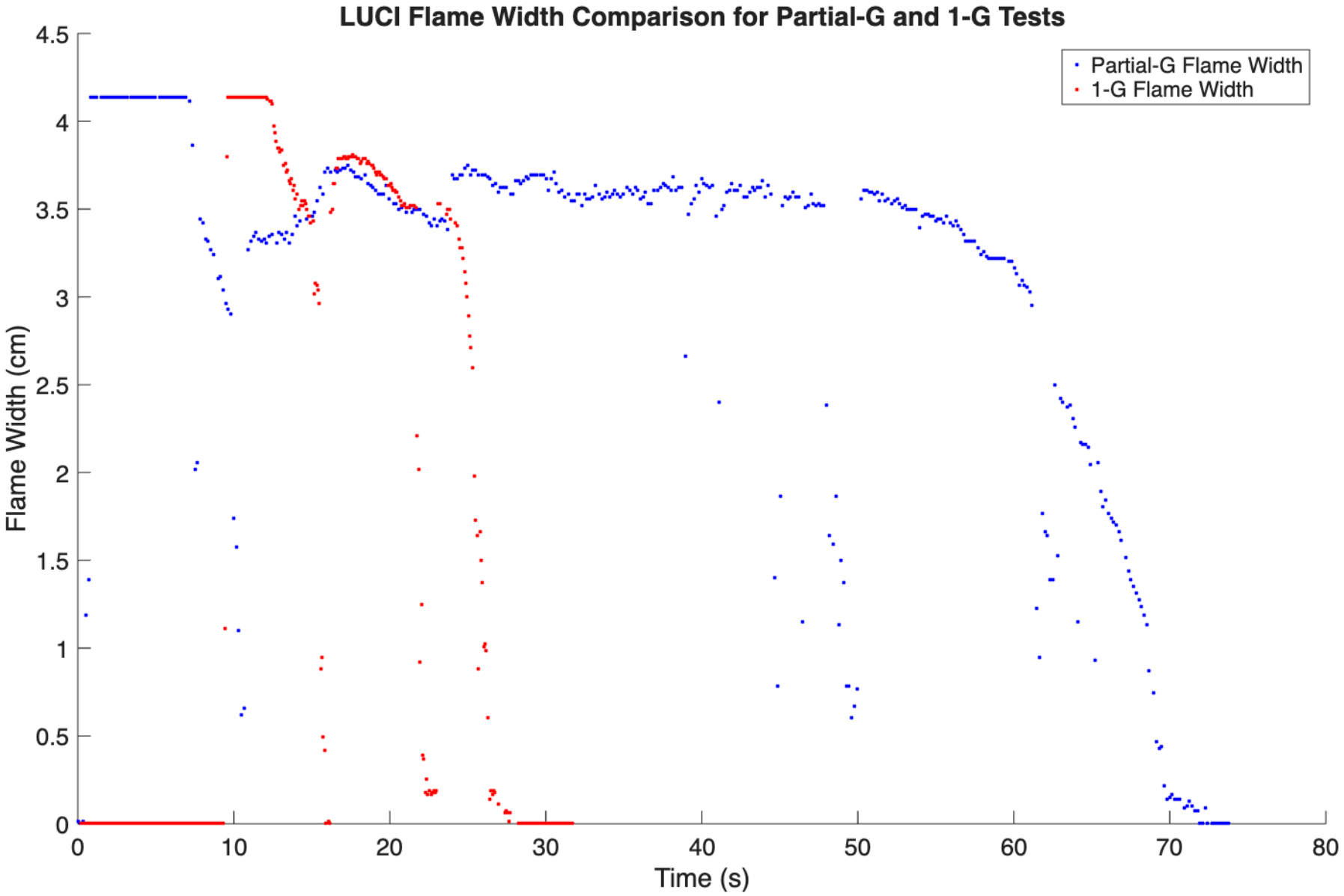


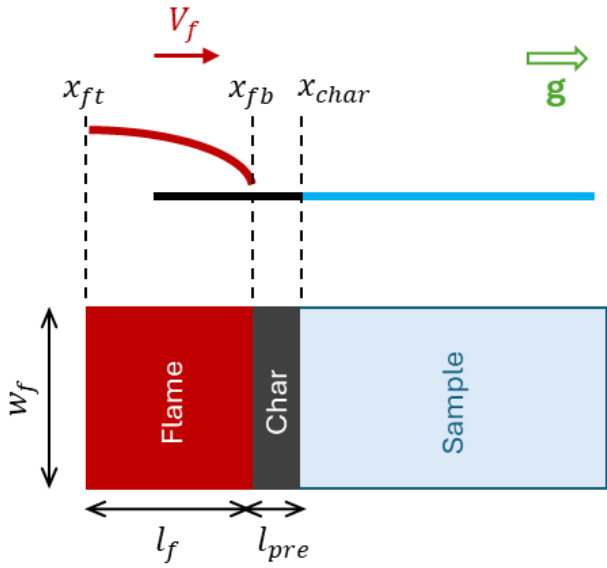


Flame Spread Rates (from linear fits):

	Partial-G (mm/s)	1-G (mm/s)	Ratio
Flame Base	.9	1.5	.6
Flame Tip	1.1	2.8	.39

SIBAL Flame Width Comparison

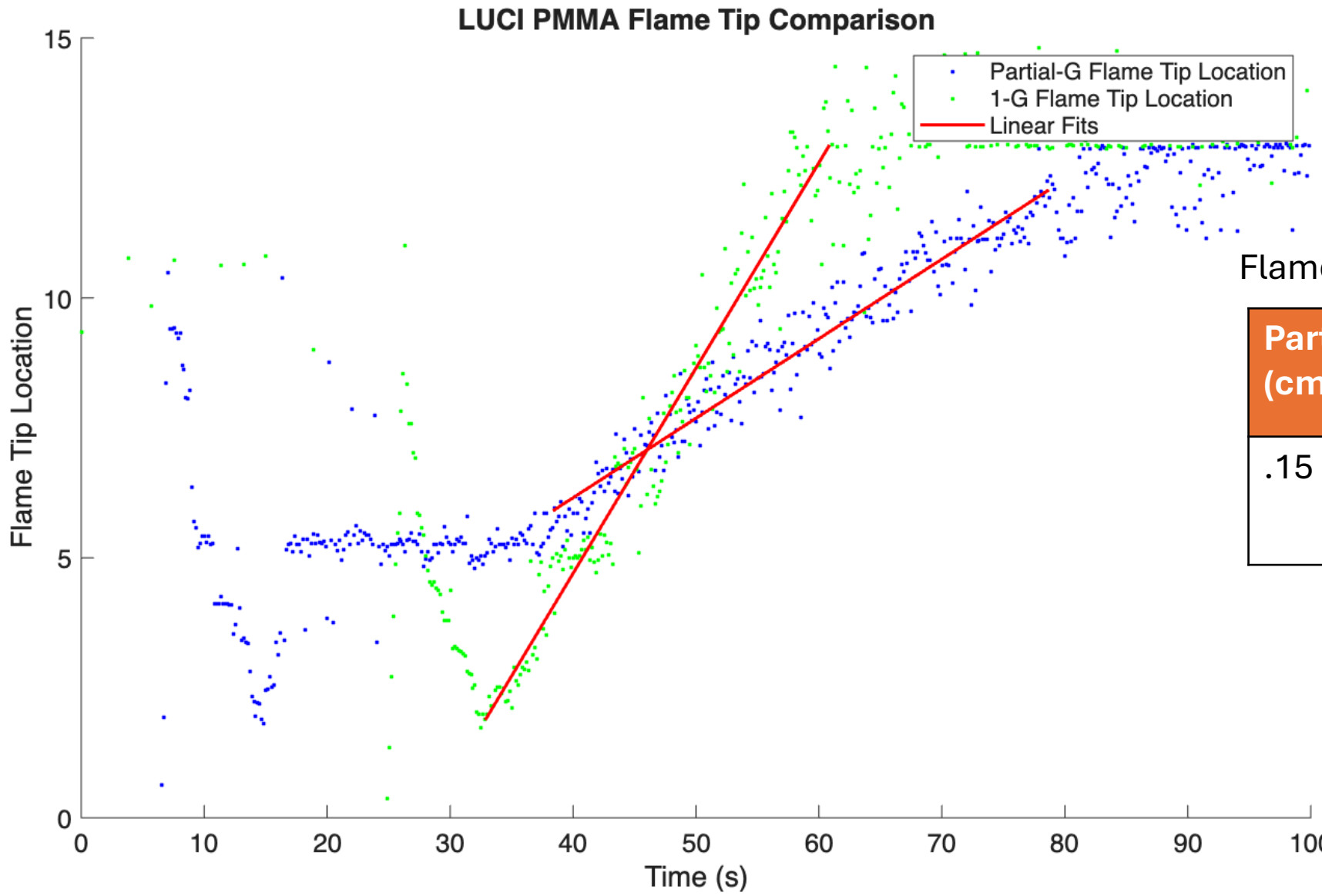


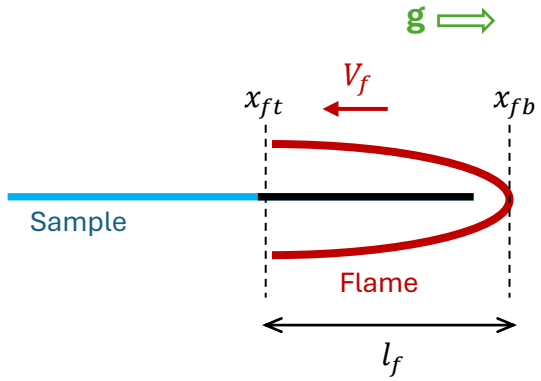


- Flame extinction for 1-g experiment occurs quicker (flame width decrease is steeper than partial-g).
- 1-g extinction happens ~ 45 seconds sooner than partial-g extinction

Combined Results: PMMA

PMMA Flame Tip Comparison





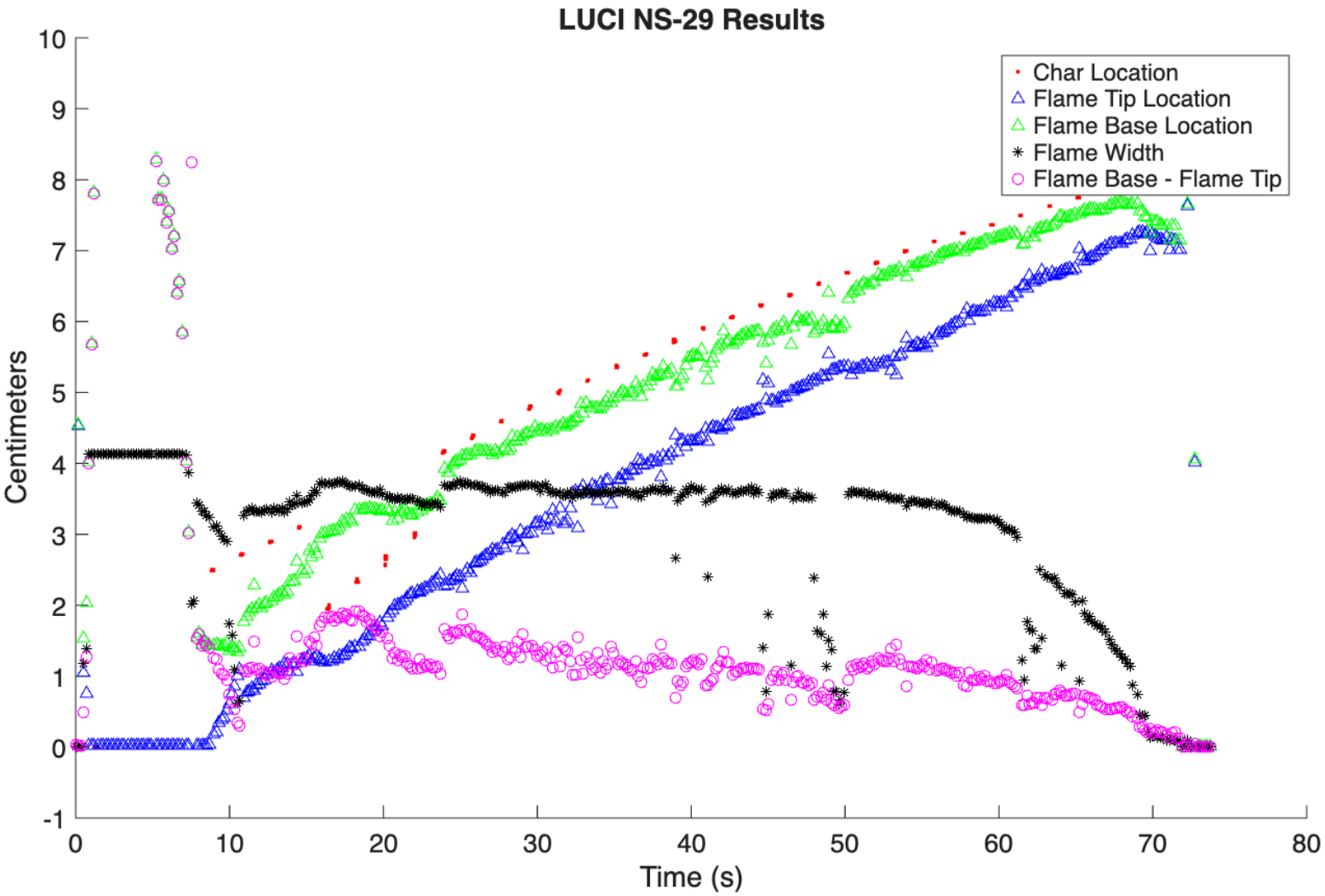
Flame Tip Spread (from linear fits):

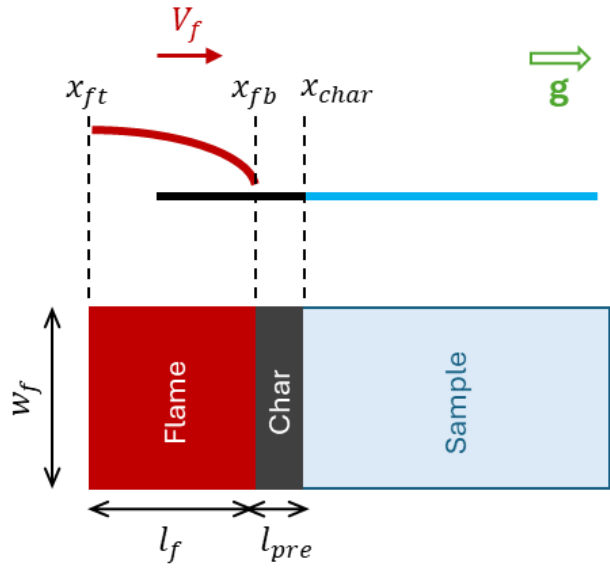
Partial-G (cm/s)	1-G (cm/s)	Ratio
.15	.40	.38

The LUCI project achieved the first-ever, extended duration combustion tests (greater than 25 seconds) in simulated Lunar gravity. The results are applicable to NASA's exploration efforts in that they guide the selection of fire-safe materials and environments and ensure safety of future spacecraft and Lunar habitats. The data also provides fundamental understanding of fires burning at reduced gravity for comparison to sophisticated numerical models. Finally, the experiment is a steppingstone to the ultimate goal of performing burn tests on the Lunar surface in the Flammability of Materials on the Moon (FM^2) experiment which will fly on a SpaceX Human Lander System unmanned test flight.

Backups

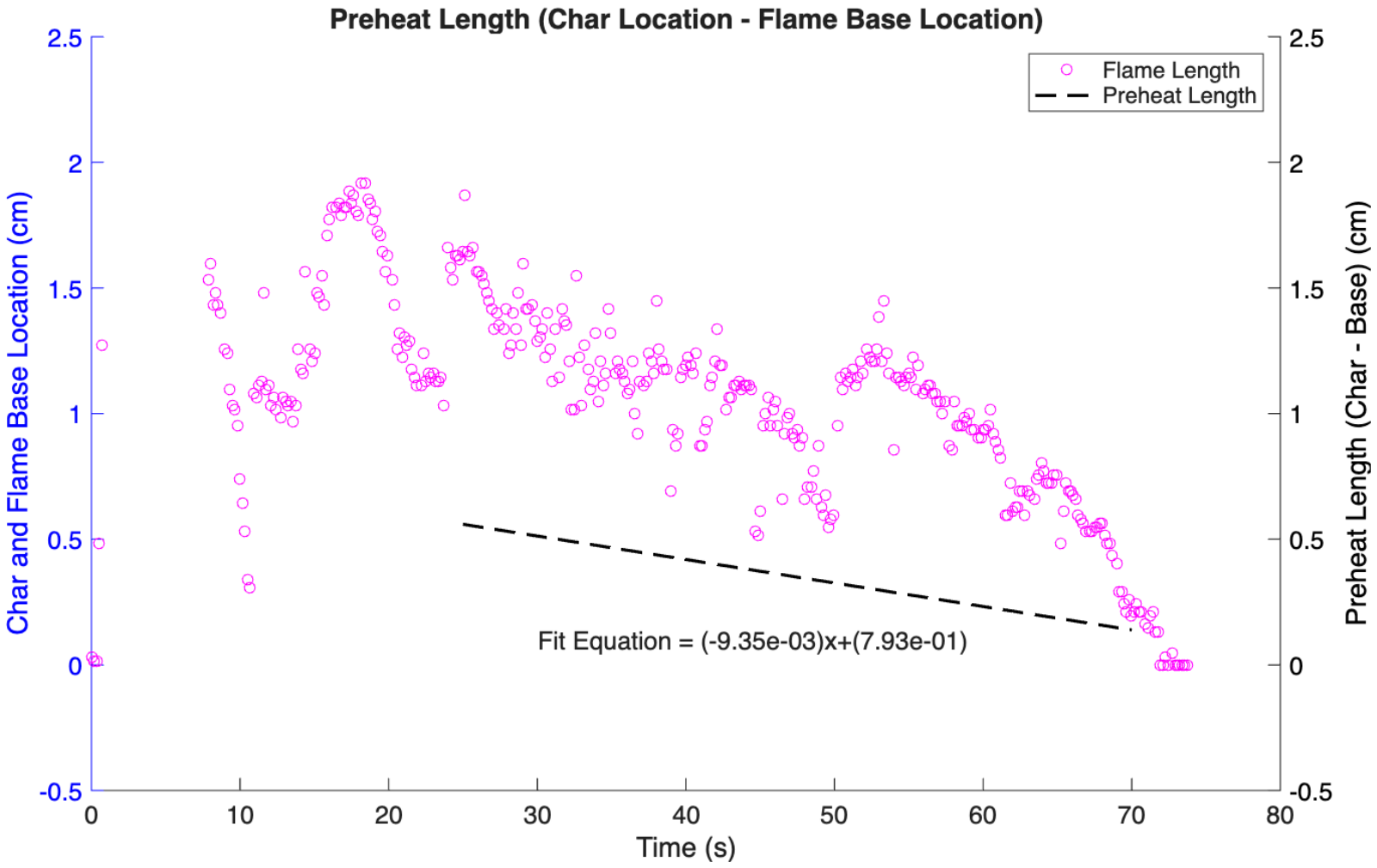
LUCI Partial-G Recap: SIBAL

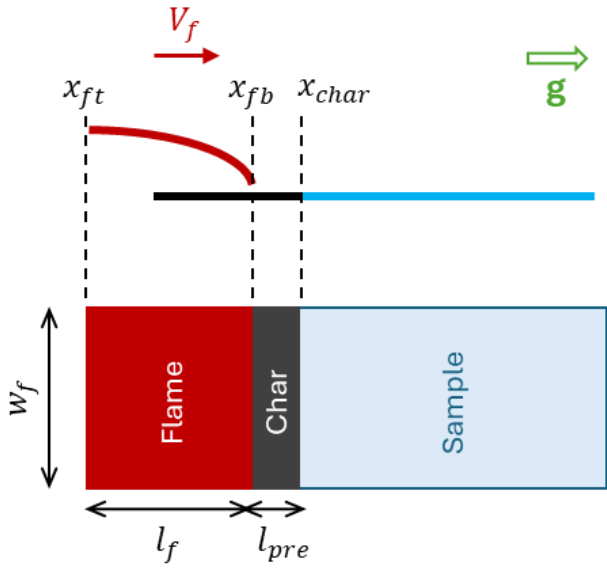




- ***Semi-steady spread*** is achieved, during which the ***constant flame width and length*** are observed (~3.2 cm and ~1.5 cm respectively).
- Flame length and width both decrease during ***extinction*** (final ~40 seconds).
- Char propagation and flame base propagation are ~parallel, indicating ***~constant preheat length.***

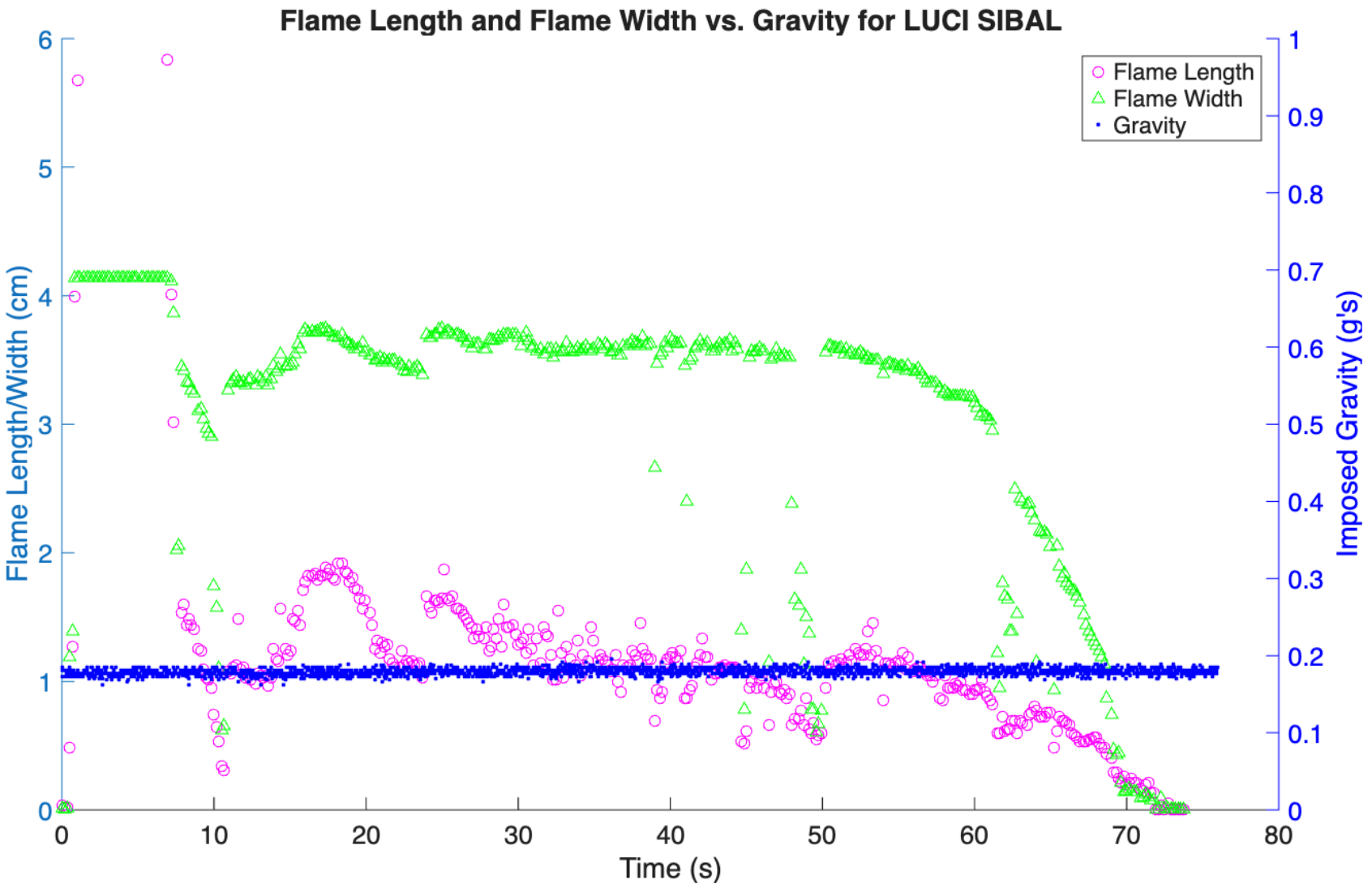
LUCI Partial-G Recap: SIBAL

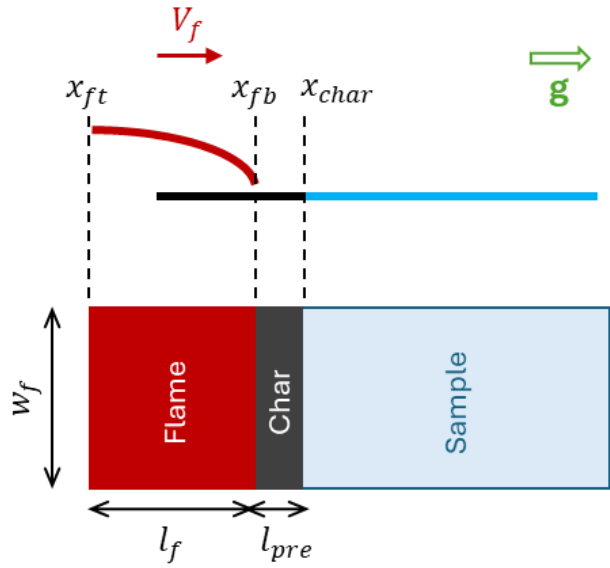




- ***Preheat Length:*** difference between ***flame base*** and ***char front*** fit equations.
- Both ***flame length*** and ***preheat length decrease*** very slowly over time (~ 1.25 cm and ~0.4 cm total respectively).
- ***Preheat length shrink rate*** = -0.094 mm/s.

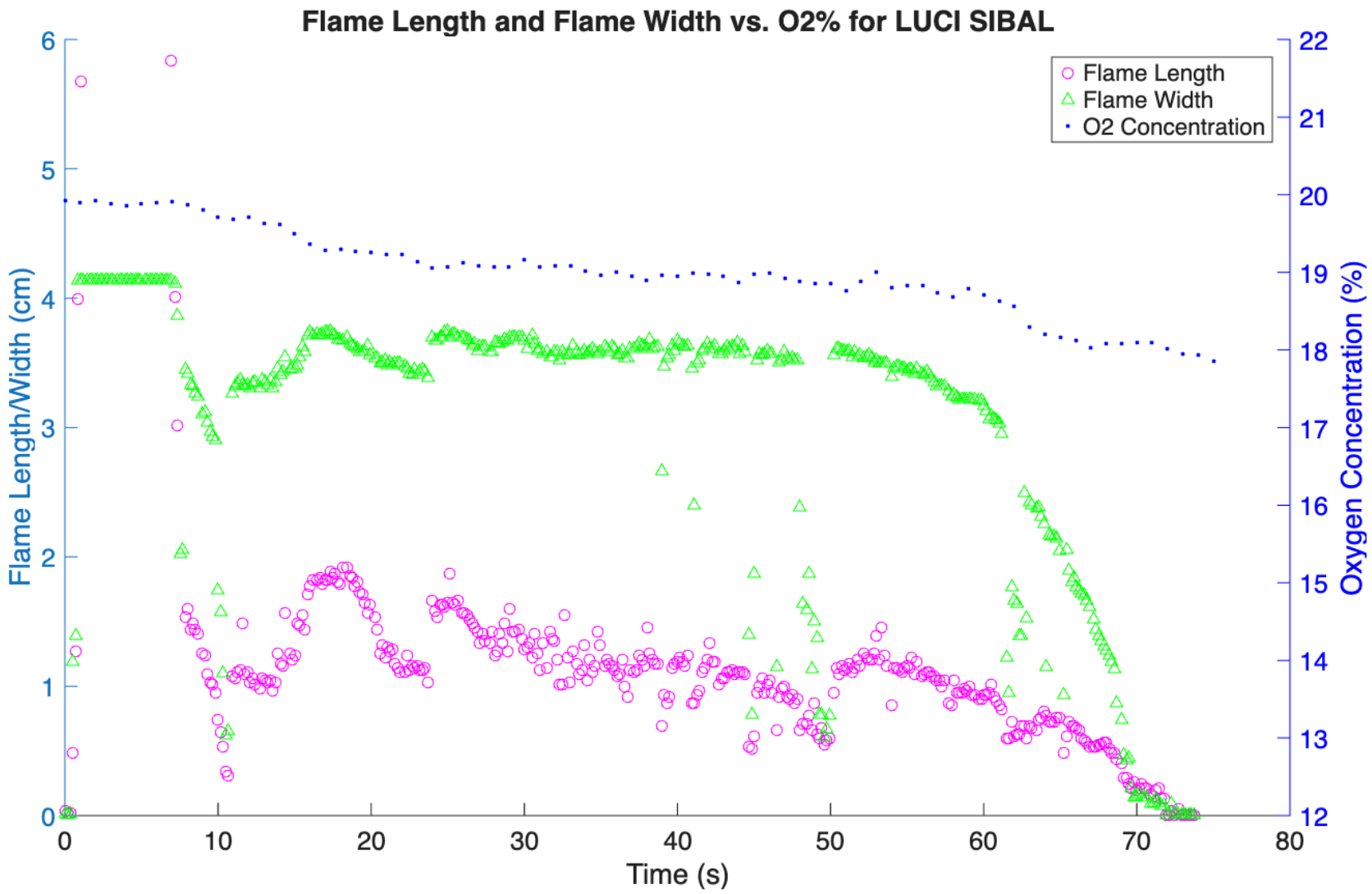
LUCI Partial-G Recap: SIBAL

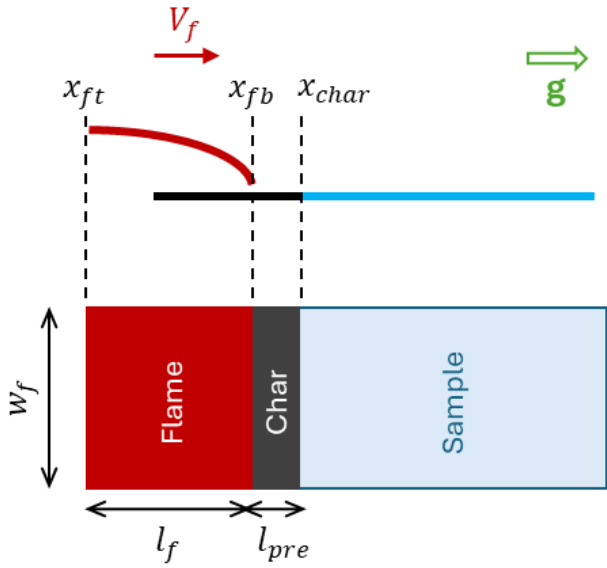




- Gravity (in g's) remains constant at lunar gravity.
- Flame extinction must be caused by other factors.

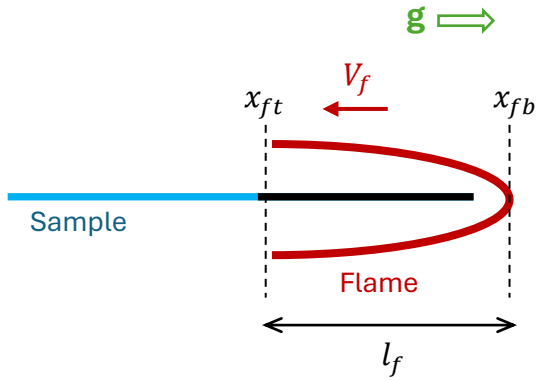
LUCI: SIBAL fabric

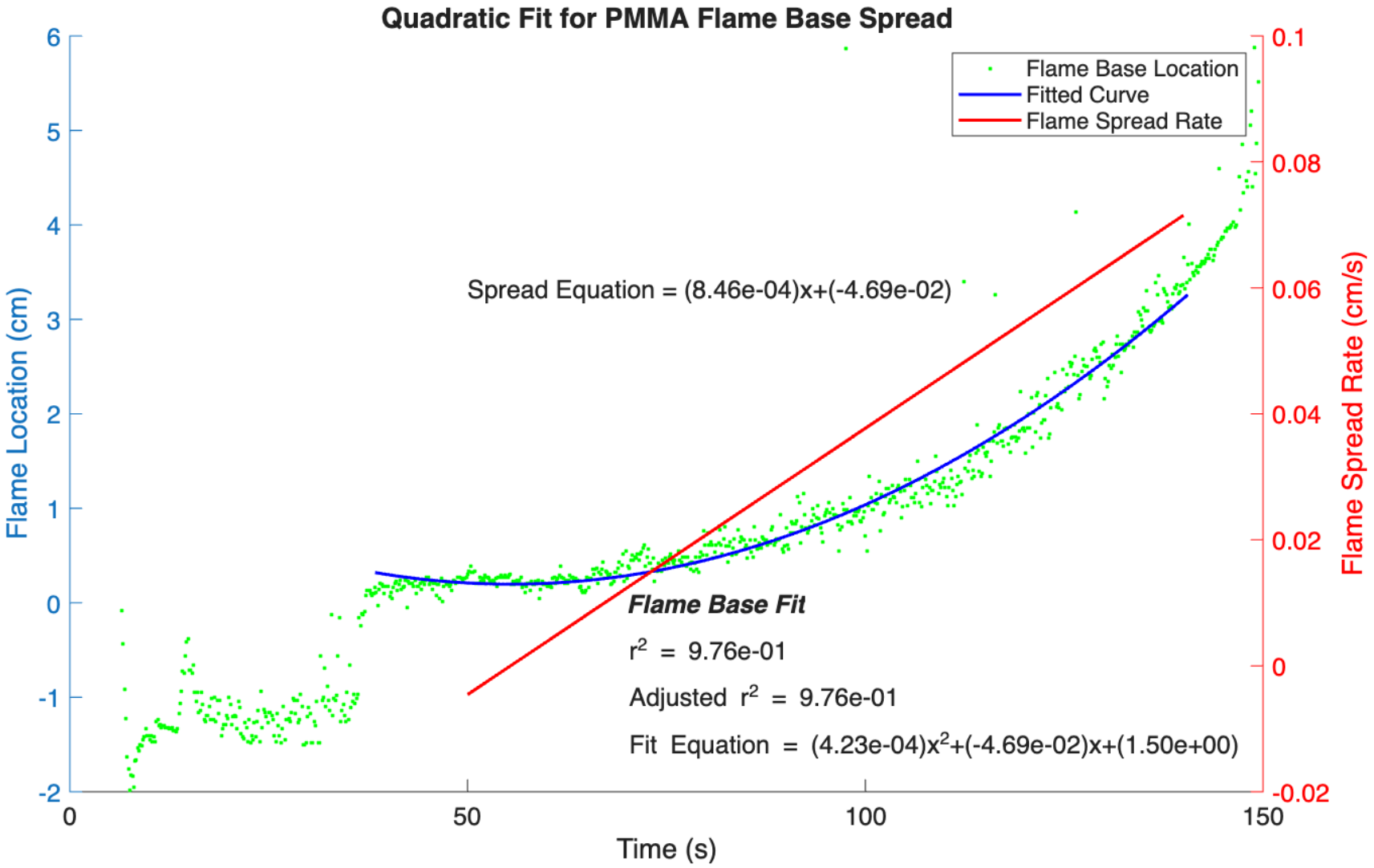




- O2 concentration ***decreases*** from ~20% to ~18%.
- O2% decreases at a roughly constant rate over the entire experiment.

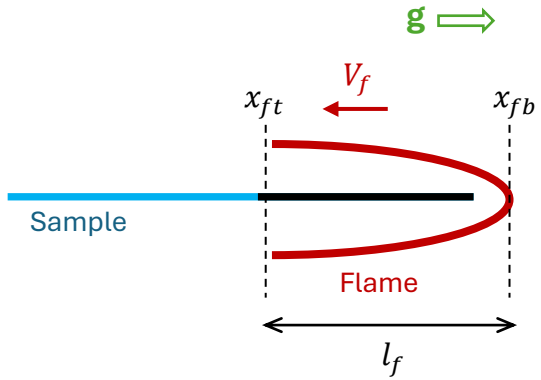
LUCI: PMMA

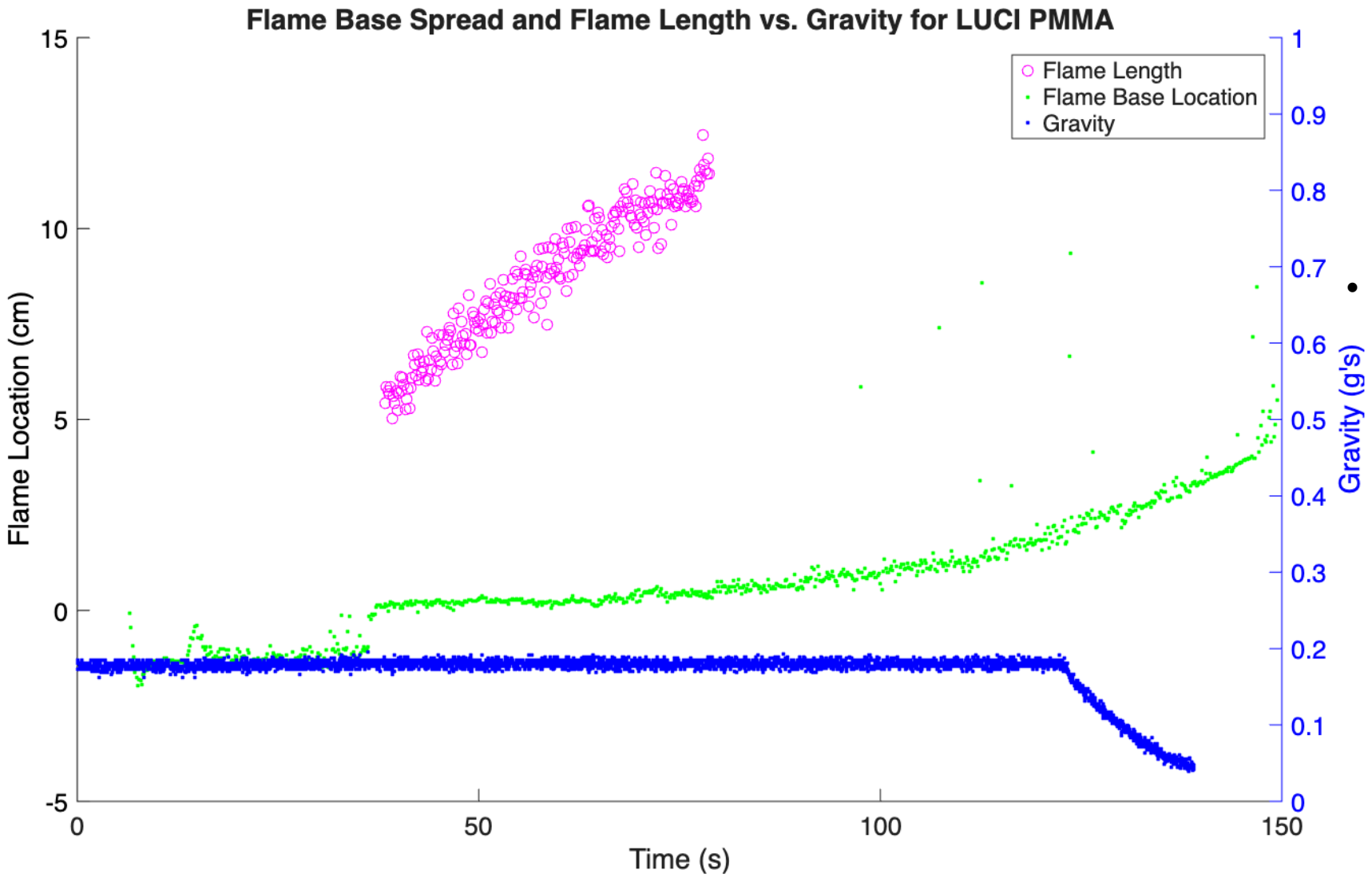




- Flame base spread is ***approximately quadratic.***
- ***Instantaneous spread rate*** (red line) is plotted derivative of fit equation (linear relation).
- ***Flame spread rate*** increases linearly from 0 to ~.6 mm/s (before gravity starts dropping at t = 125s)

LUCI: PMMA





- Gravity remains ~constant for duration of the burn.