





# Combustion Relevance

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## Combustion is:

our primary energy source (85%)  
the primary cause of global warming,  
the primary cause of air pollution—affects  
people directly every day,  
an inherent part of many industrial processes  
a major source of the loss of property and life,  
the power source for portable applications  
a catastrophic hazard for the manned space  
flight program,  
a major source of new materials (nano-tubes,  
diamond, ceramics etc.),  
arguably man's first technology but also  
remarkably complex.







## Combustion Relevance

**The biggest challenge to the discipline is that combustion has been so pervasive for so long in everyday life that people mistakenly believe it is well understood. The reality is that substantial improvements in the quality of life in space or here on earth will require improvements in our ability to predict and control combustion.**





# Topics covered

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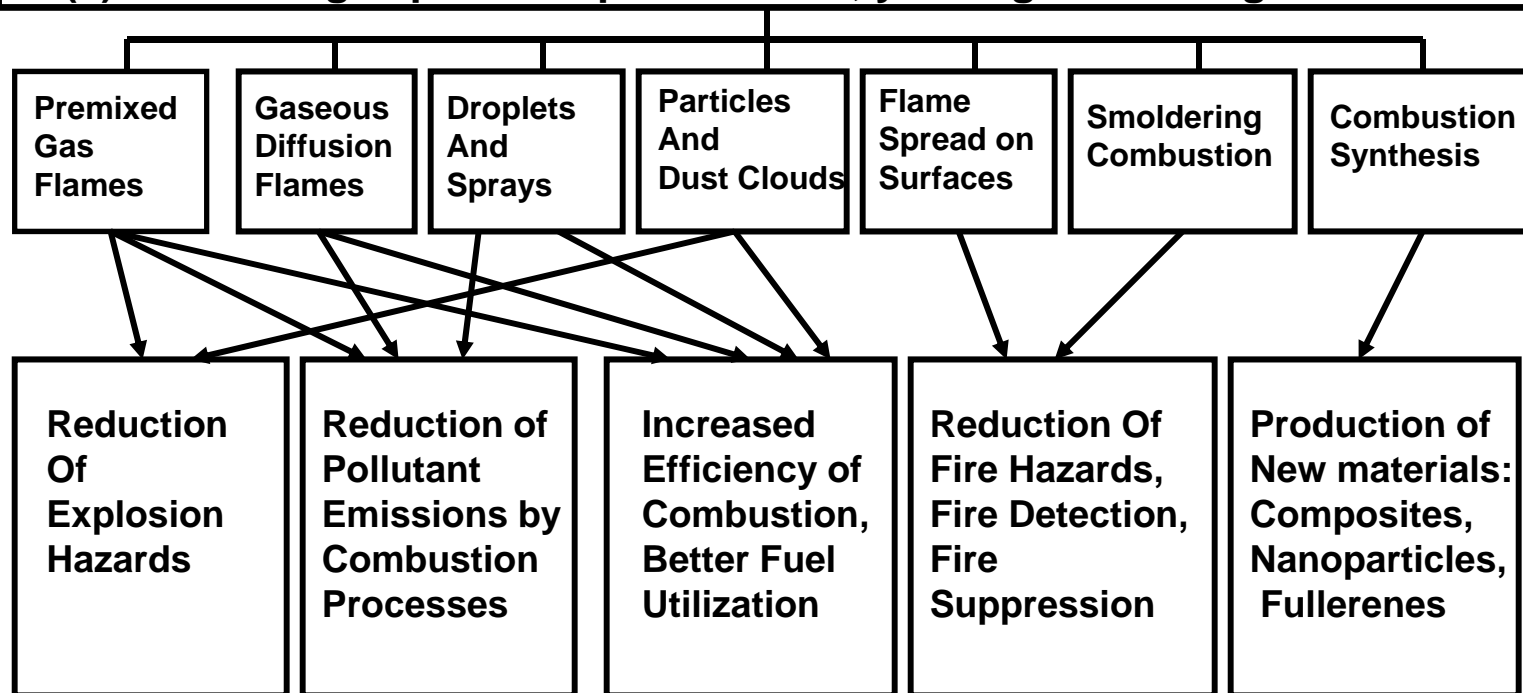
- 1. What are the areas where microgravity research can contribute to the field of combustion?**
- 2. What progress has been made in the field of microgravity combustion?**
- 3. Is there a significant potential for further progress to be made in microgravity combustion science?**
- 4. Will research in microgravity combustion make a significant contribution to NASA's exploration goals?**



# Microgravity Combustion Topics and Areas of Impact

Removing gravity permits more fundamental studies by:

- (1) Elimination buoyancy-driven flows
- (2) Eliminating settling and stratification
- (3) Permitting truly one-dimensional (spherical) geometries
- (4) Permitting expansion of parameter-space for model testing
- (5) Permitting expanded spatial scales, yielding better diagnostic resolution





# Microgravity results in textbooks (impact on the field)

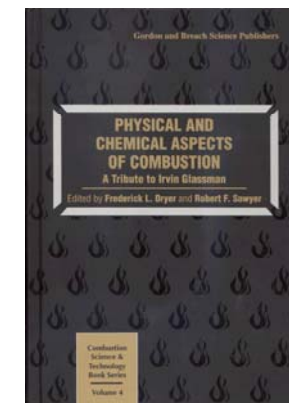
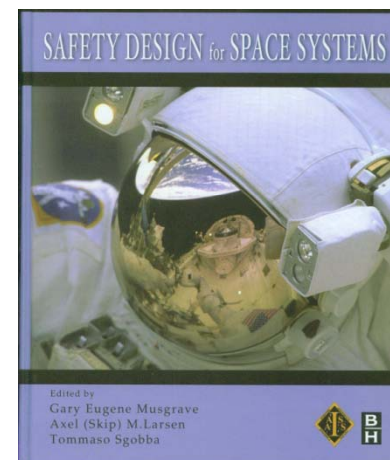
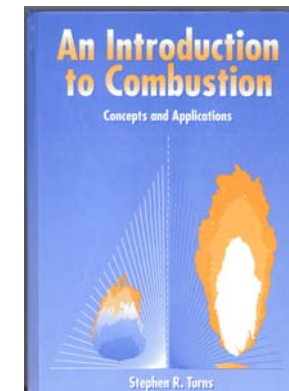
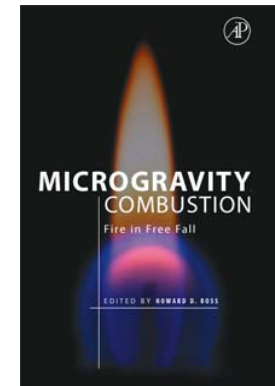
“Fire in Free Fall” edited by Howard Ross. Solicited by Academic Press.

“An Introduction to Combustion” Stephen Turns, refers to NASA’s droplet combustion research in low gravity.

“Physical and Chemical Aspects of Combustion” edited by F.L. Dryer and R.F. Sawyer discusses results of flame spread, droplet combustion research funded by NASA.

“Safety Design for Space Systems” edited by Musgrave et al. contains a chapter on fire safety based on microgravity program results.

**Candle-flame results** in low-gravity have captured the imagination of numerous people and have been used in numerous school publications.





# Flame Spread Research

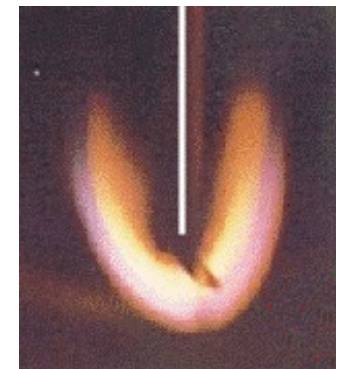
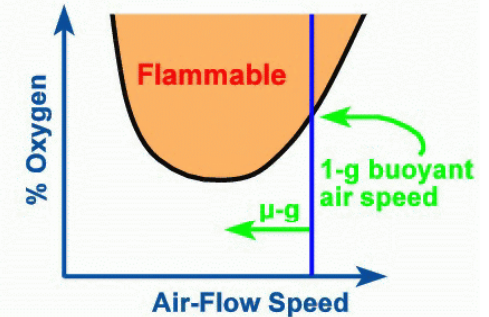
Low speed air flows achieved only in reduced gravity have a strong impact on material flammability. Flame spread behavior in low-gravity is substantially different from 1-g

Flame spread has a non-monotonic dependence on gravity level. Intermediate gravity levels may be the most hazardous.

Material ignitability can increase at reduced pressure.

Prevalent assumption that 1-g is always a worse case than low-g may be incorrect.

**Development of a predictive understanding of ignition and flame spread, particularly for thick fuels remains incomplete.**



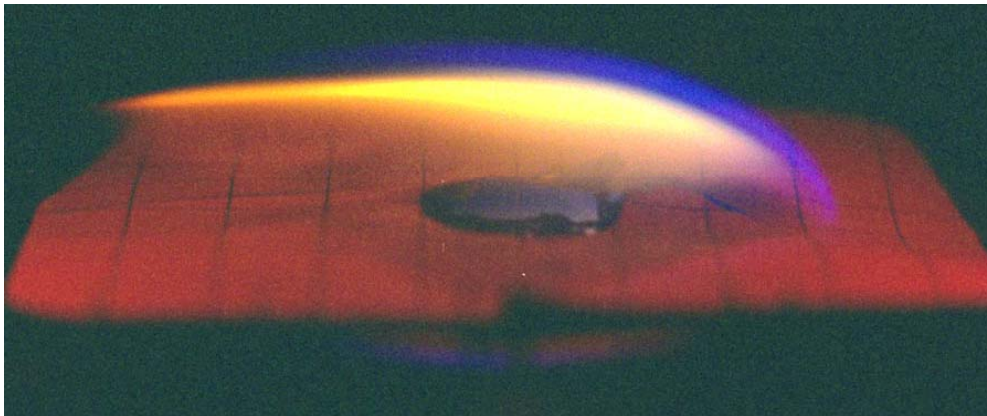




# Flame Spread

Ignition at the middle of the sample:

- Flame spreads upstream, however, in the shape of a fan.
- With an increase in the incoming air flow velocity, the fan angle increases due to an increase in oxygen supply rate.
- This is completely contrary to normal gravity
- At low air flows limiting conditions allow an unpredicted smoldering pattern to occur in thin cellulose.



(a)



(b)



(c)



(d)





# Premixed Systems

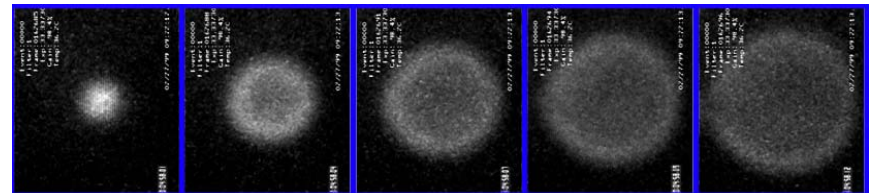
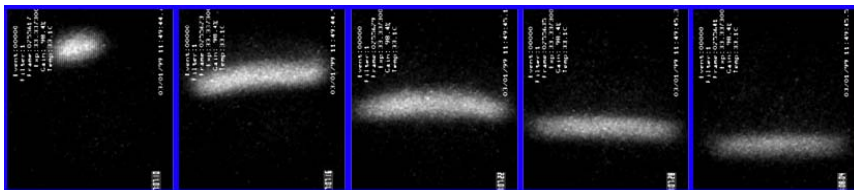
Presents a unique opportunity for low-energy flames:

Stationary, spherical flame structure (flame balls), proposed by Zel'dovich, a famous Russian mathematician, over half a century ago, achievable in low-gravity. Self-extinguishing flames and flame strings. High-Lewis number pulsating and traveling wave instabilities in premixed gas combustion.

Experimental measurements of premixed gas flammability limits in microgravity, clarify issues regarding the role of buoyancy in limit phenomena.

Opportunities to establish unusual initial conditions (stratification etc.)

**Areas of interest: flame propagation through gradients of reactivity; cool flames; diffusion properties in flame conditions; limit behavior.**



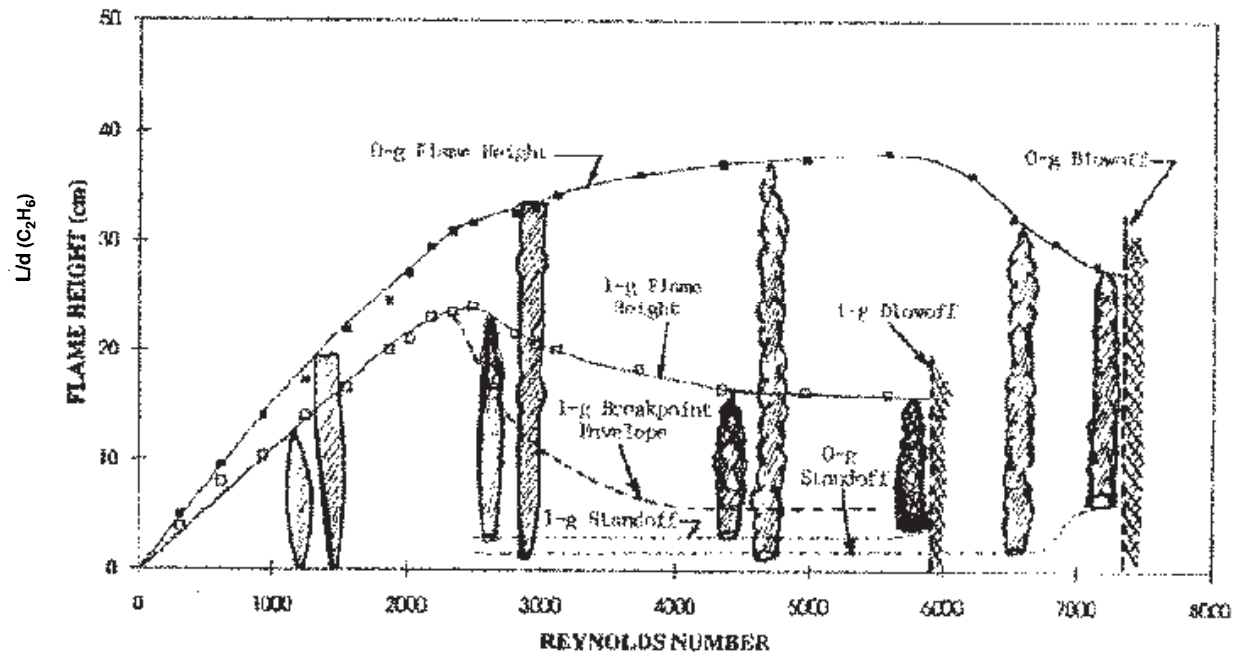
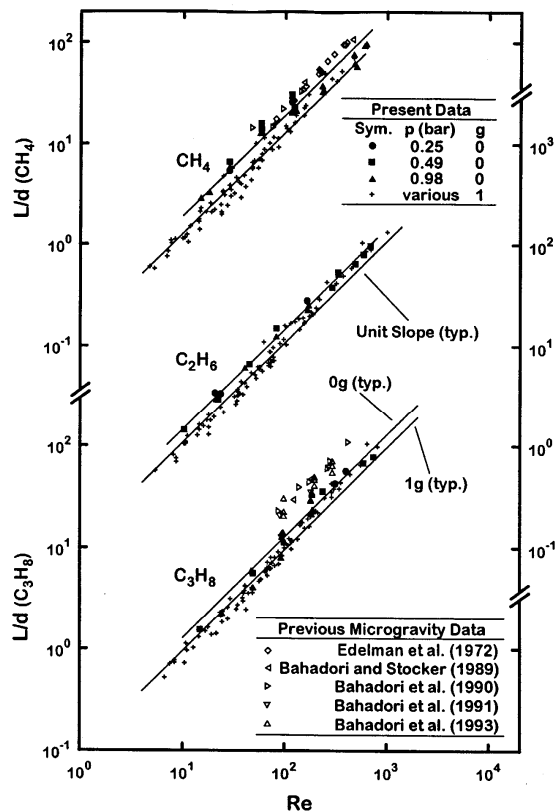


# Non-Premixed Systems

Buoyancy intrudes on flame structure even at high Froude numbers.

Simple flame shape models have now been validated by ground-based microgravity testing providing classical data for the text books of the future.

Idealized flame geometries for flame structure measurements.





## Metal Combustion

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Ground-based testing has shown that metal flammability can be substantially increased in low-gravity. Most notably copper (considered non-flammable in 1-g) burns actively in 0-g. This has serious implications for the design of oxygen systems for low-g.

This is attributed to changes in the stability of the fluid melt.

**Reduced gravity enables steady melt layer and gas flow conditions.**



# Diffusion Flames / Soot

## CANDLE FLAMES

Classical diffusive  
combustion system

Excellent tutorial for the  
public

Challenging system for  
detailed modeling

Demonstrated the long term  
viability of diffusion flames  
on condensed fuels







## Diffusion Flames / Soot

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**Soot concentrations raised in low gravity, enhanced flow and convection control. Simpler flame geometries.**

Flames dominated by momentum and diffusion e.g.,  
spherical flames

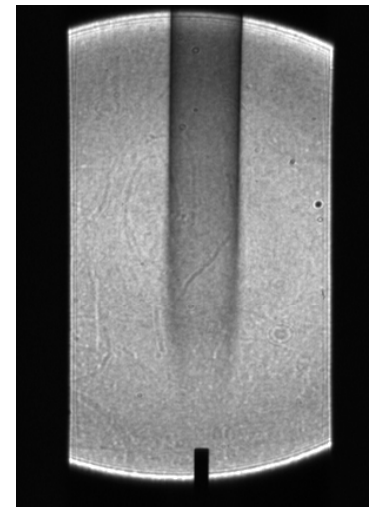
to study chemical kinetics

Flames with long residence times

enabling improved studies of soot

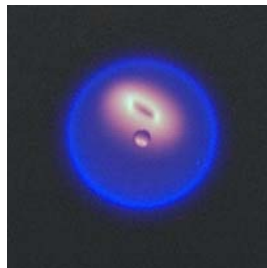
Flames with large scales

allowing improved measurement of the structure





# Droplet Combustion



## APPLICATIONS

- 85% of all US energy is derived from the combustion of fossil fuels, of this 39% (of total) is from combustion of liquid petroleum-based fuels (an astounding 97% of energy consumption in the transportation sector is liquid fuels)
- Droplet experiments provide an idealized geometry to develop fundamental experimental data to validate detailed chemical kinetic models
- Provide building blocks for detailed combustion engine modeling for optimized performance.



## Future possibilities

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**Is there a significant potential for further progress to be made in Microgravity Combustion Science?**

**The research community was not idea limited. A broad range of topics were pursued ranging from:**

- **Fundamental Combustion Theory**
- **Applied Combustion Topics**
- **Exploration Related Investigations**

**These areas still contain many unexplored opportunities.**



# Research Areas of Interest

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## **Gaseous Flames**

- Diffusion Flames
- Premixed Flames
- Partially Premixed Flames
- Triple Flames
- Flame-Vortex Interactions
- Kinetics
- Electrical Field Effects
- Magnetic Field Effects
- Flame Suppression
- Edge Flames

## **Droplets, Sprays, Particles, Dusts**

- Single Droplets
- Droplet Arrays
- Sooting Droplets
- Sprays
- Particle Combustion
- Dust Clouds
- Bubble Combustion

## **Combustion Synthesis**

- SHS
- Fullerene production via Flames
- Flame nanoparticle production
- Flame Agglomerate production
- Plasma Synthesis

## **Surface Combustion/Fire Safety**

- Flame Spread
- Flammability Testing
- Flame Detection
- Extinguishment
- Smoldering
- Liquid Pool Combustion
- Secondary Fires

## **Miscellaneous**

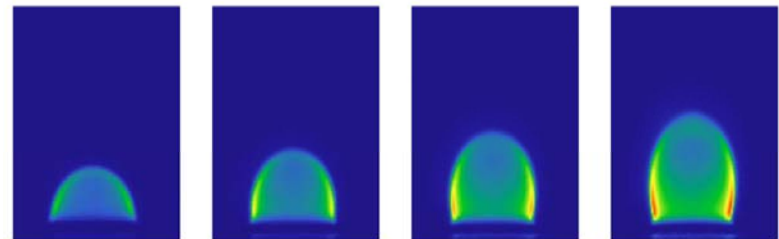
- G-Jitter Effects
- Propellant Combustion
- Cold Boundary Flames
- Diagnostics Development





# Terrestrial issues where microgravity combustion can have impact

- **Energy**
  - High-efficiency, low-emission flames can be near limit, which are unstable, where kinetics are important
- **Environment (e.g., global warming)**
  - Carbon sequestration
    - High oxygen flames
      - Oxy-fuel flames
      - Integrated Gasification Combined Cycle (IGCC)
  - Reduced CO<sub>2</sub> through use of fuels that are high in H<sub>2</sub>
    - Need for improved understanding of transport and instability
  - Soot control and reduction
- **Combustion Technology**
  - Electric field control of flames
- **Hydrogen safety (alternative fuels)**
- **Mine safety-premixed systems**





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**Can research in Microgravity  
Combustion make a significant  
contribution to NASA's exploration  
goals?**



## Exploration Areas affected by reacting systems

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Fire Prevention Detection and Suppression

Extra Vehicular Activity (through atmosphere choice)

In Situ Resource Utilization (reactor systems)

Environmental Monitoring and Control (Sensor design and post-fire cleanup)



# Fire Safety Issues

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**Atmosphere Selection-Material Flammability**

**Fire Detection**

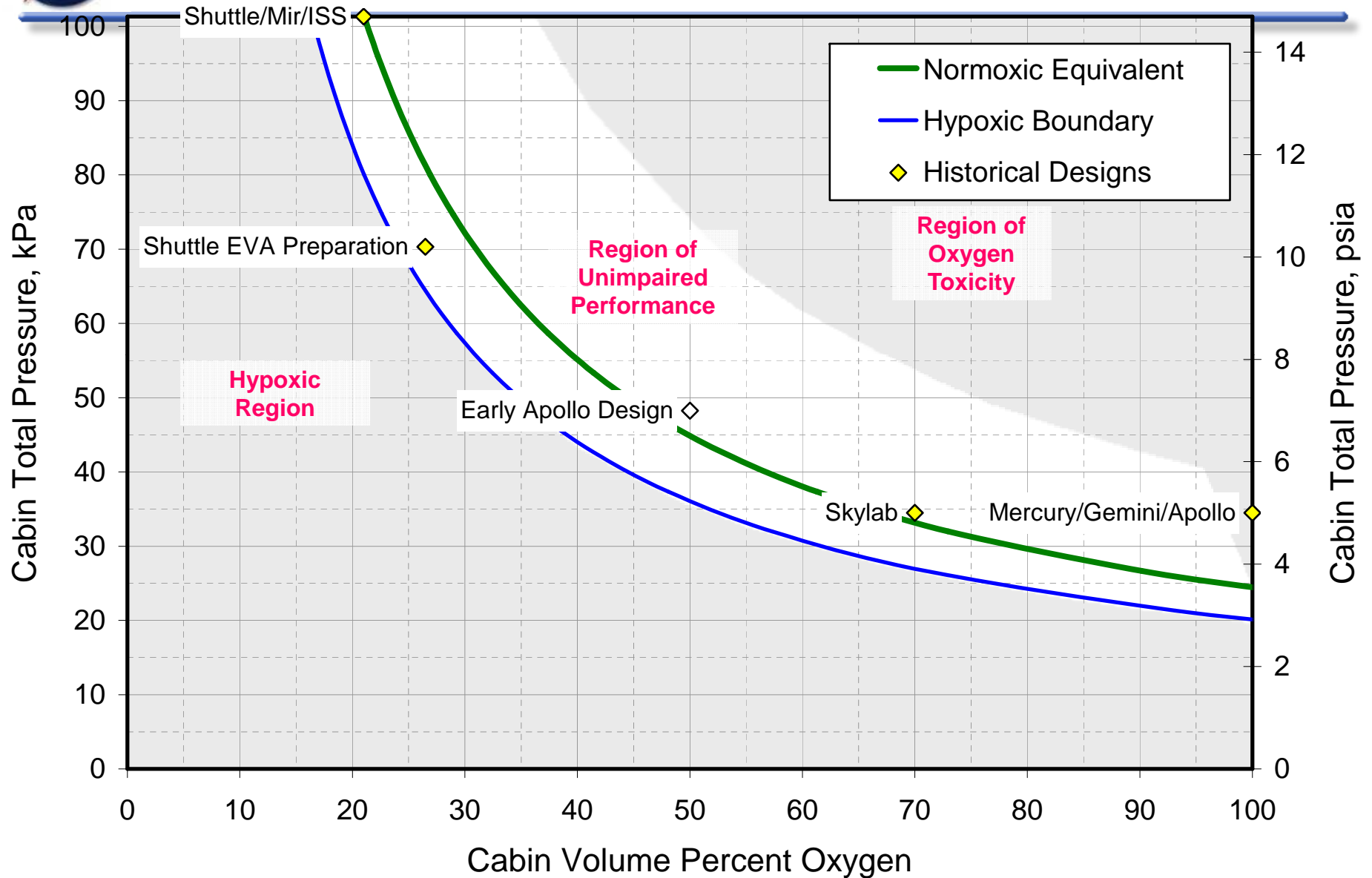
**Fire Suppression**

**Building upon the accomplishments in the ground-based and flight programs, we are at the cusp of making substantial improvements in NASA's space craft fire safety effectiveness and reliability.**



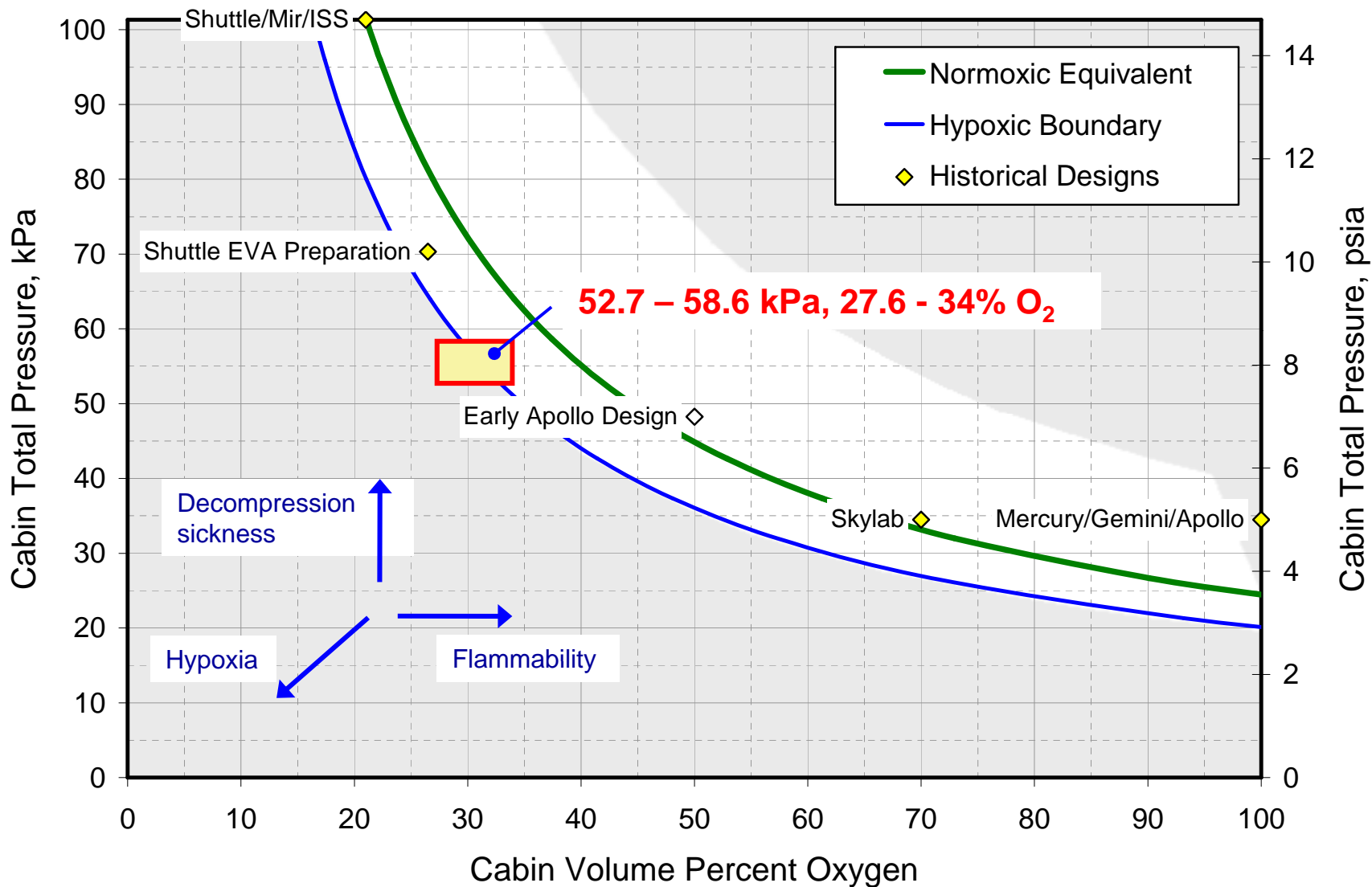


# What is the atmosphere like on spacecraft?





# Design Space for new vehicles





## **What are the Flammability concerns?**

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**Environment (34% oxygen and ~ 8 psia) is a “new condition”**

- Very limited material data**
- Pressure effects have received limited study**
- Program approach is to push ahead with existing test methodology**
- We are evaluating if this is sufficiently conservative**
  - Does ignitability change**
  - Do the flammability limits measured in NASA’s Test #1 represent the low-g behavior?**
- Some issues have not been examined (e.g. hair)**



## Fire Detection: Motivation

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- Given the increased flammability challenges imposed by the new spacecraft atmosphere. Early fire detection is of increased importance
- Virtually no work has been conducted looking in detail at the detection of fires in low-gravity.



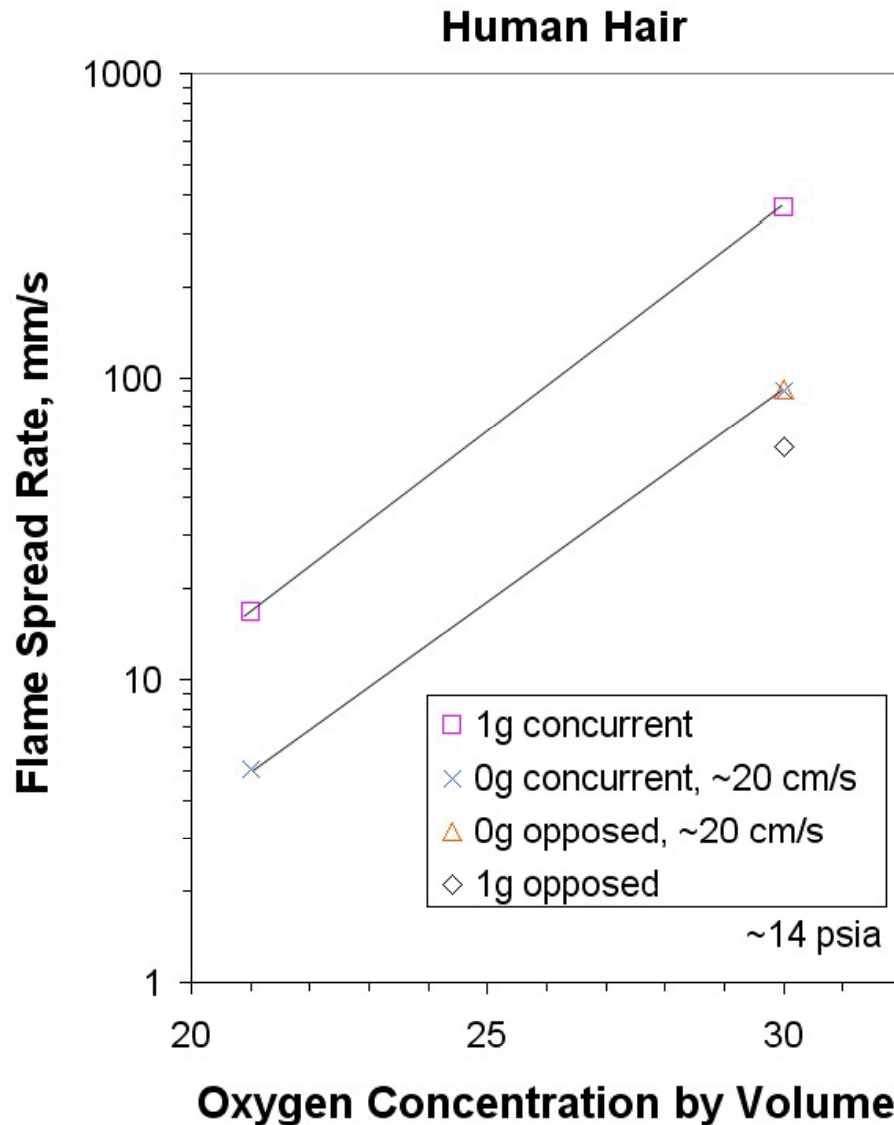


## Hair Flammability in Spacecraft Atmospheres





# Flame Spread Rates



Concurrent spread rates are more than an order of magnitude faster in 30% O<sub>2</sub> compared to 21% O<sub>2</sub>.

1g concurrent spread is faster than 0g concurrent spread.

0g is faster than 1g for opposed spread (30% O<sub>2</sub>, 14.7 psia)

Opposed and Concurrent spread rates are similar in 0g under the conditions tested (30% O<sub>2</sub>, 14.7 psia, 20 cm/s)