Centrifuge in Free Fall:
Combustion at Partial Gravity

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“In this symposium we want to explore ‘anything but micro-gravity’.

What can the use of simulated or real partial gravity and hypergravity contribute to our understanding of microgravity?

Also, since the last years attention towards partial gravity is increasing since space faring entities are focusing more and more for exploration missions to the Moon and Mars.”

Combustion at Different Gravity Levels

G-level (g/gE)

10^{4}

10^{3}

10^{2}

10^{1}

10^{0}

10^{-1}

10^{-2}

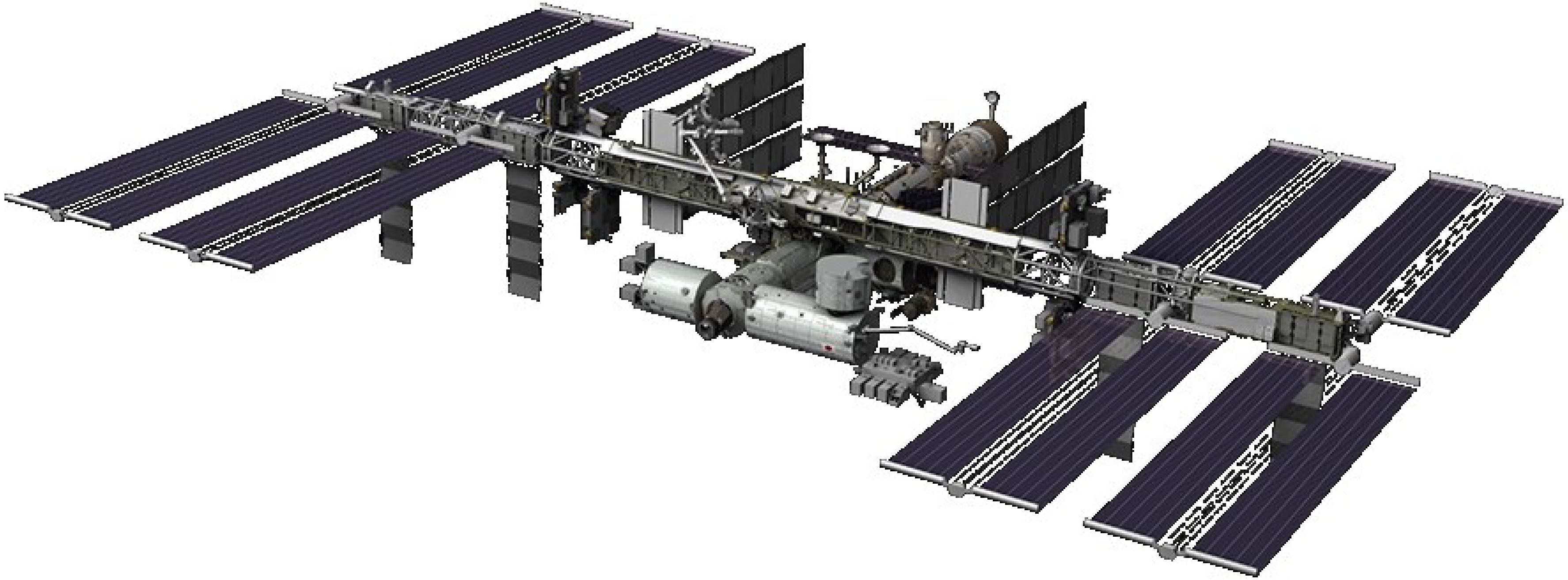
10^{-3}

10^{-4}

10^{-5}

10^{-6}

10^{-7}



Orbiting spacecraft in free drift

Combustion at Different Gravity Levels

G-level (g/gE)

10^{4}

10^{3}

10^{2}

10^{1}

10^{0}

10^{-1}

10^{-2}

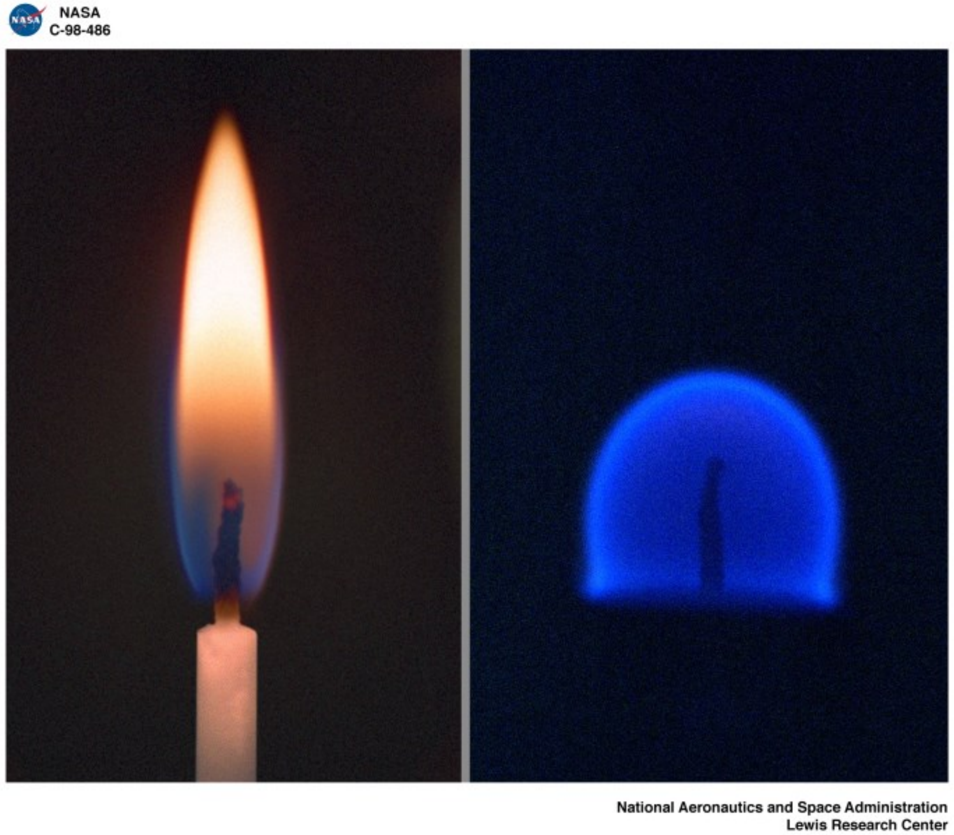
10^{-3}

10^{-4}

10^{-5}

10^{-6} → Drop towers; “normal-scale” flames essentially unaffected by this g-level

10^{-7}



Combustion at Different Gravity Levels

G-level (g/gE)

10^{4}

10^{3}

10^{2}

10^{1}

10^{0}

10^{-1}

10^{-2}

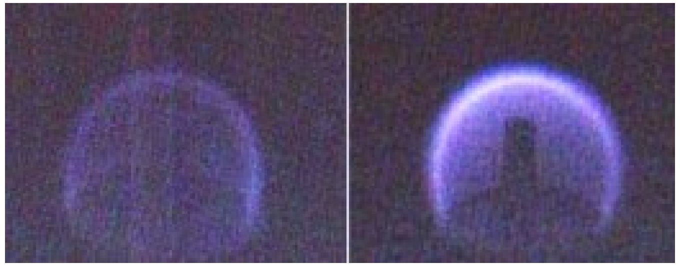
10^{-3}

10^{-4}

10^{-5}

10^{-6}

10^{-7}



Effects of buoyancy on laboratory-scale flames begin to be seen (function of flame size)

Combustion at Different Gravity Levels

G-level (g/gE)

10^{4}

10^{3}

10^{2}

10^{1}

10^{0}

10^{-1}

10^{-2}

10^{-3}

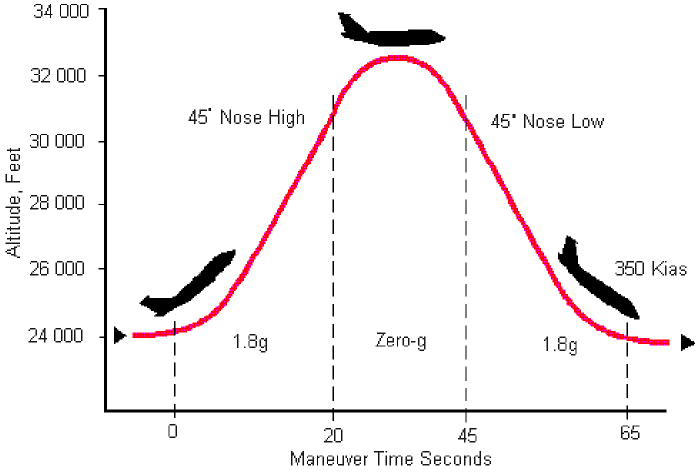
10^{-4}

10^{-5}

10^{-6}

10^{-7}

Parabolic-trajectory aircraft



Combustion at Different Gravity Levels

G-level (g/gE)

10^{4}

10^{3}

10^{2}

10^{1}

10^{0} → Earth

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

10^{-6}

10^{-7}

Combustion at Different Gravity Levels

G-level (g/gE)

10^{4}

10^{3}

10^{2}

10^{1}

10^{0}

10^{-1}

10^{-2}

10^{-3}

10^{-4}

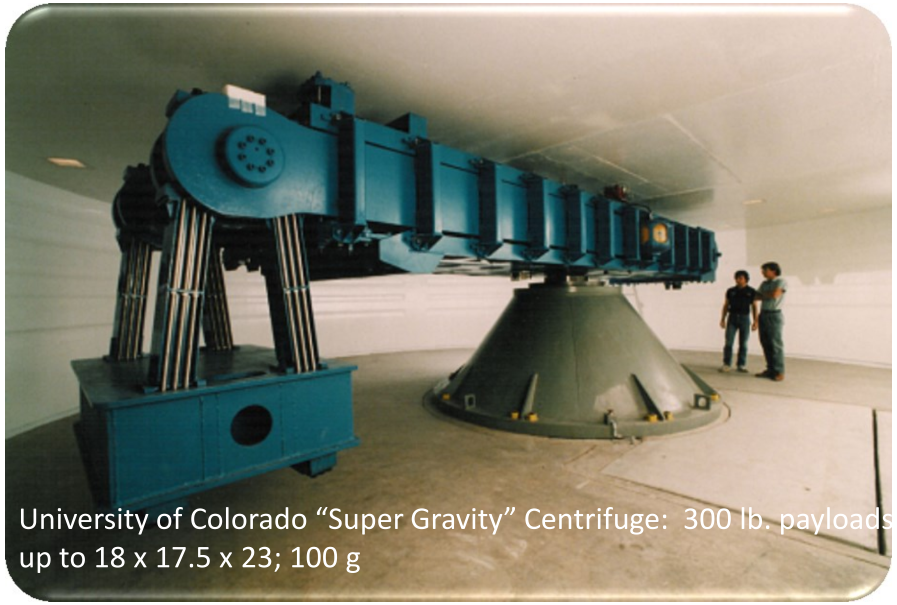
10^{-5}

10^{-6}

10^{-7}

Gas-phase diffusion flames unable to be supported

Flame may intensify compared to Earth-g but “flammability” may be reduced; system size is limited



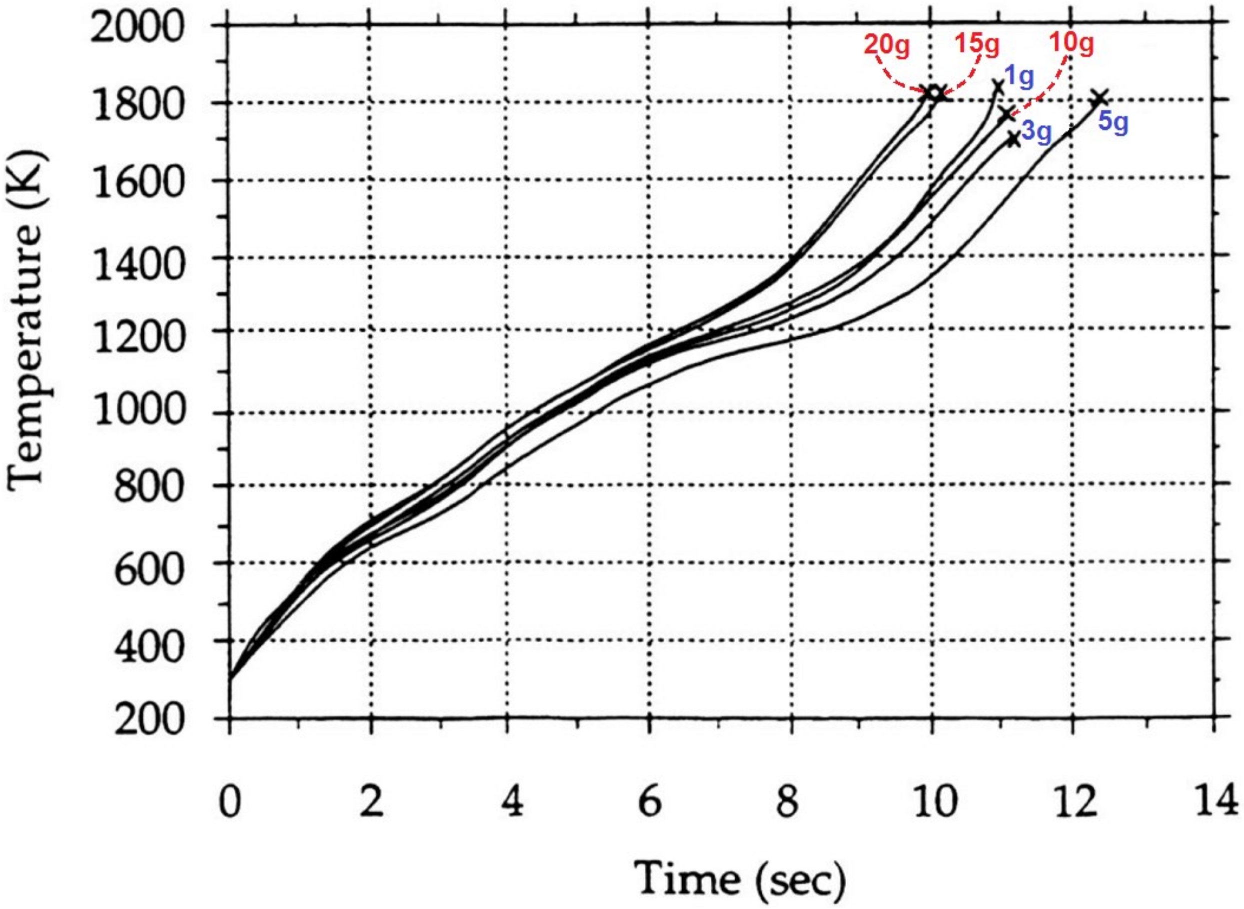
University of Colorado “Super Gravity” Centrifuge: 300 lb. payloads up to 18 x 17.5 x 23; 100 g

Combustion of Bulk Metals at Elevated Gravity

Initially, increasing g leads to more heat loss and thus slower temperature rise.

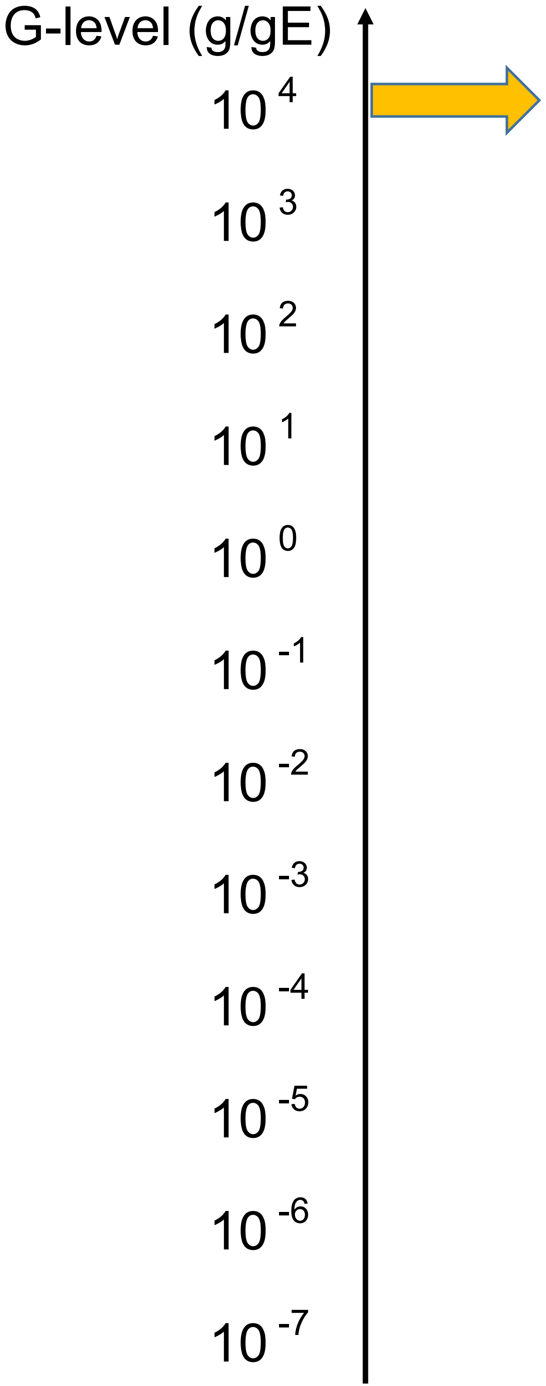
Eventually further increase in g cause increase in temperature, attributed to enhanced reaction rate due to improved convective transport of oxygen which overcomes the heat loss.

Angel Abbud-Madrid, Melvyn C. Branch, and John W. Daily, NASA Lewis Research Center, The 3rd Int'l Microgravity Combustion Workshop (1995).



Temperature vs. time behavior of bulk titanium samples subject to different gravity loads.

Combustion at Different Gravity Levels



Useful for some combustion synthesis

Highly exothermic; both ceramic and metallic products are melted

Centrifuge accelerates the phase separation and removal of gas bubbles

Up to 10,000 g/g_E

System size very limited

Combustion at Different Gravity Levels

G-level (g/gE)

10^{4} Useful for some combustion synthesis

10^{3}

10^{2}

Gas-phase diffusion flames unable to be supported

10^{1} Flame may intensify compared to Earth-g but “flammability” may be reduced

10^{0} Earth

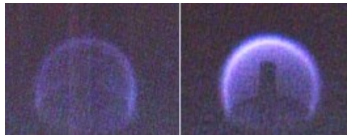
10^{-1}

10^{-2} Parabolic-trajectory aircraft

10^{-3}

10^{-4}

Effects of buoyancy on laboratory-scale flames begin to be seen



10^{-5}

10^{-6} Drop towers; “normal-scale” flames essentially unaffected by this g-level

10^{-7} Orbiting spacecraft in free drift

How are Diffusion Flames Affected by Gravity?

Buoyancy transports oxygen to the flame as hot gases rise, and fresh air is drawn in

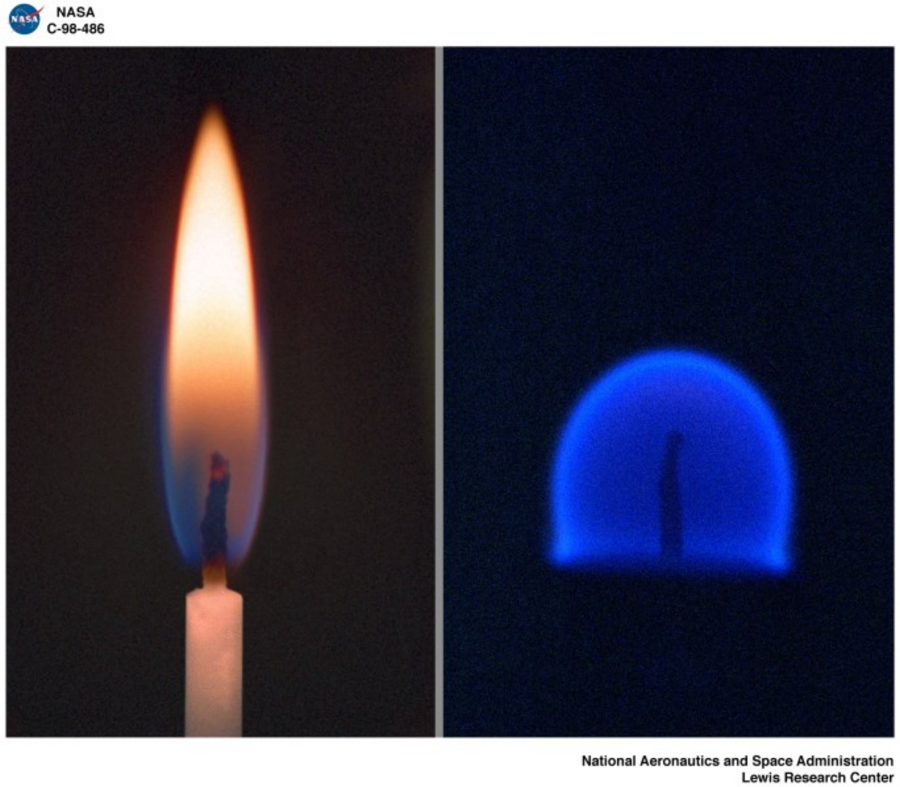
Gasified fuel and oxygen mix and react if the concentration is right and the temperature is high enough

Early studies sought to understand how flames respond in microgravity

Flames extinguish because of the lack of oxygen at zero convective flow

- Exceptions:
    1. Thin fuels: flame spreads into a region where there is enough oxygen
    2. Small spherically-symmetric flame (droplet of fuel or a candle) can be sustained simply by mass diffusion

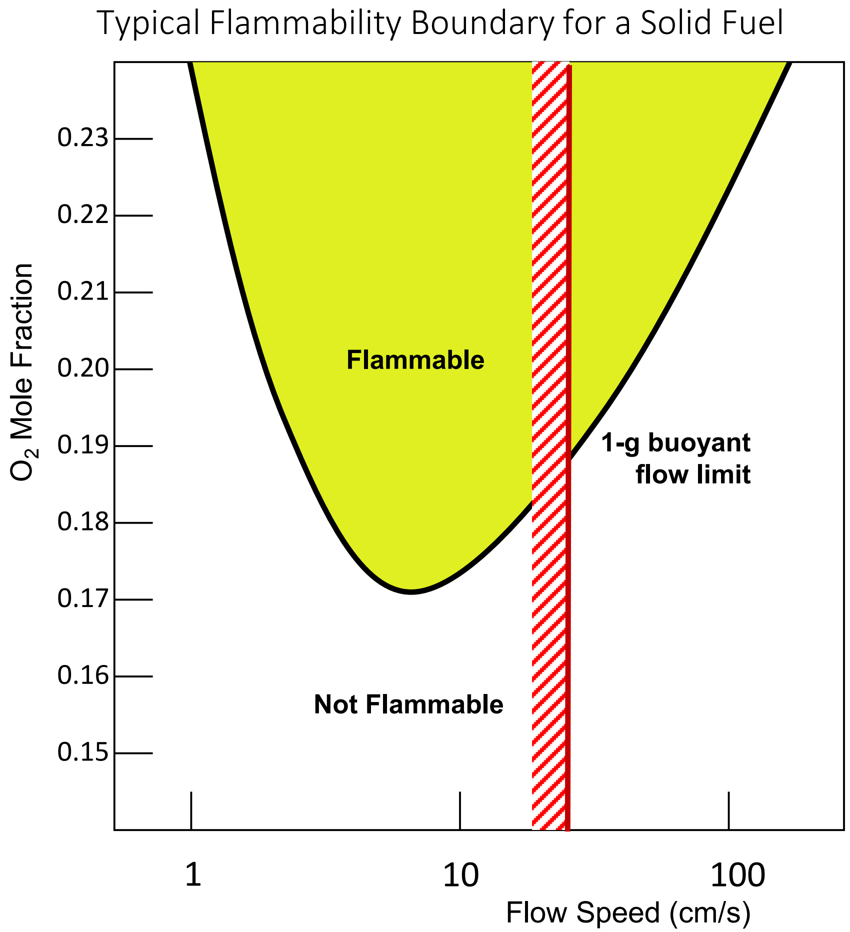
For other flames, the importance of flow is evident; even a slow flow makes an enormous difference



The Effect of Flow on Flame Spread in Microgravity

Numerical models and early drop tower experiments burning very thin fuel samples demonstrated a U-shaped flammability boundary

Much of the boundary cannot be studied in 1-g because of the minimum buoyant flow speed (~ 30 cm/s) present in every flame



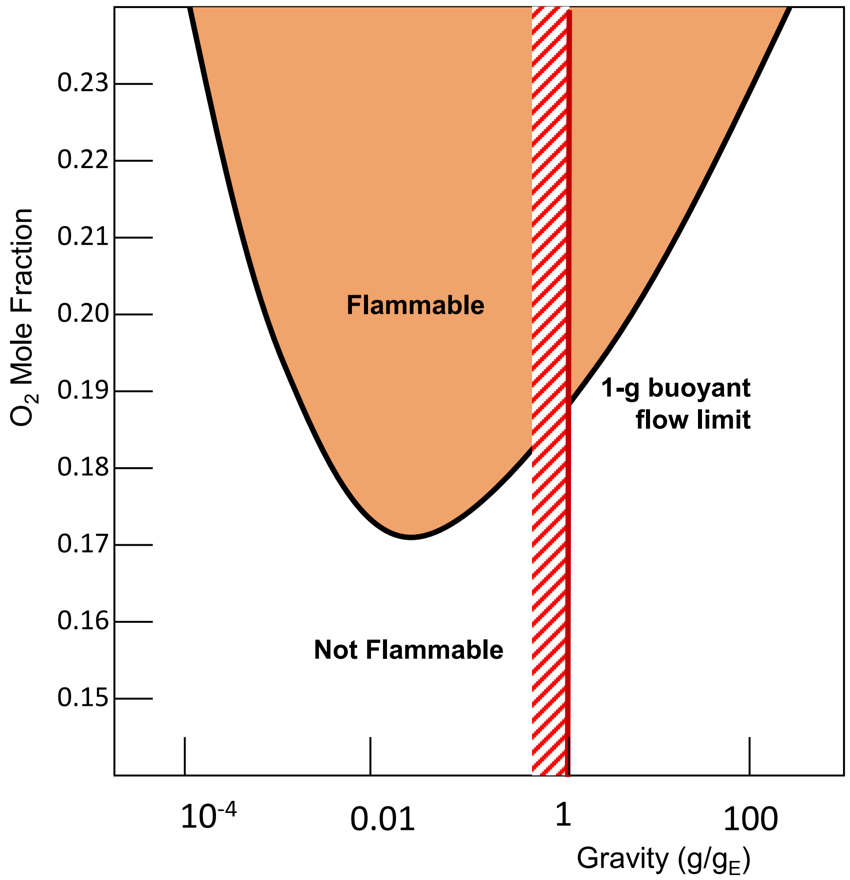
Buoyant Equivalent Flow

Since the characteristic buoyant flow speed, U_B, at the base of a flame is mostly a function of the gravity level, it is possible to correlate forced flow with gravity level

It is expected that the qualitative shape of the flammability boundary is largely unchanged when plotted against g/g_E

However, since buoyant and forced boundary layers have drastically different development lengths, assuming equivalence may lead to erroneous conclusions

Typical Flammability Boundary for a Solid Fuel

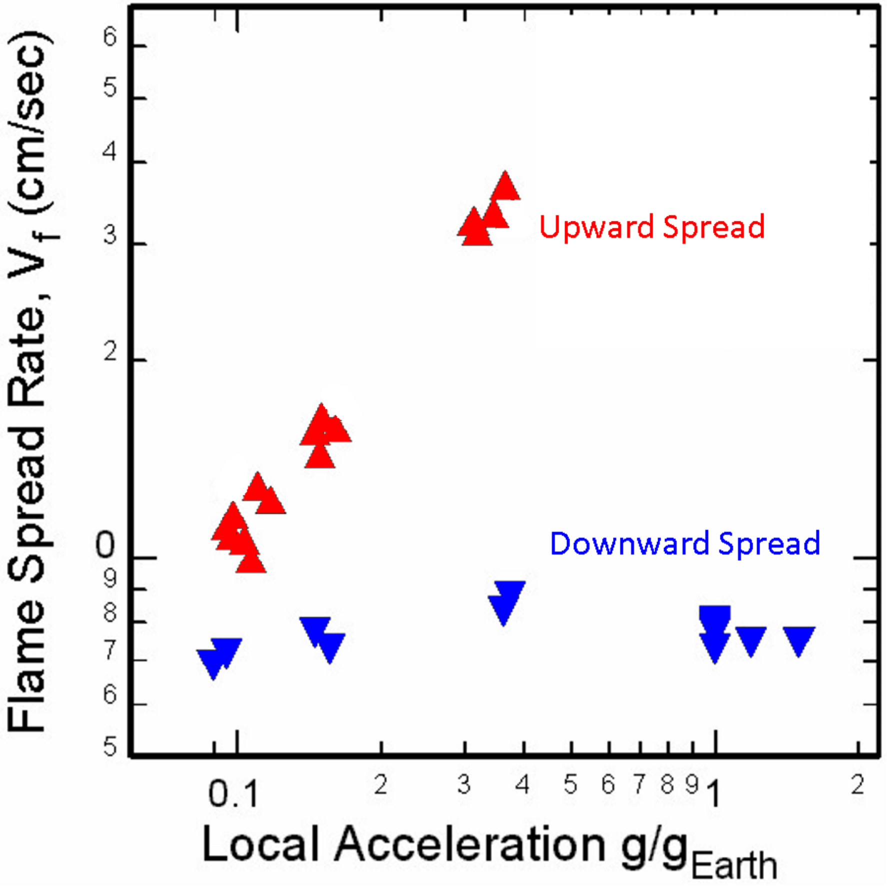


Initial interest sparked by observations of combustion tests conducted on aircraft flying <u>partial-gravity</u> parabolas:

0.01 to 0.38 g/g_E

2-cm-wide thin cellulosic samples (air at 0.27 atm)

For downward spread there is a maximum spread rate between 0 and 1 g and flame blowoff occurs at around 4.25 g/g_E



Motivation: Combustion in Partial Gravity

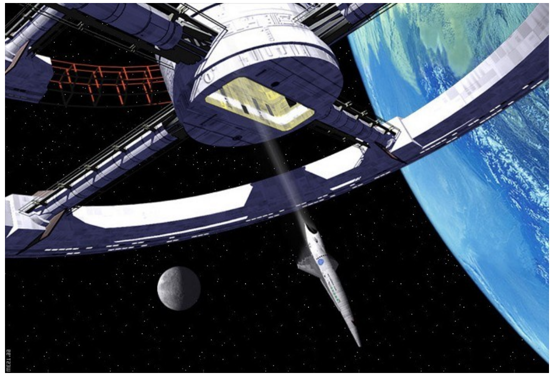
Partial Gravity is the working environment for planetary exploration and perhaps interplanetary travel, yet little is known about fluid, thermal and reacting system behavior under reduced, but non-zero, gravitational conditions.

How does partial gravity influence combustion?

What flame behavior may be unique in a partial-gravity centrifuge?

In the case of fire safety, can be more flammable in partial-gravity environments than in normal Earth gravity.

Until extended duration tests of partial-gravity are possible (e.g. rotating vehicles in Earth orbit), drop towers and aircraft can be utilized



Artist concept of a rotating spacecraft in orbit

“Plutonian” gravity (60 milli-g)

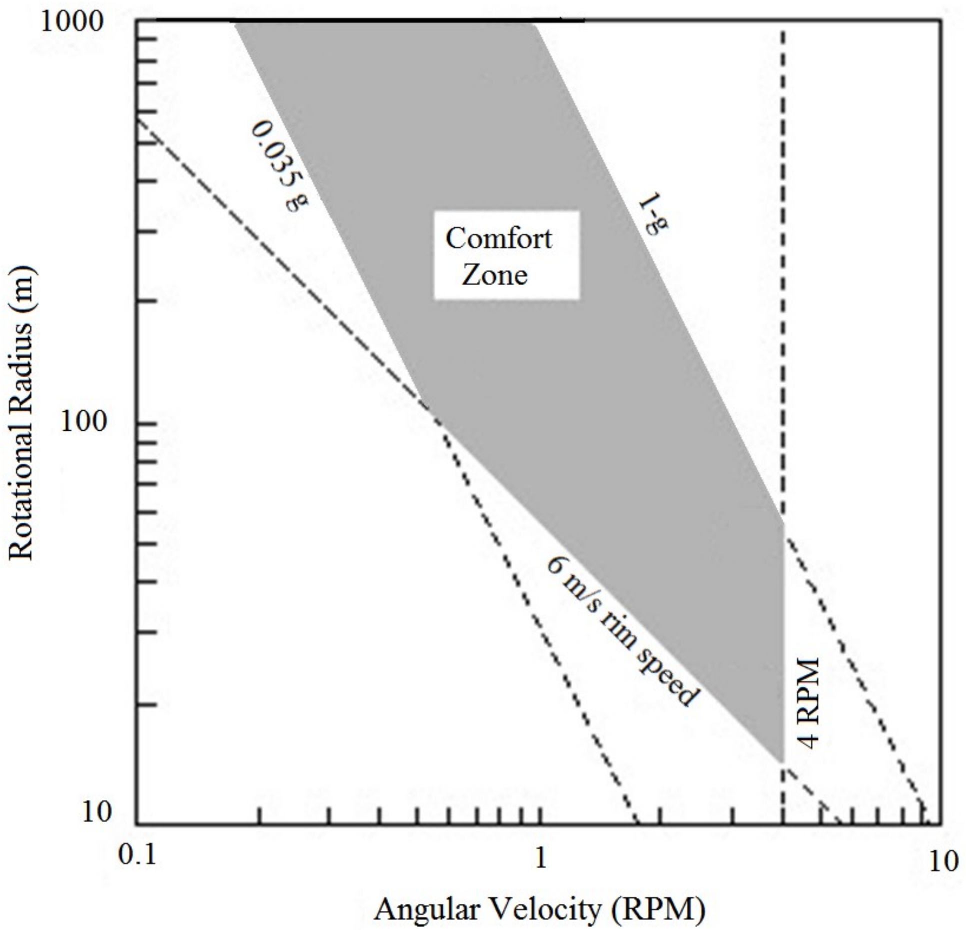
Pluto measures 2400 km in diameter

The Moon (165 milli-g)

3474 km in diameter

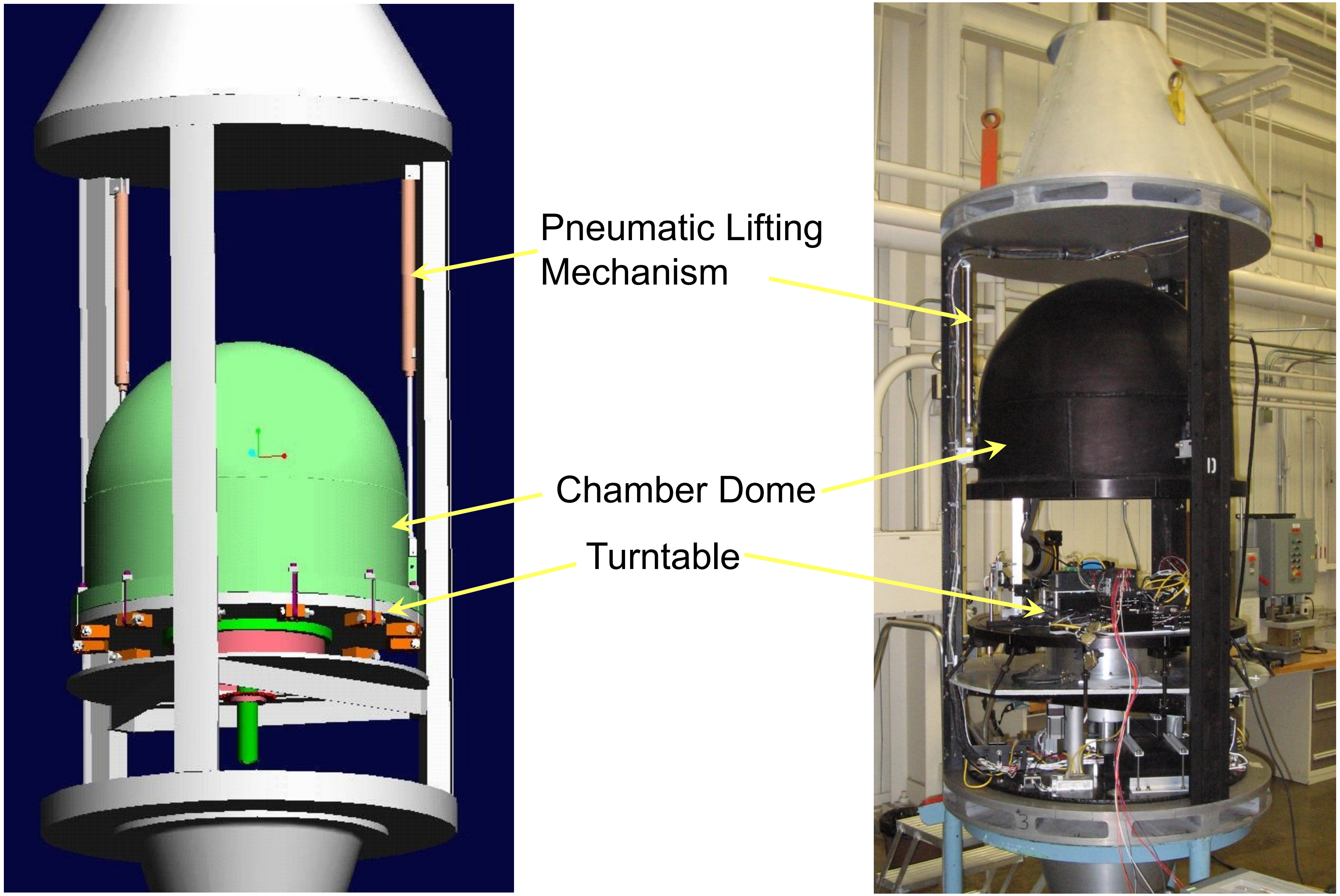
Enceladus (10 milli-g)

Hyperion (1.7 to 2.1 milli-g)



Comfort Zone" for a rotating space habitat, from NASA Habitability Data Handbook Volume 1 MSC-03909 (1971).

Centrifuge for Partial Gravity using NASA GRC Zero Gravity Facility (5.18 s Drop Tower)



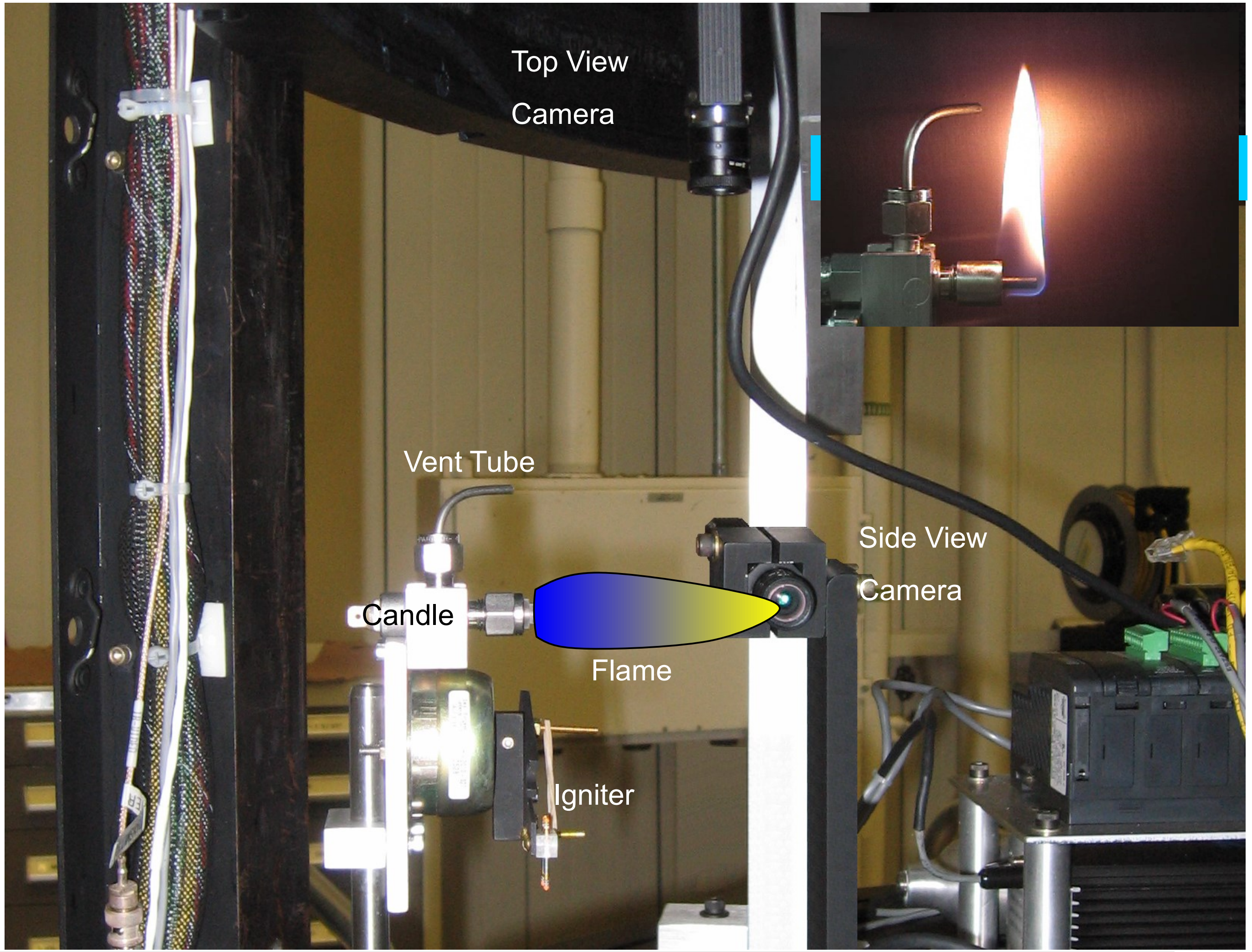
Pneumatic Lifting Mechanism

Chamber Dome

Turntable

Table I: Capabilities of the Zero-Gravity Centrifuge

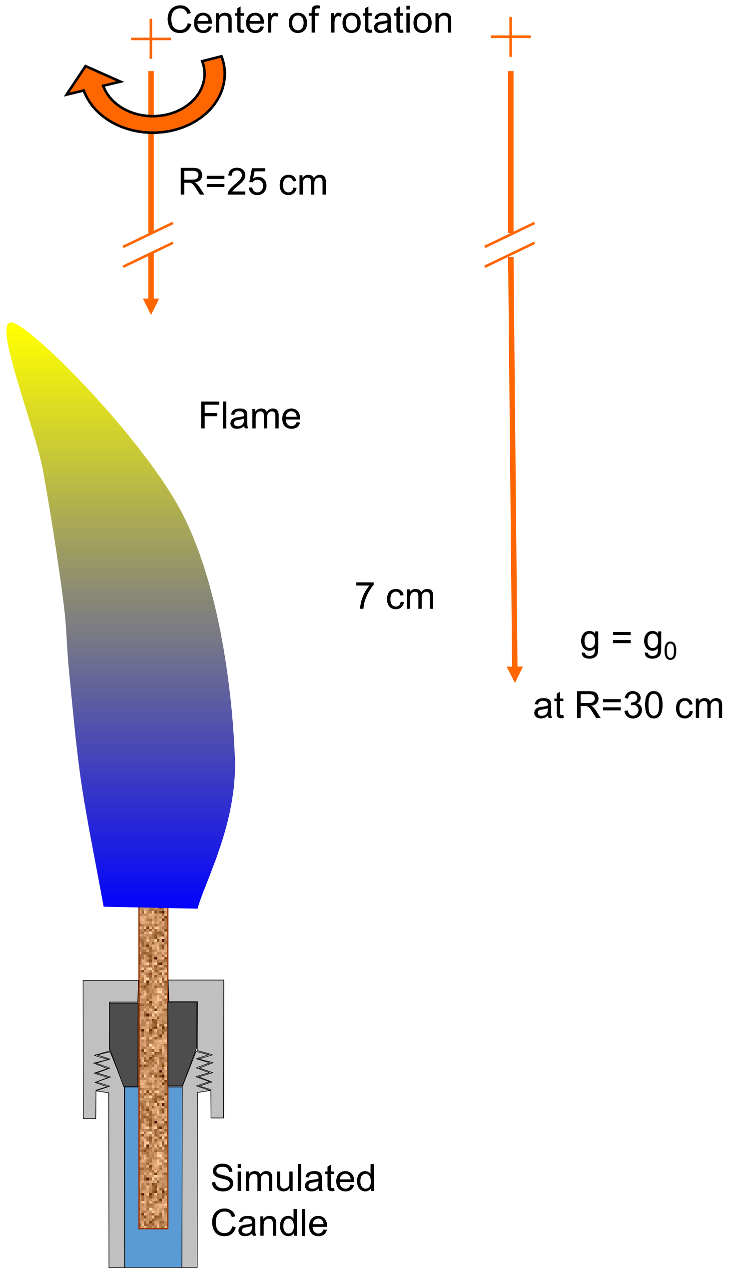
Dimensions	Cylindrical chamber 30.48 cm high, capped by hemispherical top with 81.28 inside diameter
Maximum internal radius	40.64 cm
Volume	300 liters
Pressure	Up to 2 atm absolute
Maximum rotation rate	1.1 RPS
Minimum rotation rate	0.01 RPS
Maximum centrifugal acceleration	14.3 m/s^2 (1.5 g) at a 30 cm radius
Minimum centrifugal acceleration	0.001 m/s^2 (10^{-4} g) at a 30 cm radius
Video views	Two independent video views are available
Data	Thermocouple or pressure transducer channels
Accelerometers	3-axis accelerometers are recorded
Power	28 V; slip-ring electrical feed through



Photograph showing camera layout with respect to the simulated candle. A flame as it would appear during the drop is shown schematically. The inset at upper right shows a heptane flame burning in normal gravity.

Simulated Candle Geometry

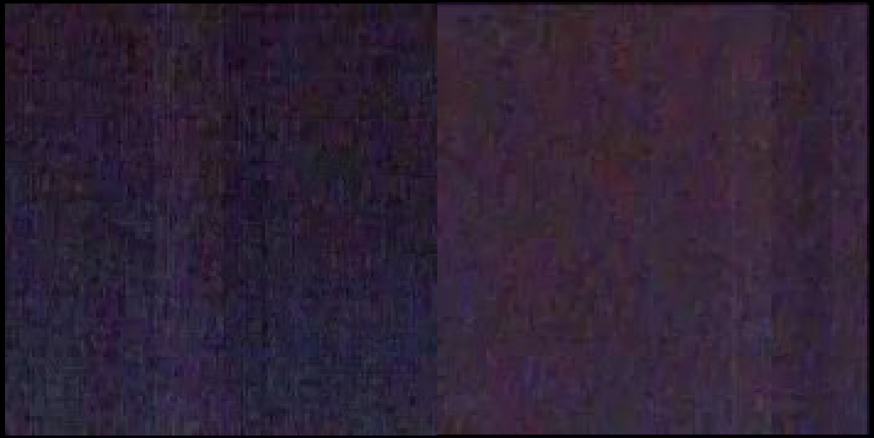
The Coriolis force causes the flame to tilt off the axis of rotation.



Heptane, 0-g

Top view Side view

Ethanol, 0-g

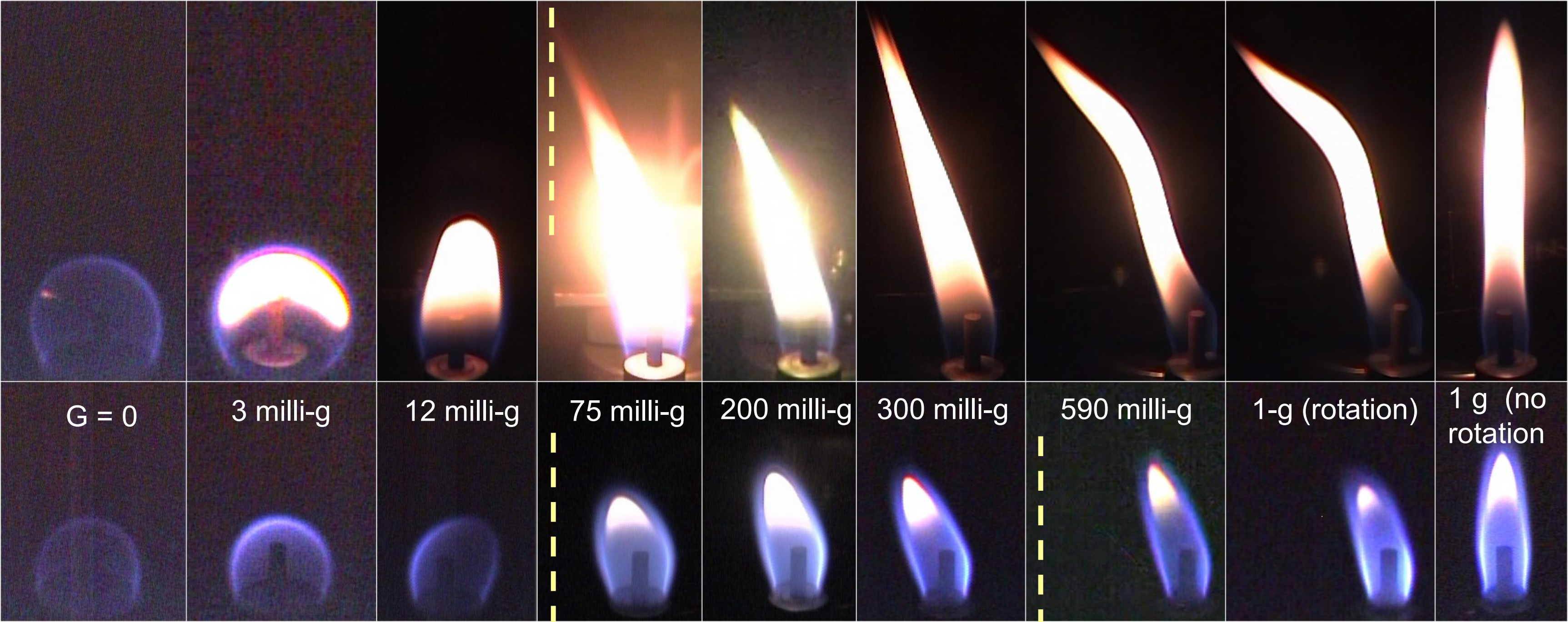


Ethanol and heptane flames at 200 milli-g

Heptane and Ethanol Flames as a Function of Gravity (Centripetal acceleration) Top View

Heptane Flames →

Heptane flames flicker



Ethanol Flames →

Ethanol flames sway

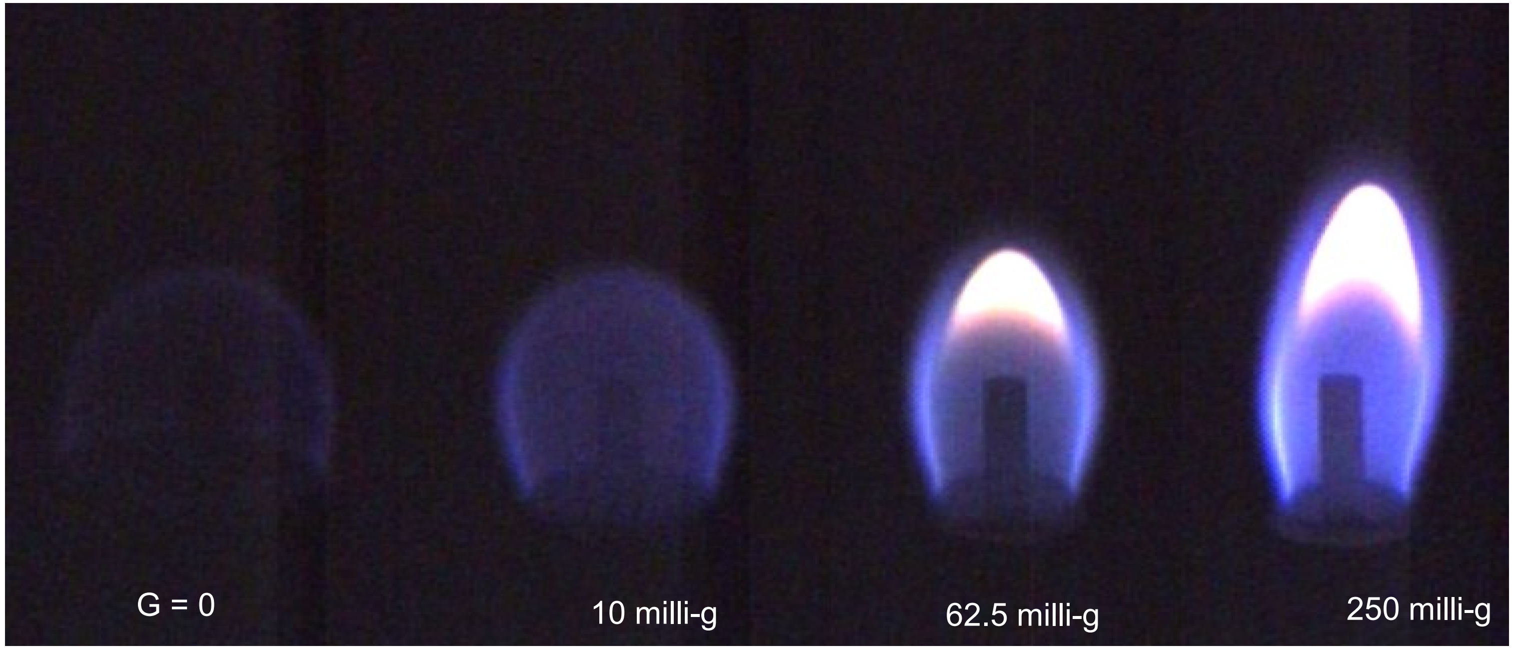
Ethanol flames flicker

1 cm

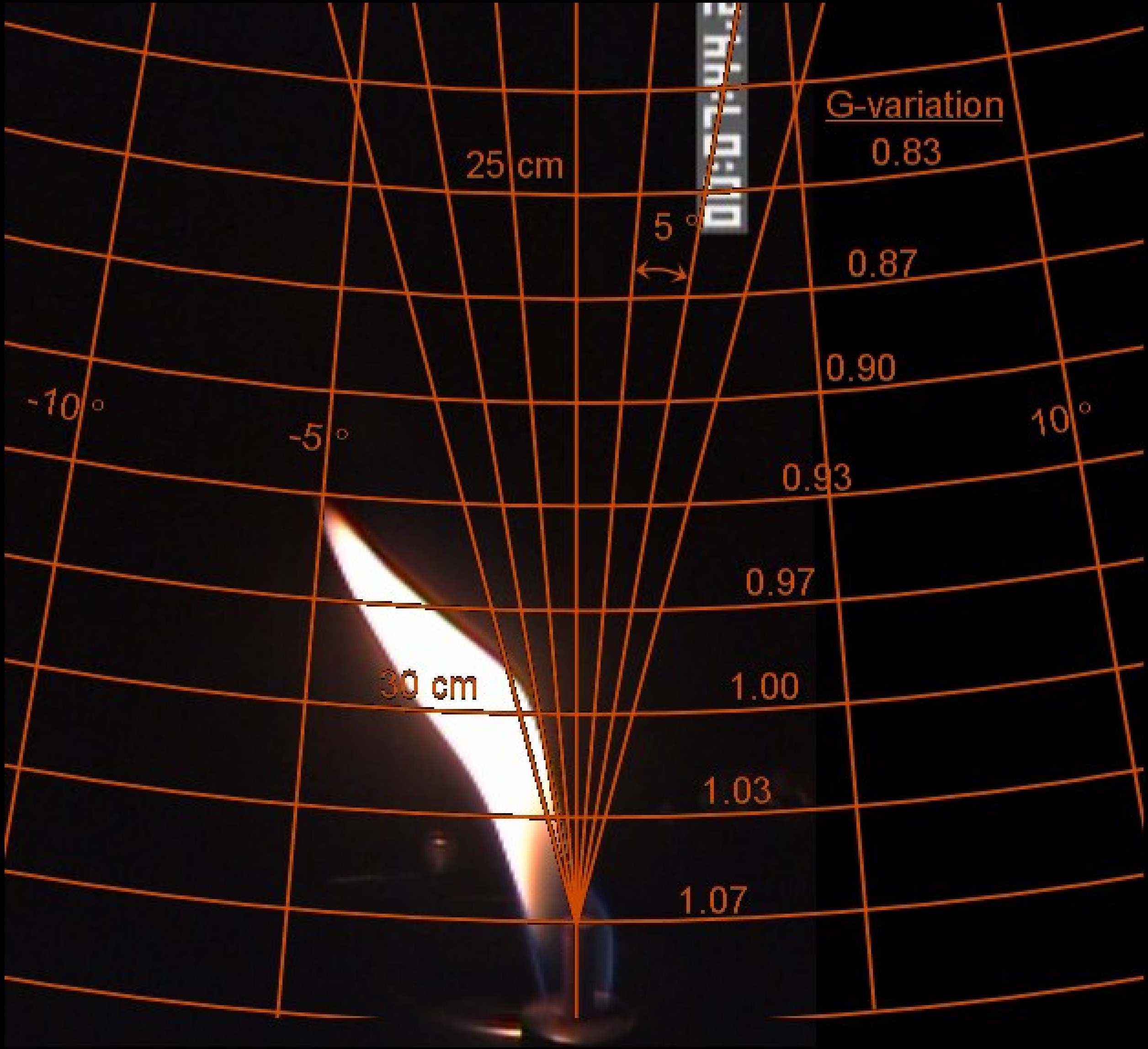
Ethanol Flames as a Function of Gravity (Centripetal acceleration)

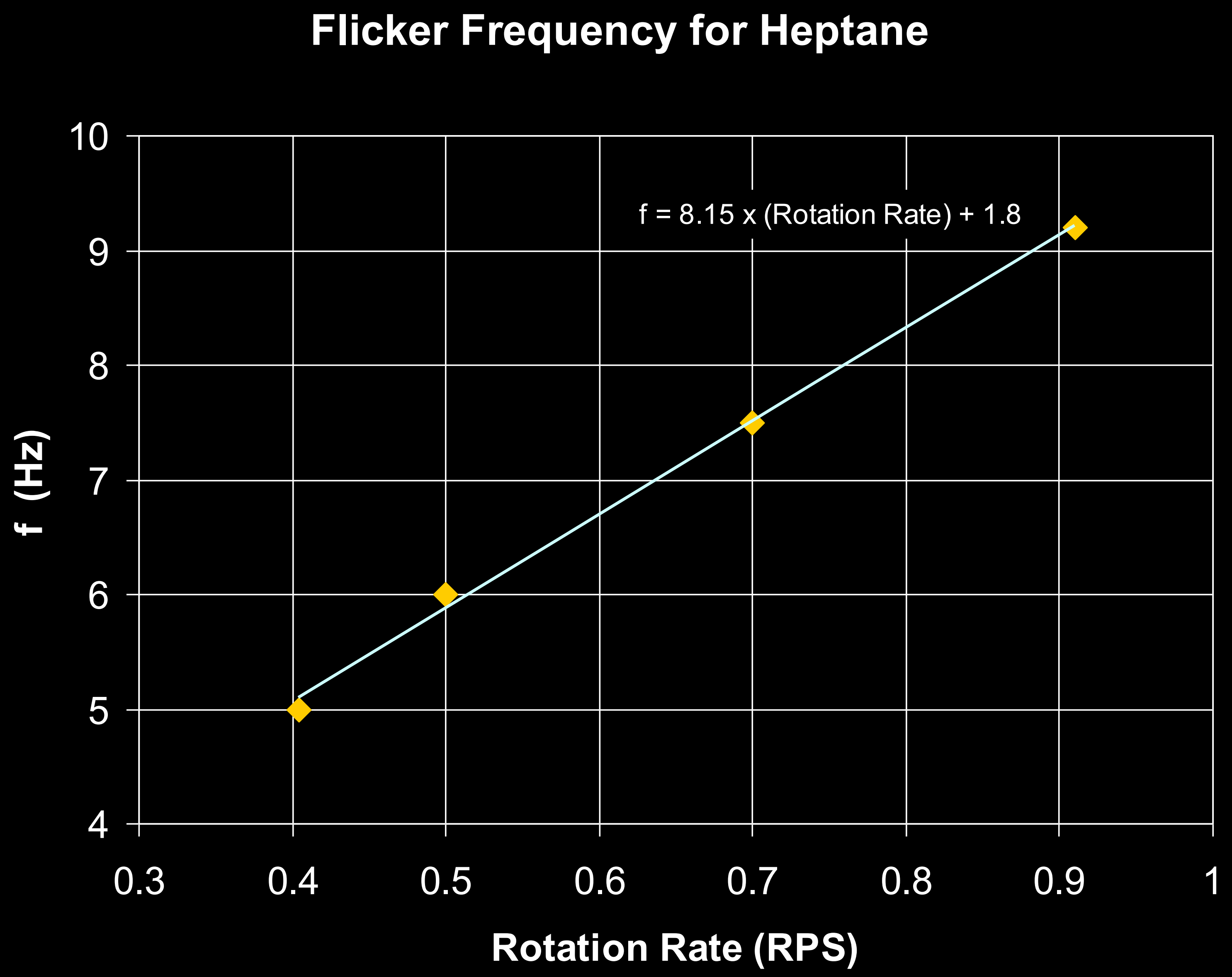
Flame size and brightness comparison

Side view



G-variation for test D-07-021, 0.91 RPS:





Flicker frequency, f, follows expected trend from theory: $f \sim (g)^{1/2}$ or $f \sim$ (Rotation Rate)

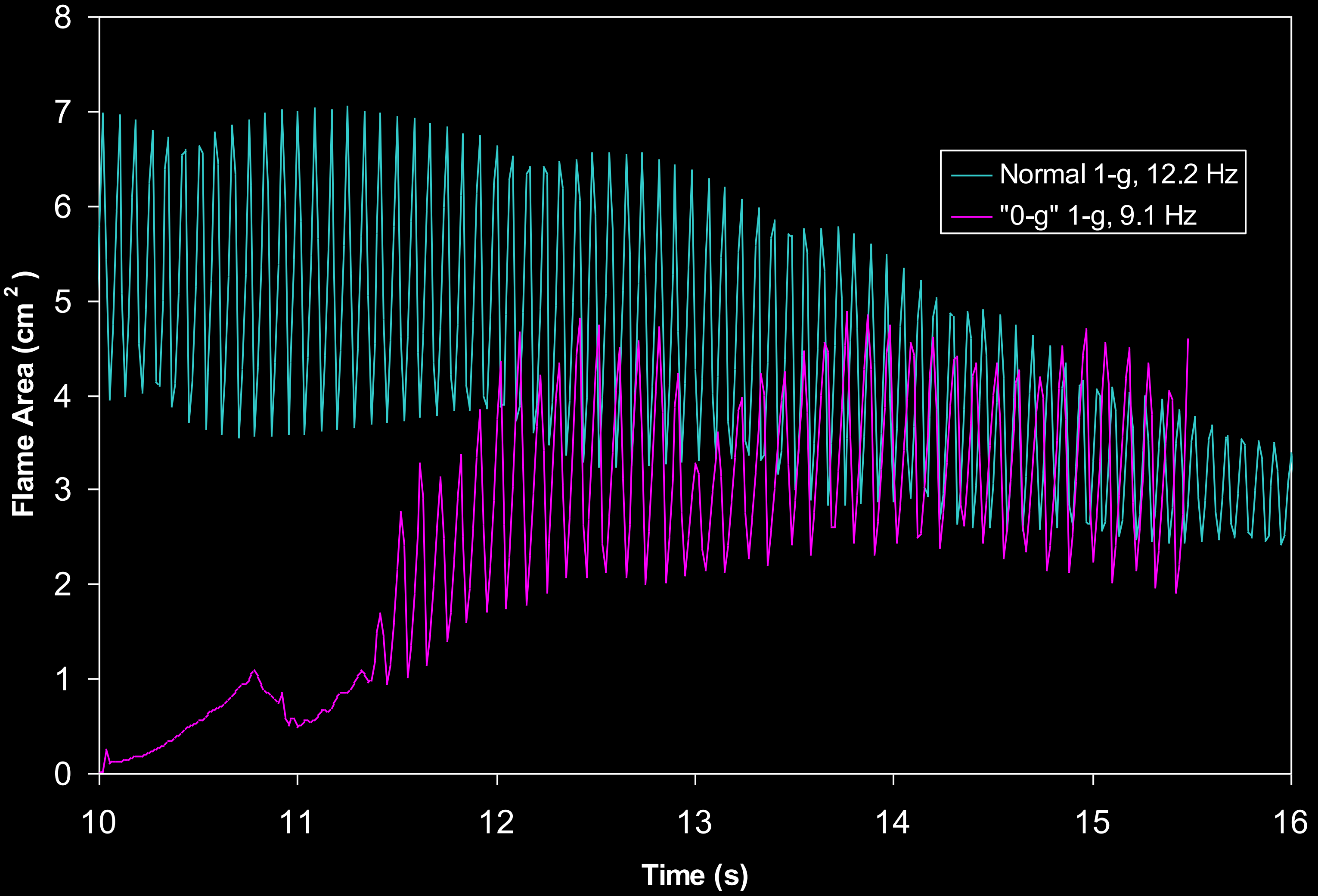
Hamins et al. (24th Symposium)

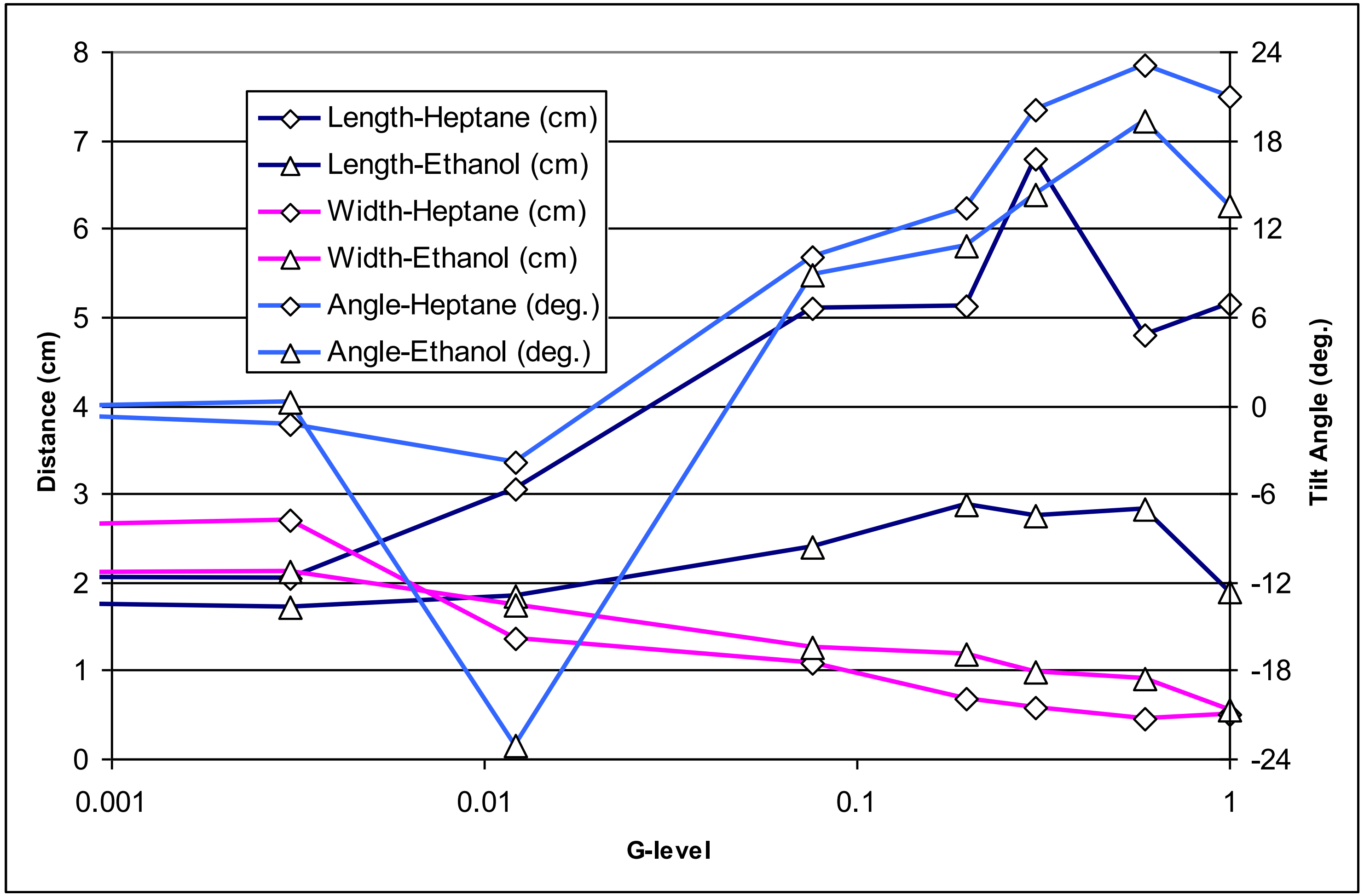
Heptane, 4 sec. loop playing at 1/3 speed

Normal 1-g

“0-g” 1-g

Heptane


Flame Area (cm^2)
Time (s)
0
1
2
3
4
5
6
7
8
10
11
12
13
14
15
16
Normal 1-g, 12.2 Hz
"0-g" 1-g, 9.1 Hz



Flame length, width, and tilt angle as a function of g-level.

Summary

23 simulated candle tests completed in centrifuge with 2 different fuels (heptane and ethanol) at 8 different centrifugal acceleration levels. Coriolis force is evident as flames tilts off axis.

Steady centrifugal accelerations (below lunar-g) were achieved. This range of accelerations is not readily attainable in aircraft because of g-jitter.

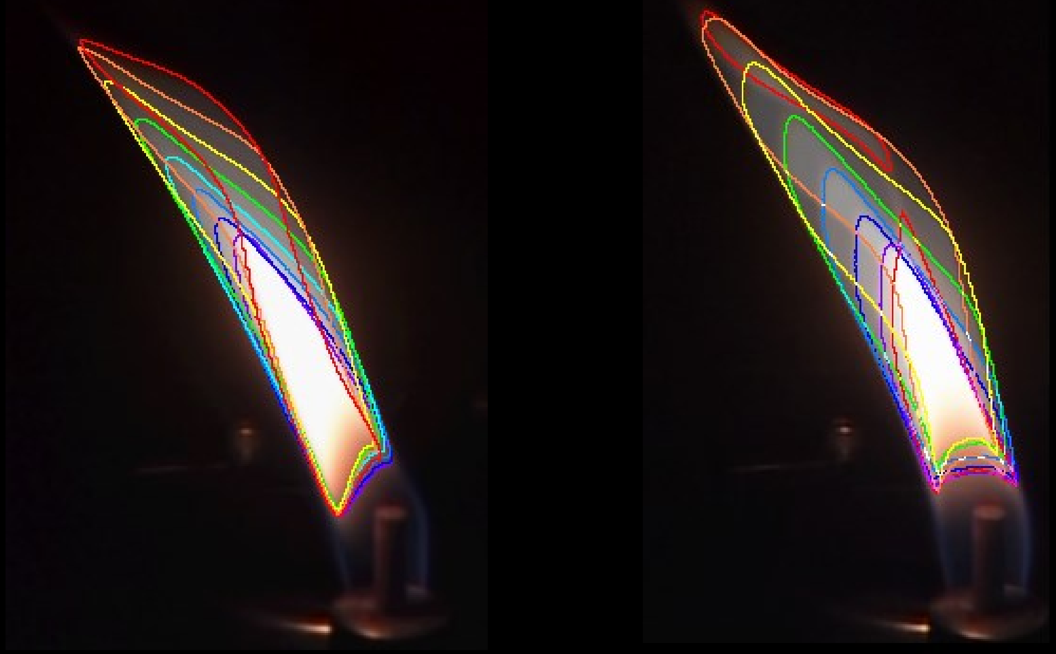
Flame flicker frequency follows expected variation with gravity.

Flame dimensions and angles measured.

Centrifuge performed well, may have application for other research areas besides combustion

Backups

Heptane Flame Visualization (successive frames shown, 1/60 sec apart)



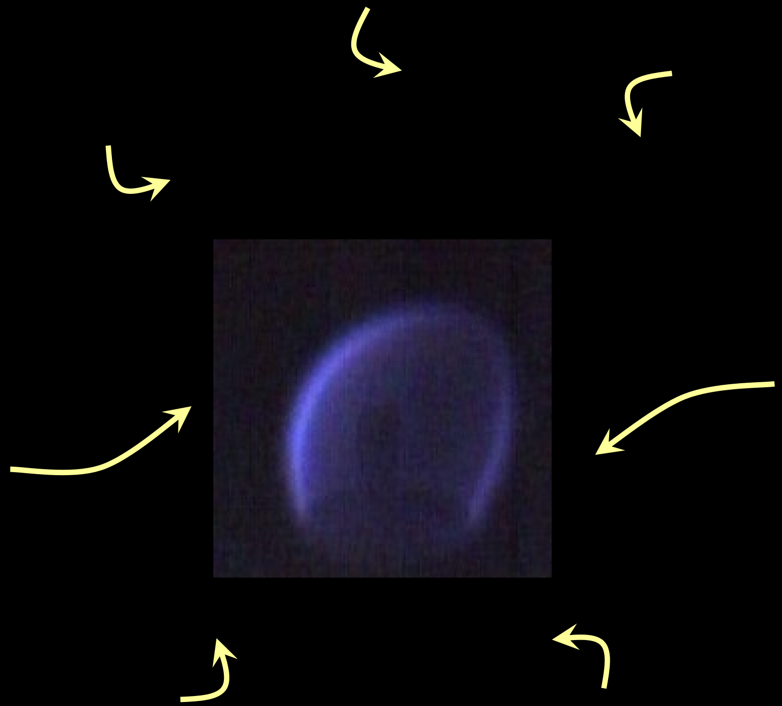
590 milli-g

1000 milli-g

Flame visualization for heptane tests at 590 and 1000 milli-g. The contours are 1/60 sec. apart. The Coriolis force causes these flames to tilt to the left, as well as induces the wavy structure as the flame pulses.

Ethanol and heptane at 12 milli-g tilt in the opposite direction:

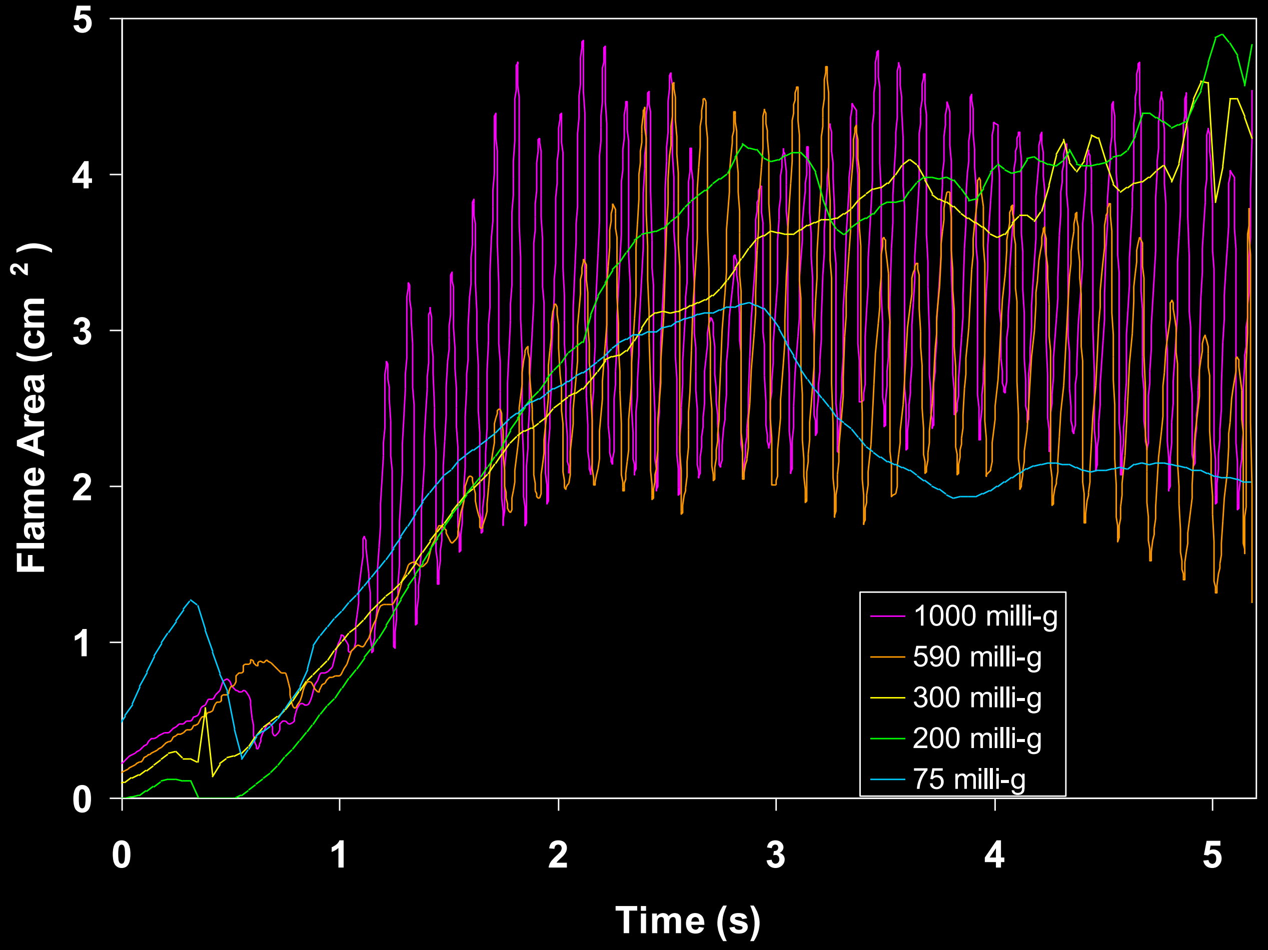
Is this a transient effect or also due to Coriolis force acting on diffusive velocity field?

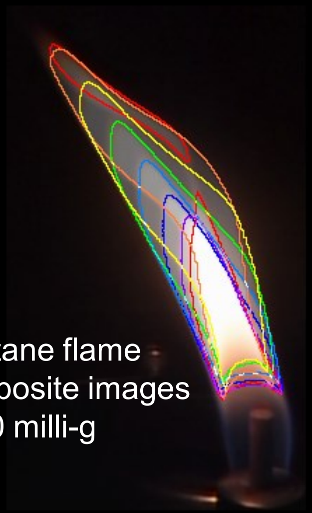


Top view

Side view

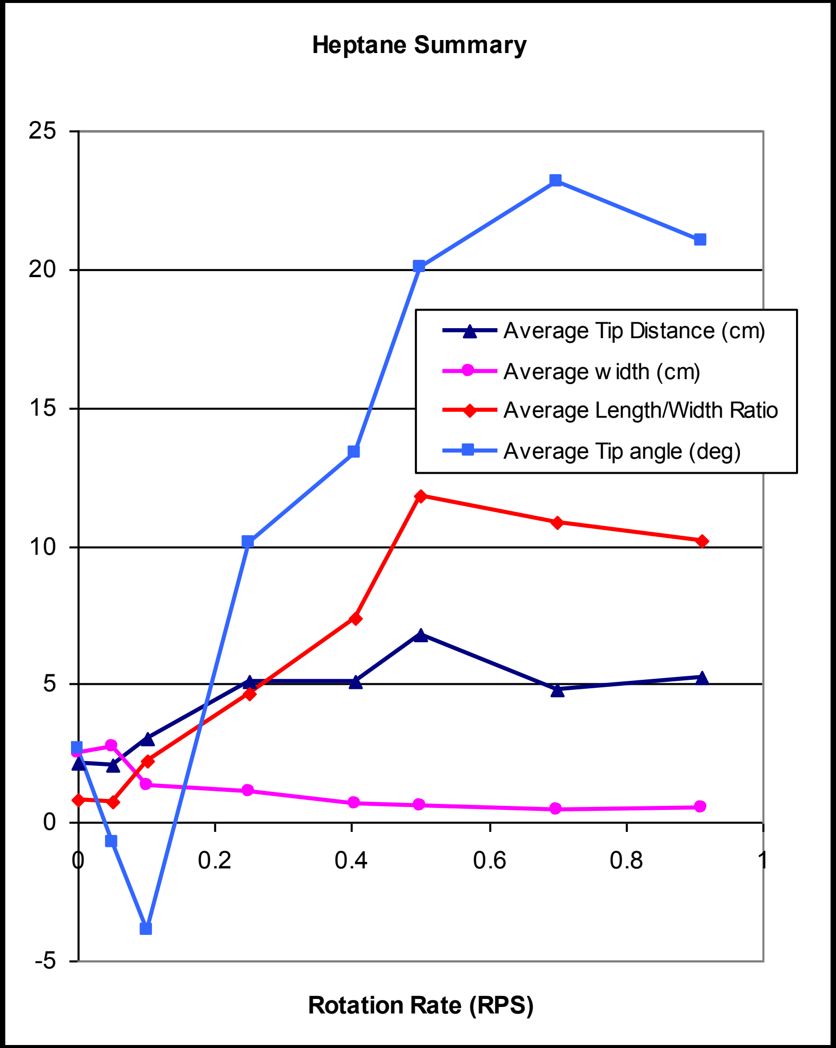
Flame Flicker as a Function of Gravity for Heptane

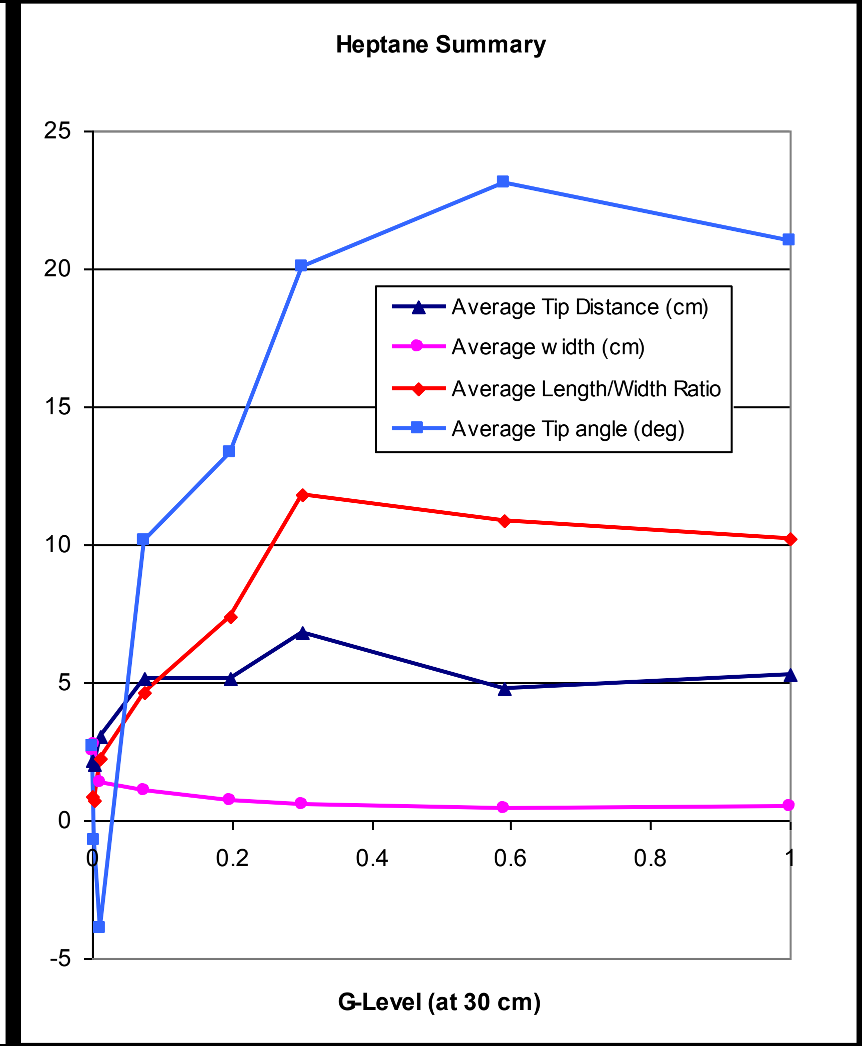




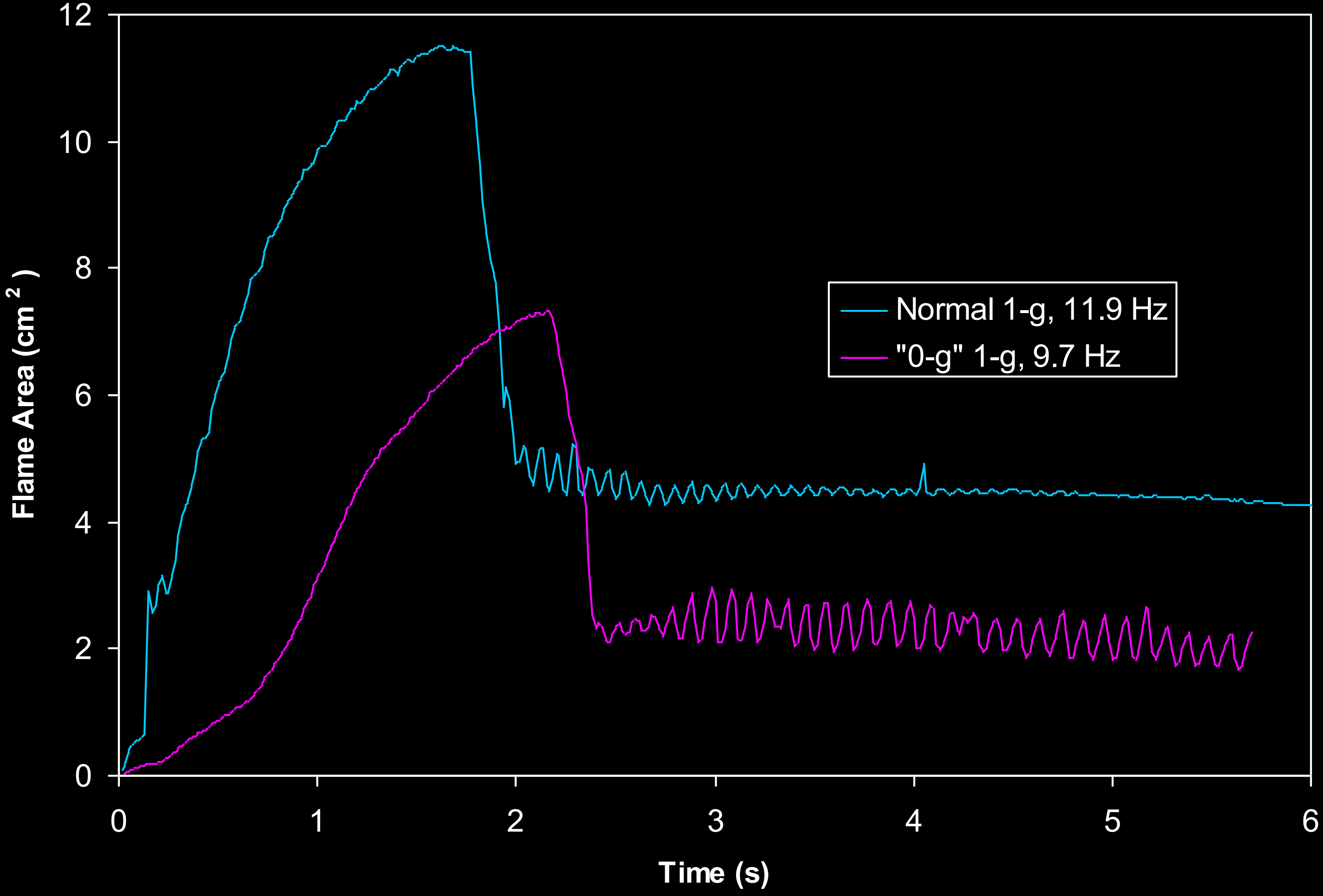
Heptane flame
composite images
1000 milli-g

Heptane flame
composite images
590 milli-g

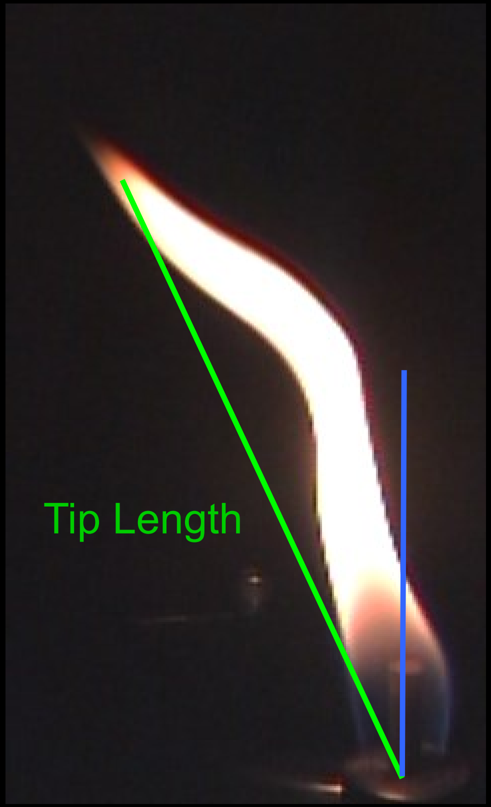

Heptane Summary
25
20
15
10
5
0
-5
0
0.2
0.4
0.6
0.8
1
Average Tip Distance (cm)
Average w idth (cm)
Average Length/Width Ratio
Average Tip angle (deg)
Rotation Rate (RPS)

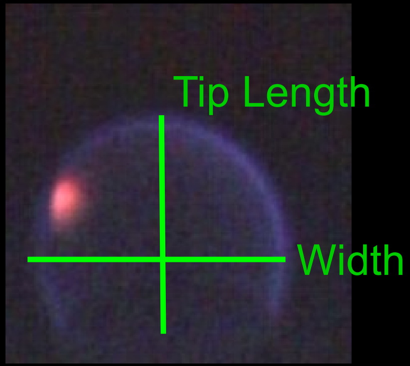

Heptane Summary
25
20
15
10
5
0
-5
0
0.2
0.4
0.6
0.8
1
Average Tip Distance (cm)
Average w idth (cm)
Average Length/Width Ratio
Average Tip angle (deg)
G-Level (at 30 cm)

Ethanol

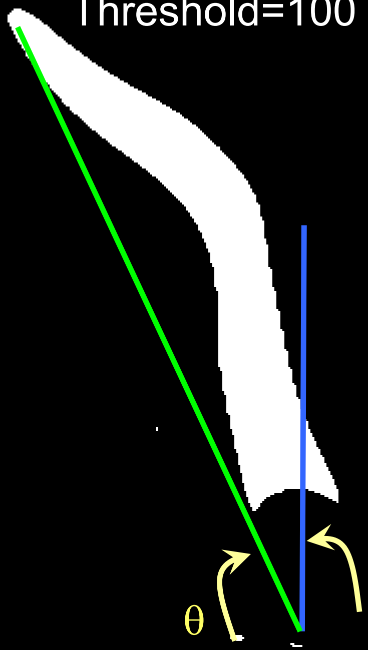

12
10
8
6
4
2
0
Flame Area (cm ^{2})
0
1
2
3
4
5
6
Time (s)
Normal 1-g, 11.9 Hz
"0-g" 1-g, 9.7 Hz

Definition of Length Scales:





Flame Area Threshold=100

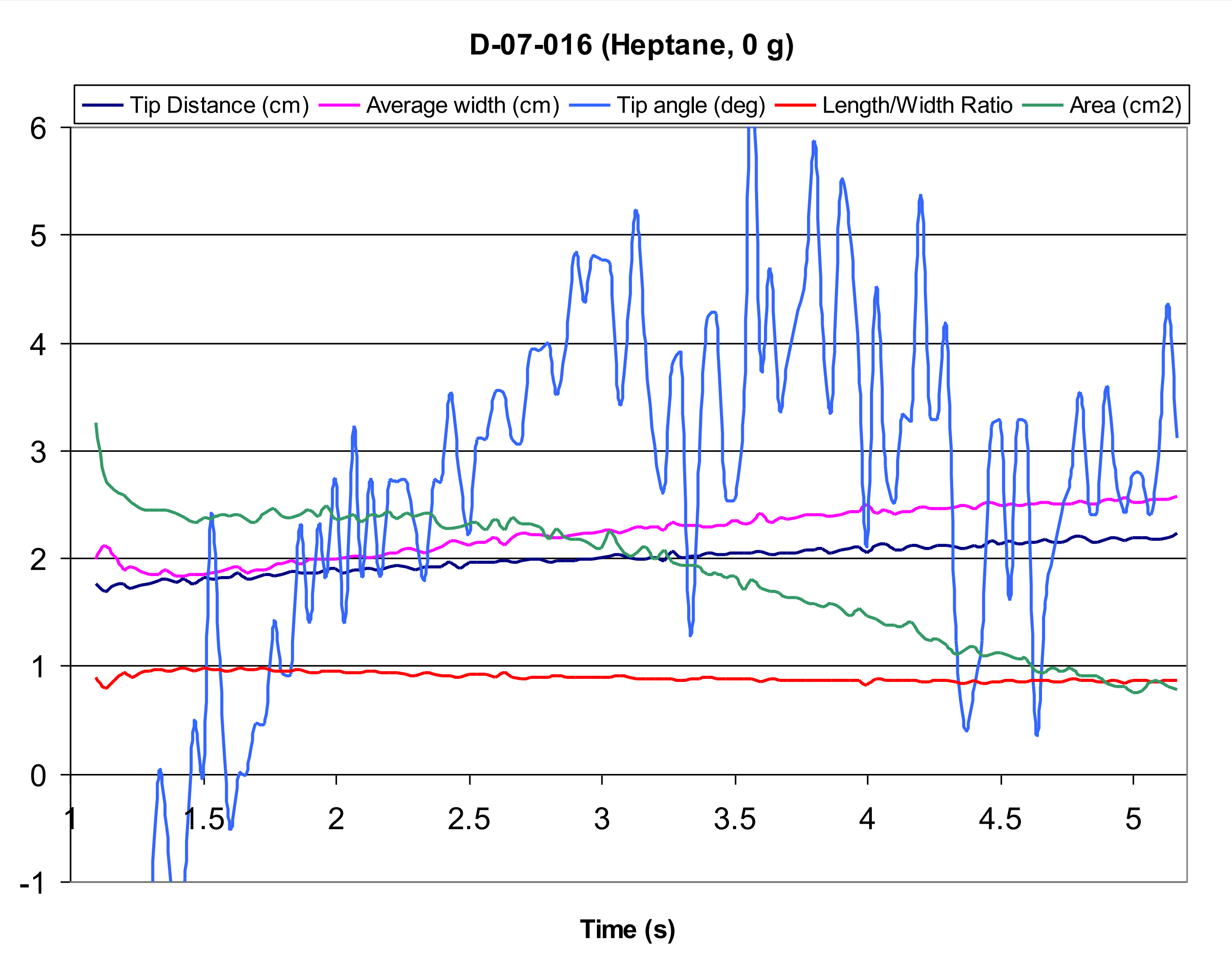


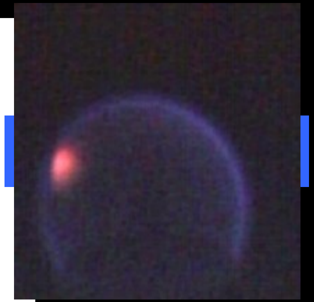
<u>Tip length:</u> Distance between wick base and flame tip

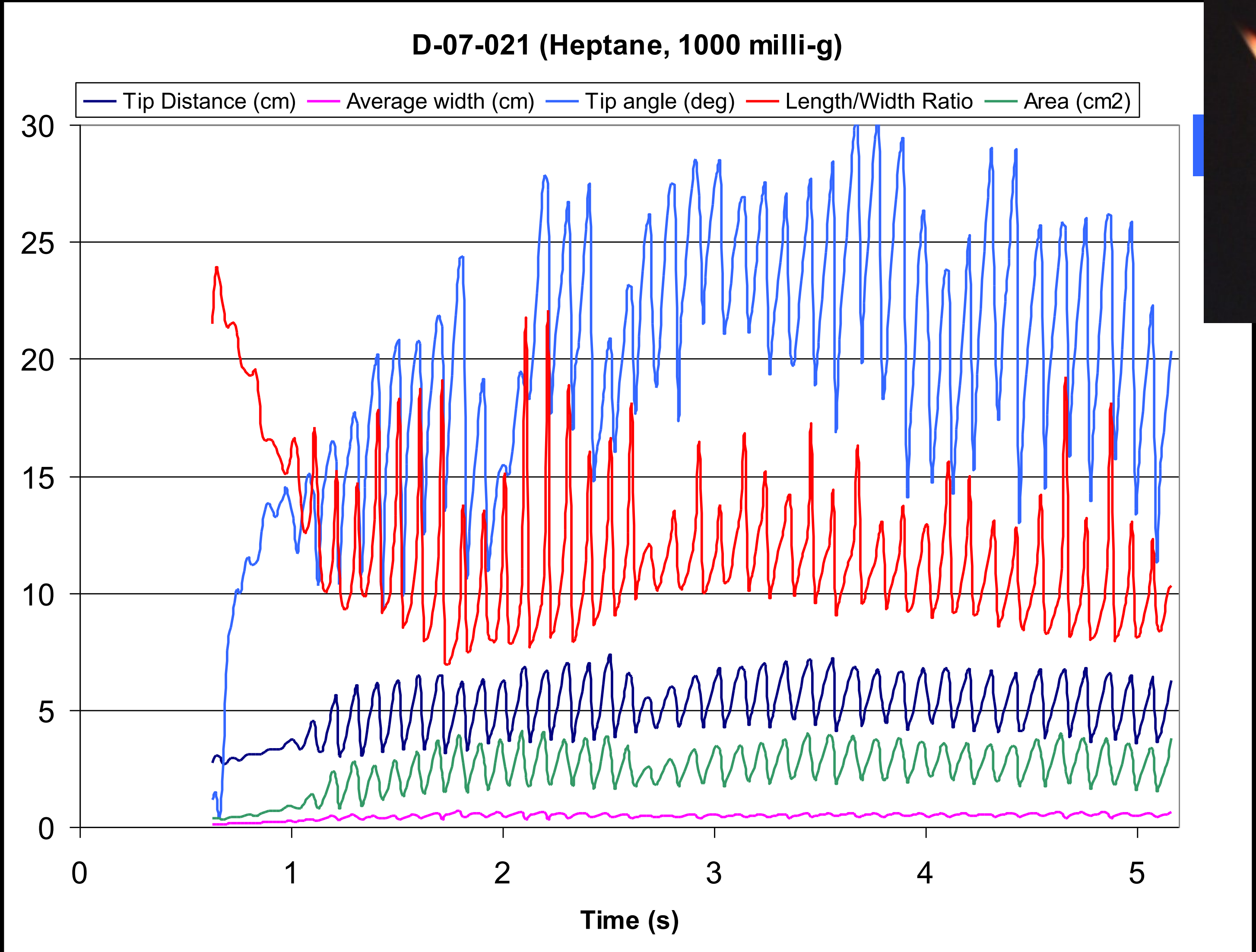
<u>Width:</u> Left-right distance

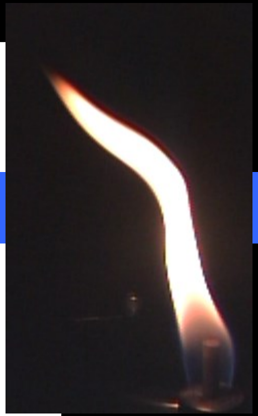
<u>Average Width:</u> defined as Flame Area divided by Tip Length (for long flames)

<u>Tip Angle, θ:</u> Angle of flame tip from axis of wick

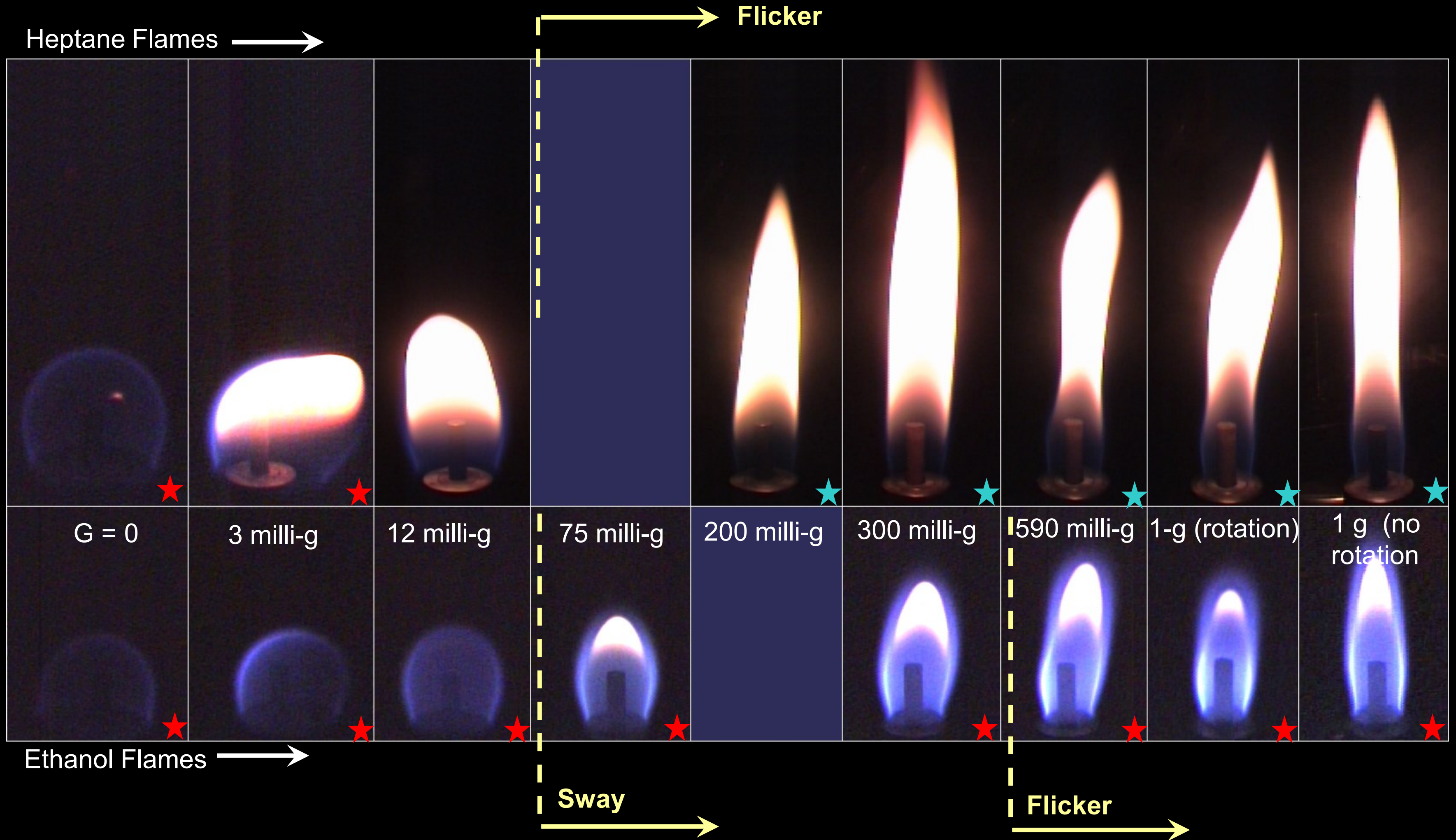

D-07-016 (Heptane, 0 g)
Tip Distance (cm)
Average width (cm)
Tip angle (deg)
Length/Width Ratio
Area (cm2)
6
5
4
3
2
1
0
-1
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (s)




D-07-021 (Heptane, 1000 milli-g)
Tip Distance (cm)
Average width (cm)
Tip angle (deg)
Length/Width Ratio
Area (cm2)
30
25
20
15
10
5
0
0
1
2
3
4
5
Time (s)



Heptane and Ethanol Flames as a Function of Gravity (Centripetal acceleration) Side View



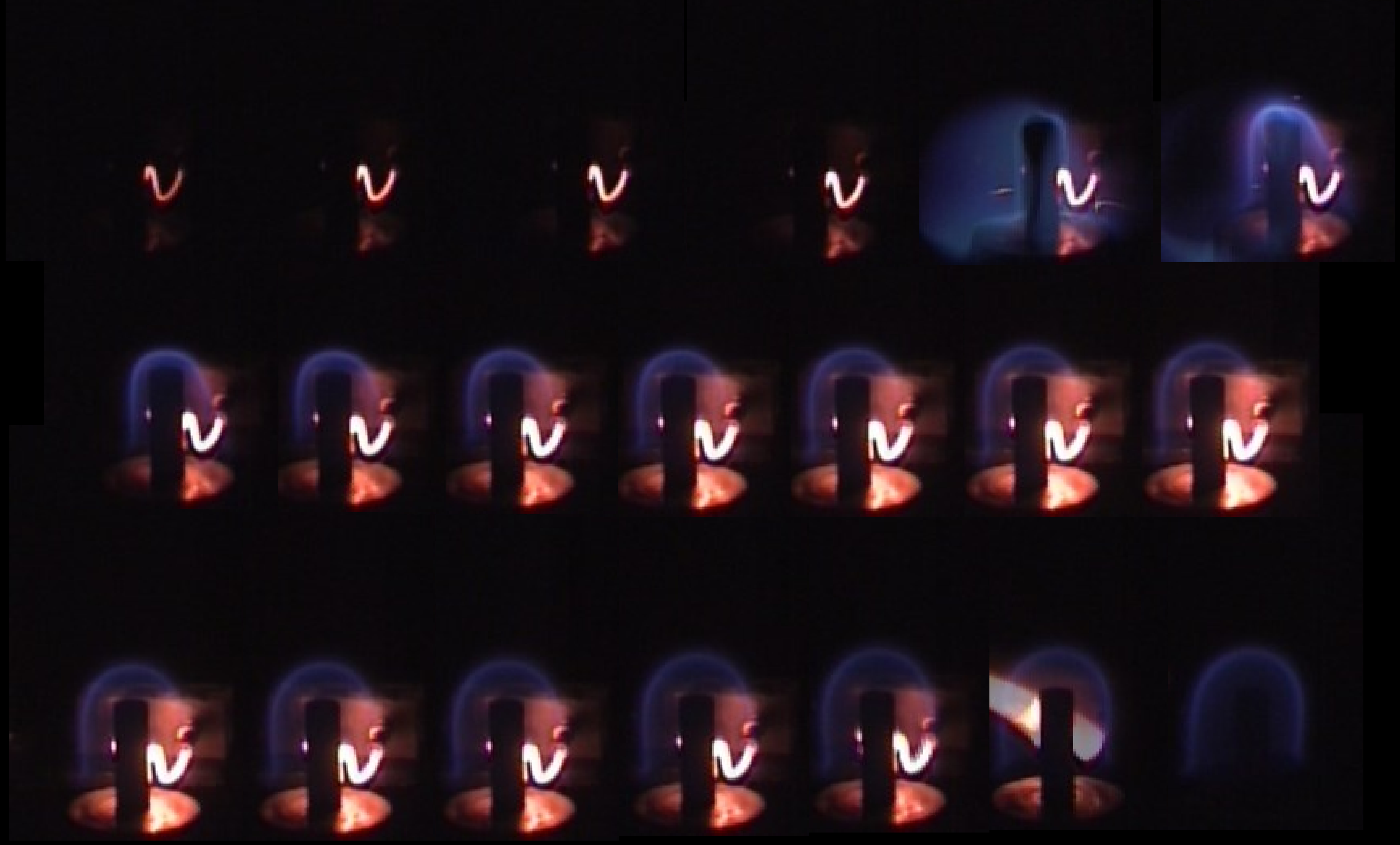
★ Image brightness is consistent (RGB x 3.5)

★ Image brightness is consistent (raw RGB)

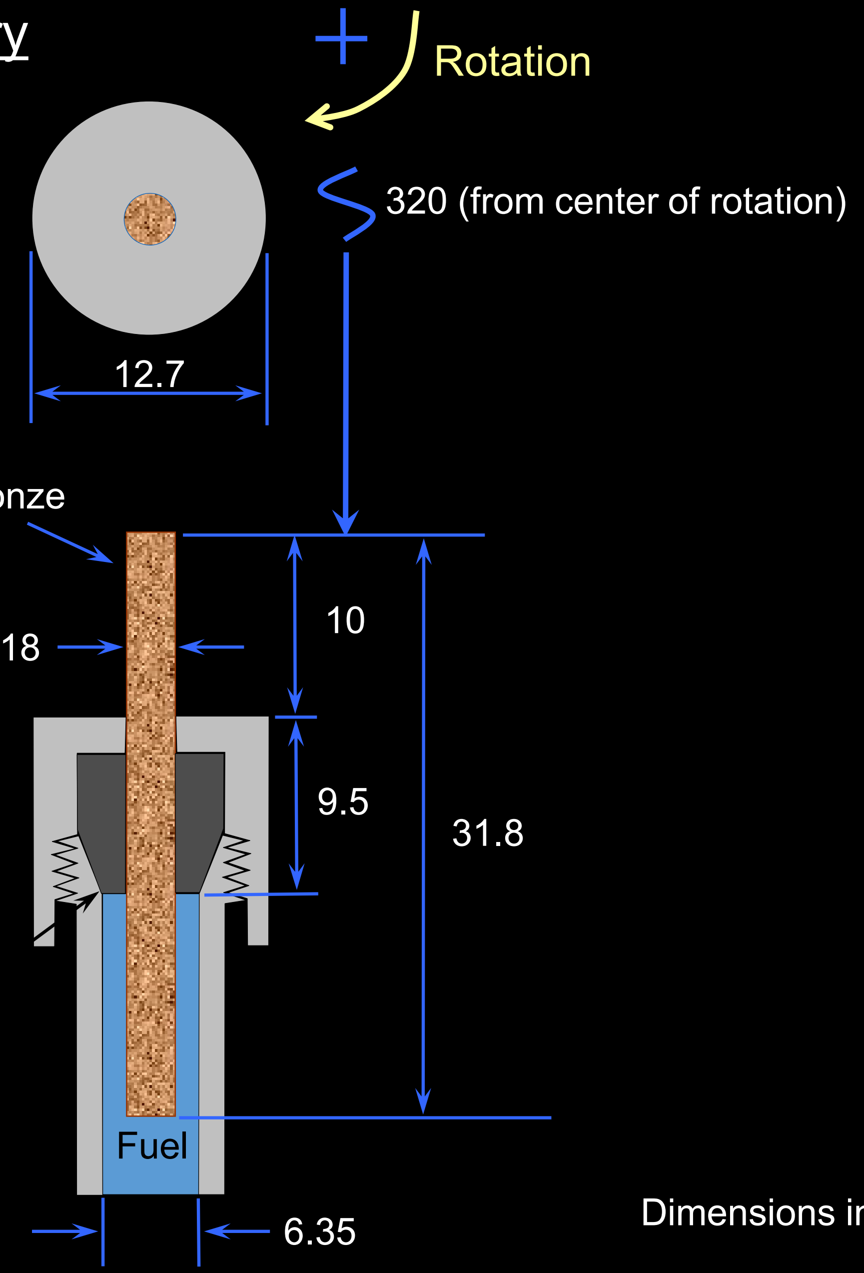
1 cm

Heptane at 12 milli-g (top view)

Ignition Sequence (1/30 sec between frames)



Simulated Candle Geometry



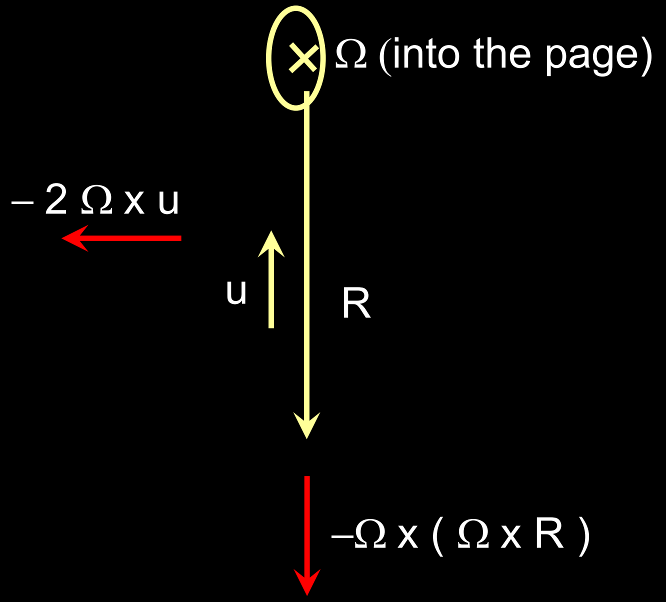
Top View

Side View

Dimensions in mm

Coriolis Force

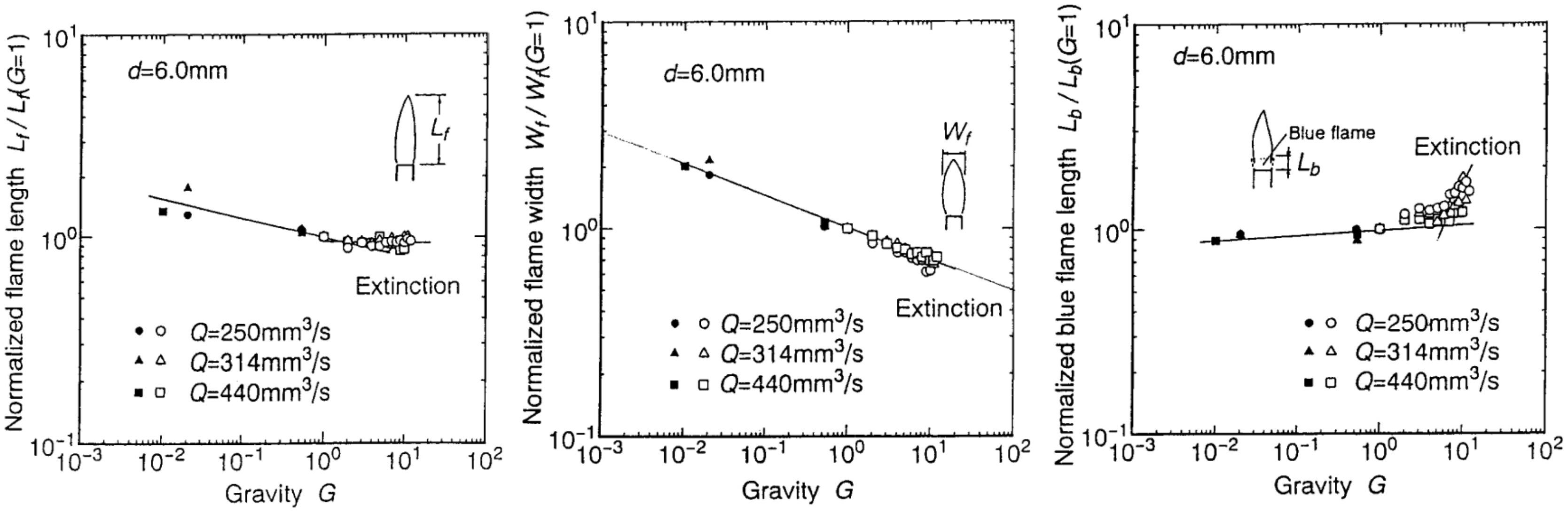
$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla P - \mathbf{\Omega} \times (\mathbf{\Omega} \times r) - 2\mathbf{\Omega} \times \mathbf{u} + \nu \nabla^2 \mathbf{u}.$$



g (at 30 cm)	Rotation Rate (RPS)	Heptane	Ethanol
0 g	0	D-07-015 (NIA) D-07-016	D-07-009
3 milli-g	0.05	D-07-001 (PRE) D-07-017	D-07-018 (NIA) D-07-019
12 milli-g	0.1	D-07-002 (PRE) D-07-008	D-07-007
75 milli-g	0.25	D-07-003	D-07-005
200 milli-g	0.404	D-07-006	D-07-004
300 milli-g	0.5	D-07-014	D-07-010 (NIA) D-07-011 (NUW) D-07-012 (WIK)
590 milli-g	0.7	D-07-020	D-07-013
1000 milli-g	0.91	D-07-021	D-07-022 (NIA) D-07-023

Key: PRE (Ignition prior to drop) NIA (No Ignition achieved)

NUW (Non-Uniform wick) WIK (New wick installed)



Flame dimensions for butane flame in reduced-gravity centrifuge.

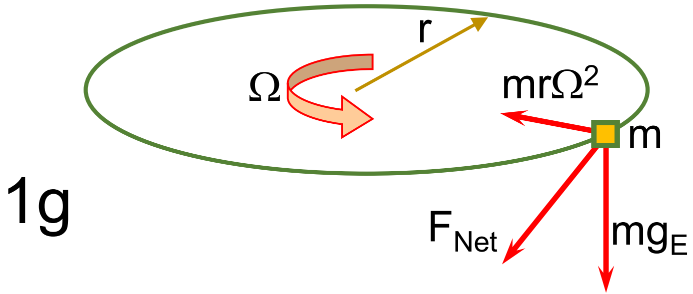
G = 0.02 to 15 (+/- 0.01g)

9m drop tower (1.3 s)

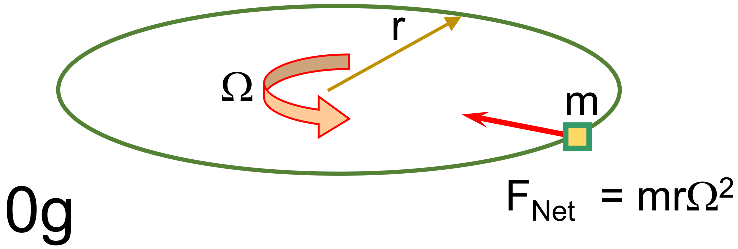
Ignition a few seconds before drop start

[Amagai et al., 1997]

Centrifuge Force Diagram



The net force acting on a rotating mass on Earth is the vector sum of the weight and centripetal force and is always greater than its weight.



The net force acting on a rotating mass in microgravity is merely the centripetal force and may be less than its weight on Earth.

Highly exothermic; both the ceramic and metallic products are melted

Centrifuge accelerates the phase separation and removal of gas bubbles

After cooling bulk ceramics are obtained together with metallic ingots.

Up to 10,000g's is necessary to realize a complete separation of metal melt and removal of gas bubbles from the ceramic melt; improved purity.

By high-gravity combustion synthesis, large samples (e.g. Ø200 mm × 15 mm) with regular shape can be prepared,

"High-gravity combustion synthesis: A fast and furnace-free way for preparing bulk ceramic materials," Guanghua Liu and Jiangtao Li, Journal of Asian Ceramic Societies (2013).