# PRIORITIES FOR MICROGRAVITY COMBUSTION RESEARCH AND GOALS FOR WORKSHOP DISCUSSIONS

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## Introduction

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 are needed to replace landfills and storage, new combustion technologies are needed for advanced aircraft and spacecraft propulsion systems, and current understanding of fires and explosion hazards is limited — particularly for space-craft environments. Thus, it is of interest to determine how experimentation using microgravity facilities can advance research relevant to these problems.

Effects of buoyancy have had an enormous negative impact on the rational development of combustion science. Thus, microgravity (μg) offers a potential breakthrough in combustion research capabilities that could be comparable to the impact of laser diagnostics and numerical computations in recent years. On the other hand, human operations in spacecraft involve fire-safety issues at μg that largely are unexplored. Thus, μg offers both unusual opportunities and unusual challenges to combustion science. The objectives of this paper are to highlight the intrusion of buoyancy on fundamental combustion studies, the current priorities of microgravity combustion program and the goals of this workshop. The present discussion is brief, see several recent reviews of aspects of μg combustion research for more details [1-6].

## Intrusion of Buoyancy

The intrusion of buoyancy is a greater impediment to combustion than most other areas of science because density changes caused by chemical reaction initiate buoyant flows that vastly complicate both the execution and interpretation of measurements. Thus, the presence of gravity prevents some fundamental phenomena — most laminar one-dimensional premixed and diffusion flames, low Reynolds number heterogeneous flames, flame spread in dispersed heterogeneous media, etc. — from being observed at all. Perversely, problems of buoyancy are greatest for fundamental laboratory experiments where good temporal and spatial resolution are needed; few practical combustion phenomena are dominated by effects of buoyancy.

The limitations of buoyancy on combustion studies have been quantified using phenomenological theories [4-6]. For example, for effects of buoyancy to be small in a motionless combustion environment at atmospheric pressure, the dimensions of the flame should be no larger than 100 μm; unfortunately, it is not possible to resolve experiments on such scales using either existing or anticipated combustion apparatus and instrumentation [4-6]. Experiments at subatmospheric pressures can increase allowable flame sizes, and this has been exploited in the past, however, the available range is limited due to low reaction rates leading to extinction at low pressures, see [6] and references cited therein.

Experiments in the presence of flow velocities offer a way of circumventing buoyancy effects, however, relatively large velocities must be used causing spatial resolution problems similar to those just discussed, and problems with approaching limiting conditions where either combustion rates or flow velocities are small. Thus, for effects of buoyancy to be small for premixed flames, at atmospheric pressure, laminar flame speeds should be greater than 1 m/s [4-6]. This prevents approaching flammability limits without effects of buoyant motion, which is problematical because premixed flames are unusually responsive to stretch induced by gas motion near limits [7]. Similarly, nonpremixed flames should have characteristic Reynolds numbers of 100 or more to avoid effects of buoyancy at atmospheric pressure [4-6]. This prevents approach to the low Reynolds number Stokes flow regime that has been invaluable for understanding fluid mechanics.

The effect of buoyancy is so ubiquitous that we generally do not appreciate the enormous negative impact that it has had on the rational development of combustion science. For example, aside from limited exploratory work at μg conditions, we have never observed the most fundamental processes of combustion without substantial disturbances of buoyancy. This includes simple one-dimensional configurations and low Reynolds number flows that have been invaluable in other areas of science. Thus, buoyancy prevents the rational merging of theory, where buoyancy frequently is of little interest, and experiments, which always are contaminated by effects of buoyancy at normal gravity (ng).

Turbulent flames, one of the most important unresolved problems of combustion science, provides a graphic example of how buoyancy impedes the parallel development of theory and experiment. Three-dimensional time-dependent numerical simulations provide a rational way to study some phenomena of turbulence but the calculations only will be tractable at low Reynolds numbers for some time to come [8]. Unfortunately, such conditions cannot be duplicated in the laboratory at ng because buoyancy immediately accelerates any low-speed initial condition into a high Reynolds number flow. Similar problems abound for other important combustion problems, e.g., the combustion of sprays and particles due to problems of phase separation, etc. With no massive breakthrough in computer technology in the offing, combustion experiments at μg offer the most promising approach toward resolving this theoretical/experimental dichotomy of combustion science.

### Spacecraft Fire Safety

The same features that make μg attractive for fundamental combustion experiments introduce hazards of fires and explosions that have no counterpart on earth. The main concern is that virtually all existing information concerning design procedures to control fires and explosions is based on experience at ng. Even current qualification procedures for materials used in space involve tests at ng, justified by rather limited measurements at μg [3]. Since we know that combustion processes are very different at ng and μg, there is little basis for confidence that this practice is correct. Additionally, excessive caution to reflect our poor understanding of μg fire environments can unduly restrict our capabilities for exploiting space [3].

Addressing spacecraft fire safety concerns at μg will require a substantial research effort. Curiously, an alternative that could eliminate many of these concerns has not received much attention. This involves the use of fire-safe atmospheres in spacecraft, similar to the methods used to avoid fires in undersea systems [9]. This potential exists because fire-related phenomena tend to be functions of the *fractional* amount of oxygen in the atmosphere while human comfort and performance mainly depend on the ***absolute*** amount of oxygen in the atmosphere. Thus, it may be possible to find a composition for spacecraft atmospheres that will not support combustion but will support normal human activities indefinitely. However, available information concerning fire-safe atmospheres — combustion properties at μg, the performance and health of humans and other biological systems, and potential impacts on spacecraft design and operation — are woefully inadequate in view of the importance of this selection. Thus, fire-safe atmospheres appear to merit a broad-based interdisciplinary research program due to their potential impact on future human activities in space.

## Current Priorities for Microgravity Combustion Research

An objective of this workshop is to identify priority areas within combustion science where microgravity-based investigations are needed. Based on the results of the First International Microgravity Combustion Workshop, the Discipline Working Group (DWG) that advises NASA in the area of microgravity combustion science has set the following priorities: (1) turbulent reacting flows; (2) heterogeneous combustion such as droplets, particles, slurries, solid fuels and pools of liquid fuels; and (3) laminar homogeneous combustion phenomena such as ignition, flameholding, flammability limits, flame instabilities, and diffusion flames. Prioritization also was made with respect to applications, with spacecraft fire safety selected as the single most important application area.

The current microgravity combustion science program only reflects these priorities with respect to relevance to spacecraft fire safety, with the bulk of the work associated with heterogeneous combustion. This status is summarized in Table 1. In this table, flight studies denote investigations that are candidates for experimentation in space. Other studies either use ground-based μg facilities, such as drop towers and aircraft flying parabolic trajectories, or are theoretical studies. The relatively few studies of turbulent combustion is surprising in view of the current high priority of this area. In contrast, seven flight studies and 18 total studies are related to spacecraft fire safety, implying a strong response to this priority area following the last NASA Research Announcement (NRA) in 1989.

Table 1 Current Microgravity Combustion Science Program

| Priority | Area | Flight Studies | Total Studies |
|---|---|---|---|
| 1 | Turbulent Reacting Flows | 1 | 3 |
| 2 | Heterogeneous Combustion | 7 | 19 |
| 3 | Laminar Homogeneous Flames | 2 | 6 |

## Goals for Workshop Discussions

As the microgravity combustion science program develops both the priorities and the focus of the research program will change. Thus, an objective of the workshop is to highlight areas where changes should be encouraged. Some questions that might be addressed during the discussions are as follows:

1. Are the areas and priorities selected by the DWG appropriate?

2. Are there new areas, e.g., combustion synthesis, metal combustion, etc., that merit emphasis in the next NRA?

3. What should be done to improve the content and balance of the flight and ground-based programs. and of experimental and theoretical programs?

4. Should a major interdisciplinary research program on spacecraft fire-safe atmospheres be recommended and what should be the combustion component of any such program?

5. Does the present program adequately address fundamental research issues relevant to spacecraft fire safety?

Funding is competitive within the microgravity combustion science program, and perhaps more importantly, between this program and other research areas of interest to NASA and other government agencies. Thus, an active high-quality microgravity combustion science program is required to assure continuing funding levels — much less increases. This workshop is one step in developing such a program; therefore, lively and productive discussions here will be a valuable service to the field of combustion.

## Acknowledgements

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## References

1. "Microgravity Combustion Science: A Program Overview;" NASA TM 101424, 1989.

2. "Microgravity Combustion Science: Progress, Plans and Opportunities," NASA TM 105410, 1992.

3. Sacksteder, K., *Twenty-Third Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1990, pp. 1589-1596.

4. Law, C.K., AIAA Paper No. 90-0120, 1990.

5. Faeth, G.M., AIAA/IKI Microgravity Science Symposium, Moscow, AIAA, Washington, 1991, pp. 281-293.

6. Law, C.K. and Faeth, G.M., "Opportunities and Challenges of Combustion in Microgravity," in preparation, 1992.

7. Kwon, S., Tseng, L.-K. and Faeth, G.M., Combust. Flame, Vol. 90, 1992, pp. 230-246.

8. Pope, S.B., *Twenty-Third Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1990, pp. 591-612.

9. Gann, R.G., Stone, J.P., Tatem, P.L., Williams, F.W. and Carhart, H.W., Combust. Sci. Technol., Vol. 18, 1978, pp. 155-163.

## COMMENTS

Question (Takashi Kashiwagi, NIST): (1) I am not sure that a flame-limited, atmospheric approach removes fire problems in a spacecraft entirely. Smoldering under certain conditions, such as well insulated and preheated cases, can continue even in several percent of $O_2$. It seems to me as long as there is manned flight there are fire safety issues.

(2) I should like to see clearly defined policy in which the combustion research areas related to fire research could be considered in Microgravity Science Program.

Answer: Fire-safe atmospheres to eliminate conventional unwanted fires would represent a substantial improvement of fire safety in spacecraft. Whether this can be achieved, and the conditions needed to prevent smoldering in microgravity, are open issues at this time that clearly merit further study. Your second comment relates to NASA policy issues, however; my understanding is that relationship of studies in the microgravity combustion program to spacecraft fire safety is a strong point in establishing the relevance of the research.

Question (Fred Dryer, Princeton University): My comment deals with prioritization of microgravity science to practical fire safety problems. Fire safety standards regarding the permissible concentrations of flammable gases and liquids are typically referred to about 10% of the lean limit, a value which apparently will change little from absence or presence of gravity. This does not mean that the science of flammability limits is not important to understand, only that its outcome may have little impact in the fire safety arena. On the other hand, limiting oxygen index apparently changes by as much as a factor of 2, an absolute change of substantial consequence to defining (fire) inert atmospheres. Finally, on Earth there is no experience with the flammability characteristics of wide-range polydisperse aerosols, a likely aerosol character in microgravity conditions.

In addition to the smoldering problem (which must be materials-controlled and studied), the latter two areas of microgravity combustion science would appear to me to be much higher priority than flammability limits.

Answer: My reference to flammability limits, in connection with fire-safe atmospheres, was meant to be generic and not related to a specific criterion like the lean flammability limit or the limiting oxygen index. Your point is well taken that the criteria to be used will influence the definition of fire-safe atmospheres. Clearly, the research issues in this area must involve both the nature and criteria for fire-safe atmospheres.

Question (A. Gomez, Yale University): One of the identified priority areas is that of turbulent reacting flows. Would you agree that before this research area can benefit from microgravity experimentation, we should wait for substantial improvement on available diagnostic techniques?

Answer: No, I see no reason to wait for improved diagnostics in order to address problems of turbulent reacting flows. First of all, available instrumentation at this point is equivalent to methods used to develop much of our understanding of turbulent flames. Next, the environment itself, which allows turbulent-like flame processes to proceed at much smaller velocities than on Earth, provides new potential for conventional experimental methods. Finally, I hesitate to exclude the possibility of some new approach being developed from available technology.