

SPACE STATION FREEDOM COMBUSTION RESEARCH

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ABSTRACT

Extended operations in microgravity, on board spacecraft like Space Station Freedom, provide both unusual opportunities and unusual challenges for combustion science. On the one hand, eliminating the intrusion of buoyancy provides a valuable new perspective for fundamental studies of combustion phenomena. On the other hand, however, the absence of buoyancy creates new hazards of fires and explosions that must be understood to assure safe manned space activities. These considerations - and the relevance of combustion science to problems of pollutants, energy utilization, waste incineration, power and propulsion systems, and fire and explosion hazards, among others - provide strong motivation for microgravity combustion research.

The intrusion of buoyancy is a greater impediment to fundamental combustion studies than to most other areas of science. Combustion intrinsically heats gases with the resulting buoyant motion at normal gravity either preventing or vastly complicating measurements. Perversely, this limitation is most evident for fundamental laboratory experiments; few practical combustion phenomena are significantly affected by buoyancy. Thus, we have never observed the most fundamental combustion phenomena - laminar premixed and diffusion flames, heterogeneous flames of particles and surfaces, low-speed turbulent flames, etc. - without substantial buoyant disturbances. This precludes rational merging of theory, where buoyancy is of little interest, and experiments, that always are contaminated by buoyancy, which is the traditional path for developing most areas of science. The current microgravity combustion program seeks to rectify this deficiency using both ground-based and space-based facilities, with experiments involving space-based facilities including: laminar premixed flames, soot processes in laminar jet diffusion flames, structure of laminar and turbulent jet diffusion flames, solid surface combustion, one-dimensional smoldering, ignition and flame spread of liquids, drop combustion, and quenching of particle-air flames.

Unfortunately, the same features that make microgravity attractive for fundamental combustion experiments, introduce new fire and explosion hazards that have no counterpart on earth. For example, microgravity can cause broader flammability limits, novel regimes of flame spread, enhanced effects of flame radiation, slower fire detector response, and enhanced combustion upon injecting fire extinguishing agents, among others. On the other hand, spacecraft provide an opportunity to use "fire-safe" atmospheres due to their controlled environment. Investigation of these problems is just beginning, with specific fire safety experiments supplementing the space-based fundamental experiments listed earlier; thus, much remains to be done to develop an adequate technology base for fire and explosion safety considerations for spacecraft.

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COMBUSTION RESEARCH**

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INTRODUCTION

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RELEVANCE OF COMBUSTION SCIENCE

SEVERAL CONCERNS MOTIVATE FUNDAMENTAL COMBUSTION RESEARCH:

- **Combustion-generated pollutants are re-emerging as a major problem.**
- **New combustion technologies are needed for effective energy utilization.**
- **Municipal and hazardous waste incineration is needed to replace landfills and storage.**
- **Fire and explosion hazards remain a source of excessive injuries, and loss of life and property on earth.**
- **New combustion technologies are needed for advanced aircraft and spacecraft propulsion systems.**
- **Current understanding of fire and explosion hazards in spacecraft is very limited.**

OPPORTUNITIES AND CHALLENGES

THE MICROGRAVITY ENVIRONMENT OF SPACECRAFT OFFERS BOTH OPPORTUNITIES AND CHALLENGES TO COMBUSTION SCIENCE:

- **The implications of microgravity experimentation are as important as the development of computers and optical diagnostics.**
- **Increased activity in space implies new fire and explosion hazards beyond our earth-bound technology base.**

COMBUSTION SCIENCE OPPORTUNITIES

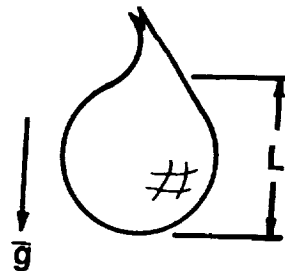
BUOYANCY LIMITATIONS OF MOTIONLESS FLAMES

BUOYANCY IS AN INTRUSION BECAUSE FEW PRACTICAL FLAMES
ARE BUOYANT:

- Buoyant/molecular transport is given by the Grashof number:

$$Gr = \Delta\rho g L^3 / (\rho \nu^2)$$

- For flames, $\Delta\rho/\rho \sim 1$, while $Gr \ll 1$ for negligible buoyancy.



- At atmospheric pressure, this implies:
 $L < \text{Order } (100 \mu\text{m})$

EXPERIMENTS ON SUCH SCALES CAN NOT BE RESOLVED BY
EXISTING, OR ANTICIPATED, COMBUSTION INSTRUMENTATION.

BUOYANCY LIMITATIONS OF PROPAGATING FLAMES

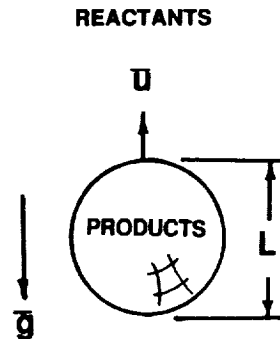
THE CRITERION FOR NEGLIGIBLE BUOYANCY EFFECTS DIFFERS FOR PROPAGATING FLAMES:

- Buoyant/propagation convection is given by the Richardson number:

$$Re = \Delta\rho gL / (\rho u^2)$$

- For flames, $\Delta\rho/\rho \sim 1$, $L > 10$ mm while $Ri \ll 1$ for negligible buoyancy
- This implies:

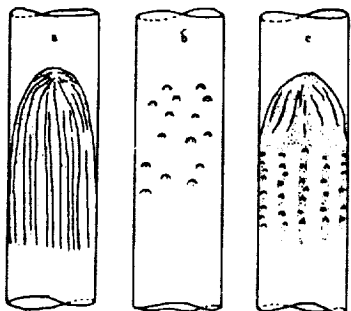
$u > \text{Order (1 m/s)}$.



THIS IS COMPARABLE TO MAXIMUM BURNING VELOCITIES BUT PRECLUDES STUDIES NEAR FLAMMABILITY LIMITS.

FLAMMABILITY LIMITS

BUOYANCY HAS THWARTED ATTEMPTS TO UNDERSTAND FLAMMABILITY LIMITS — AN IMPORTANT FUNDAMENTAL PROPERTY OF FLAMES:



Lean Flammability Limits
(% Fuel in Air)^a

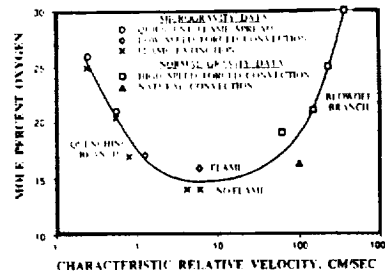
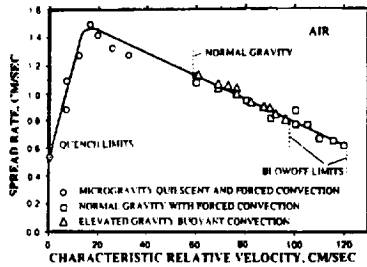
Config.	Methane	Propane
Downward	5.85	2.20
Upward	5.25	2.15
Microgravity	5.25	2.06

^aFrom Strehlow et al. (1986)

- Upward propagation exhibits obvious instabilities but buoyancy affects all flame orientations.
- Lean limits generally are lower in microgravity than normal gravity for hydrocarbons, except for methane.

FLAME SPREAD ALONG SOLID SURFACES

FLAME SPREAD ALONG SURFACES IS AFFECTED BY BUOYANCY, AMBIENT OXYGEN CONCENTRATION AND OPPOSING FLOW ALONG THE SURFACE:



- Microgravity conditions allow a low velocity regime to be reached that is inaccessible at normal gravity.
- Spread rates are highest and flammability limits are lowest in this low velocity regime.

NOTABLY, THE LOW VELOCITY REGIME IS TYPICAL OF NORMAL VENTILATION CONDITIONS ON SPACECRAFT.

BUOYANCY LIMITATIONS OF CONVECTING FLAMES

BUOYANCY PREVENTS STUDY OF LOW REYNOLDS NUMBER FLAMES:

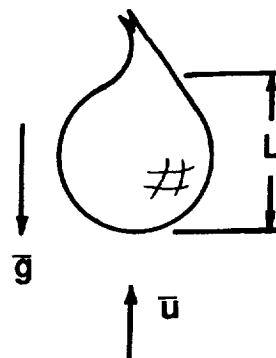
- The characteristic Reynolds number of a forced flame is:

$$Re = Lu/v = (Gr/Ri)^{1/2}$$

- For L ca. 10 mm, $Gr = \text{Order } (10^3)$ while $Ri < \text{Order } (10^{-1})$ for negligible buoyancy.

- This implies:

$$Re > \text{Order } (10^2)$$

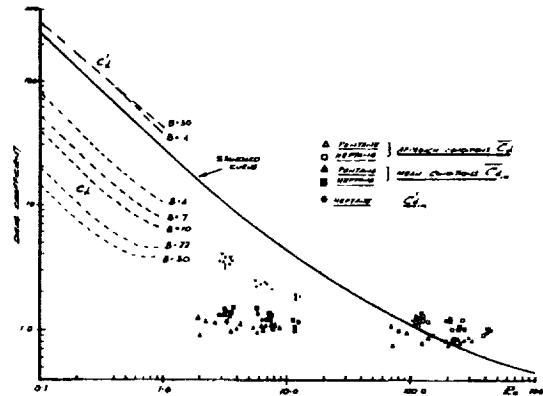


THUS, THE STOKES FLOW REGIME ($Re < 1$) IS NOT ACCESSIBLE, WHILE THE LARGE Re LIMITS SPATIAL RESOLUTION AND CAUSES TRANSITION TO TURBULENCE.

CONVECTIVE DROP COMBUSTION

BUOYANCY HAS PREVENTED RESOLUTION OF EFFECTS OF CONVECTION ON DROP BURNING RATES — AN IMPORTANT HETEROGENEOUS FLAME:

- Exact theories are limited to low Reynolds numbers.
- Buoyancy prevents reaching low Reynolds numbers for experimentation.
- Deformation and internal circulation intrude at accessible Reynolds numbers.

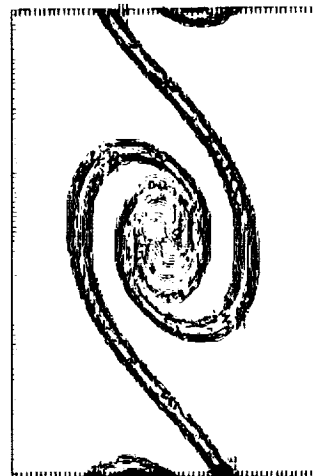


THUS, CONTROVERSIES ABOUT CONVECTIVE EFFECTS CONTINUE; ONLY EXPERIMENTS IN MICROGRAVITY CAN RESOLVE THIS ISSUE.

TURBULENT COMBUSTION

TURBULENT COMBUSTION IS THE FOREMOST UNRESOLVED PROBLEM OF COMBUSTION SCIENCE:

- Numerical simulations are limited to low Reynolds number conditions.
- Buoyancy immediately accelerates combusting flows to high Reynolds numbers.
- Computer development rates imply 50-100 years before feasible experiments can be simulated.



EXPERIMENTS IN MICROGRAVITY CAN ACCOMPLISH THE MERGER MUCH SOONER AND OFFER VALUABLE INSIGHTS OF THEIR OWN.

COMBUSTION SCIENCE CHALLENGES

PERSPECTIVES ON SPACECRAFT FIRE SAFETY

"FIRE IS ONE OF THE MOST FEARED HAZARDS IN SPACECRAFT."

"...STRICT LIMITATIONS ON ACCEPTABLE MATERIALS, AND STRINGENT HIGH-SAFETY-FACTOR OPERATING PROCEDURES ALL CAN RESTRAIN USEFUL ACTIVITIES IN SPACE MISSIONS."

"PRESENT SPACECRAFT FIRE-SAFETY PROCEDURES ARE ADEQUATE, TO THE EXTENT OF THE LIMITED KNOWLEDGE OF FIRE BEHAVIOR IN THE MILIEU OF SPACE ... FUTURE SPACECRAFT CONCEPTS, HOWEVER, WILL MAKE MORE DEMANDS ON FIRE SAFETY."

**R. Friedman and K. R. Sacksteder
NASA/LeRC, 1988**

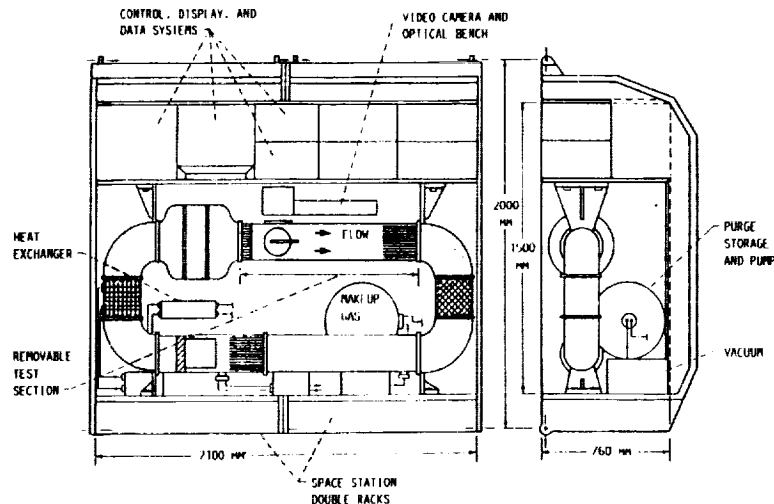
EFFECTS OF MICROGRAVITY ON FLAMES

FIRE HAZARDS IN MICROGRAVITY DIFFER FROM OUR EARTH-BOUND EXPERIENCE:

- Flammability limits and flame spread rates are not the same, and can be less conservative.
- Flame volumes are much larger, and flame radiation is more dominant, if forced flows are absent.
- Limited space enhances problems of smoldering fires whose properties are not understood in microgravity.
- The response of fire detectors is slower, and the effect of fire extinguishing agents is modified.
- Aerosols do not settle, yielding conditions having no counterpart on earth, and greater fire hazards.

SPACE STATION FREEDOM FLOW LOOP FACILITY

THIS FACILITY IS DESIGNED FOR FLAMMABILITY STUDIES WITH VARIABLE FORCED VELOCITIES:



FIRE-SAFE ATMOSPHERES

- **Atmospheres that support life but not combustion are known, and are used successfully for underwater systems.**
- **Thus, fire hazards would be left behind on earth if the same approach could be developed for spacecraft.**
- **This is not feasible — near term — due to system complications and uncertainties of flame properties and human factors.**
- **The implications of fire-safe and inerting atmospheres are enormous; defining them should have high priority.**

SUMMARY

CURRENT MICROGRAVITY COMBUSTION SCIENCE FLIGHT PROGRAM^a

Title	Investigator	Affiliation
Solid Surface Combustion ^b	R.A. Altenkirch	Miss. State U.
One-Dimensional Smoldering	A.C. Fernandez-Pello	UC-Berkeley
Soot Processes in Jet Flames	G.M. Faeth	U/Michigan
Laminar & Turbulent Jet Flames	M.Y. Bahadori	SAIC
Laminar Flames: Limits	P.D. Ronney	Princeton U.
Liquid Pool Flames	H. D. Ross	NASA/LeRC
Combustion of Pure Fuel Drops	F.A. Williams	UC-San Diego
Combustion of Blended Drops	A. Gökalp	CNES
Dust-Air Mixture Flames	J.H.S. Lee	McGill U.

^aThe glove-box facility on USML-2 also has been used for preliminary tests of flame spread, smoldering and liquid combustion.

^bFlown on the Space Shuttle.

SUMMARY

- Gravity has impeded fundamental understanding of combustion more than most areas of science; access to microgravity should yield major breakthroughs.
- Flames in microgravity are very different from our earth-bound experience; rational safety considerations for spacecraft require an improved technology base.
- Fire-safe atmospheres could permanently eliminate fire hazards from future spacecraft; this interdisciplinary research problem merits high priority.