OVERVIEW OF NASA'S MICROGRAVITY COMBUSTION SCIENCE AND FIRE SAFETY PROGRAM

N93-20180

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The study of fundamental combustion processes in a microgravity environment is a relatively new scientific endeavor. A few simple, precursor experiments were conducted in the early 1970's. Today the advent of the U.S. space shuttle and the anticipation of the Space Station *Freedom* provide for scientists and engineers a special opportunity -- in the form of long duration microgravity laboratories -- and need -- in the form of spacecraft fire safety and a variety of terrestrial applications -- to pursue fresh insight into the basic physics of combustion. Through microgravity, a new range of experiments can be performed since:

- ***Buoyancy-induced flows are nearly eliminated.*** Due to the hot, less dense reaction products of combustion, buoyancy-induced flows tend to develop in normal gravity experiments, promoting self-turbulization and instabilities. Microgravity reduces these flows and their attendant complications, thus, furthering understanding of low-gravity behavior and, by direct comparison, related normal-gravity combustion processes.
- ***Normally obscured forces and flows may be isolated.*** Buoyancy frequently obscures weaker forces, such as electrostatic, thermocapillary, radiative and diffusional forces, which may be important near flammability limits. Further, the effect of low velocity forced flows can not normally be studied due to the onset of mixed convection. By removing buoyancy, the roles of these forces and flows may be observed, and compared to theory.
- ***Gravitational settling or sedimentation is nearly eliminated.*** Unconstrained suspensions of fuel droplets or particles may be created and sustained in a quiescent environment, eliminating the need for mechanical supports, levitators, or stirring devices and enabling a high degree of symmetry and/or quiescence to be achieved.
- ***Larger time or length scales in experiments become permissible.*** To limit buoyancy effects in normal gravity experiments, the size or duration of tests is often constrained. Microgravity permits larger scale experiments which in turn allow more detailed diagnostic probing and observation. Microgravity also enables new tests of similitude through experiment.

Combustion experiments have now been completed in drop towers and aircraft and have flown successfully on the Shuttle. As will be discussed in various papers at this workshop, unexpected and unexplained phenomena have been observed -- with surprising frequency -- in microgravity combustion experiments, raising questions about the degree of accuracy and completeness of our textbook understanding and our ability to estimate spacecraft fire hazards.

The interest in microgravity combustion science is not strictly academic. There have been four internal "fire" incidents in the U.S. Shuttle program, involving overheating or smoldering of wire insulation and electrical components from localized loss of cooling air or electrical short circuits. In each case, the crew observed the evolution of particles and odors; the potential fire was immediately suppressed by switchin g off the appropriate circuits, without resorting to the discharge of fire extinguishers. A severe incident was reported for the Soviet Salyut 7, requiring both the discharge of an extinguisher and venting of the uninhabited cabin atmosphere to the vacuum of space. The atmosphere of the space station was later replenished by stores from a supply flight. This experience has demonstrated that present spacecraft fire protection can respond to a variety of in-flight incidents. Nevertheless, there is growing appreciation for

* This paper is excerpted in part from NASA TM105410 entitled "Microgravity Combustion Science: Progress, Plans, and Opportunities" which was authored by members of the Microgravity Combustion Branch, Space Experiments Division, NASA Lewis Research Center. I have expanded it with several personal opinions and assessments.

the need for fundamental research and technology development with the longer-term objective of investigating and improving spacecraft fire-safety practices. A more complete understanding of combustion phenomena and flame characteristics contributes to the improvement of material acceptance standards, fire detection, extinguishment, and postfire rehabilitation in space. Moreover, low-gravity combustion research is necessary in assessing the effects of certain hazards that may be unique to or aggravated in space — smoldering or aerosol fires, for example.

Low-gravity combustion experiments may also yield methods to produce exotic materials such as fullerenes or highly ordered ceramic - metal composites. In this author's opinion, the costs of producing such materials in a space environment will probably prohibit their widespread manufacture in space; however, the results from space-based experiments could lead to needed understanding to produce these or related materials more readily or cheaply on Earth. Similarly fundamental experiments in heterogeneous combustion systems such as particle or aerosol clouds support improved understanding of Earth-based fire environments (e.g. grain bins, mine safety, spray combustion processes). One recent idea this author has heard involves using the long soot residence times available in microgravity to study agglomeration phenomena to be used to understand atmospheric contamination by particles from large-scale fires such as those which occurred recently in the oil fields in the Persian Gulf.

MICROGRAVITY LABORATORIES AND FACILITIES

There are several test facilities which provide a free fall or semi-free fall condition where the force of gravity is offset by linear acceleration, thus enabling a reduced gravity environment available for scientific studies. Each of the facilities has different capabilities and characteristics that must be considered by an investigator when selecting the one best suited to a particular series of experiments. Perhaps the most unique and challenging feature for researchers working in these facilities is the facility constraints. The researcher must place new emphasis on experimental requirements for power, volume, operating time, and weight. Operation is remote, being automated in the drop towers or through astronauts on the shuttle. Delicate hardware must be considered for shock isolation in the drop towers although items such as mirrors and incandescent lights regularly survive landing. Compatibility with vacuum environments may be needed as well. Balanced against these difficulties or constraints is the unique opportunity for scientific discovery, already verified in combustion experiments in microgravity: thought-provoking and surprising observations are the norm for nearly every experiment we have conducted.

To date, the majority of combustion studies have taken place in the NASA Lewis Research Center's (LeRC) two drop towers and Model 25 Learjet. The 2.2 Second Drop Tower, as the name implies, provides 2.2 seconds of low gravity test time for experiment packages with up to 150 kilograms of hardware mass. To lower residual acceleration, the experiment freely falls inside in an air drag shield. The facility offers both low cost and rapid turnaround time between experiments. It is often used for proof-of-concept or precursor experimentation; most microgravity combustion experimental investigations start here. The 5.18 second Zero-Gravity Facility with its 132 meter free fall distance in an evacuated drop chamber (again to lower residual accelerations) allows experiments of up to 450 kilograms in mass mounted in a one meter diameter drop bus. This facility probably provides the lowest available accelerations available today.

Specially modified jet aircraft flying parabolic trajectories can provide significant increases in low-gravity experiment time when compared to drop towers but not without the penalty of higher gravity levels. For an experiment fixed to the body of an aircraft, accelerations in the range of 10^{-2} g can be obtained for up to 20 seconds. During one flight several trajectories are possible. While aircraft may not offer true microgravity, they offer the significant advantages of permitting researchers to monitor their experiments in real-time, reconfigure them between trajectories and utilize delicate instrumentation precluded in drop tower tests because of severe shock loadings at the end of the drop. NASA's larger KC-135 aircraft at the Johnson Space Center also permits free-floated experiments achieving acceleration levels in the range of 10^{-4} g for 5 to 8 seconds. Up to 40 trajectories can be performed in a single flight.

Although they have not yet been used by the U.S. microgravity combustion program, sounding rockets can provide a reduced gravity environment of 10^{-4} g for about 300 seconds. Their use is presently being considered for experiments in flame spread over liquid pools and thick solids; the hardware is being built with plans for future users to fly the same or similar hardware for other combustion experiments.

Truly long duration microgravity combustion experiments require space-based laboratories such as the U.S. space shuttle or Space Station *Freedom*. Qualification of materials and assurance of safety for combustion experiments imposes an all-new set of concerns to the new researcher, although here NASA engineers who are experienced with the voluminous handbooks and requirements provide a great deal of help. The shuttle flight duration for science missions is 7 to 13 days; our experience with combustion experiments is they required as little as 0.5 crew-hours or, for the set of experiments on USML-1 (STS-50), up to 20 crew-hours (this is not a hard limit). Power, volume, and weight allowances depend on where an experiment is mounted in the shuttle (e.g. mid-deck locker, glovebox, cargo bay) and the type of mission (e.g. Spacelab). Substantial astronaut involvement is not only possible but encouraged for mid-deck or Spacelab experiments. While the crew is not necessarily expert in combustion, they are quite knowledgable on the unique features of microgravity and have improved, in real-time, the scientific yield from several experiments due to this knowledge.

The most common complaint of microgravity researchers is the long hardware development time and the difficulty in gaining frequent access to a space environment. In the future, Space Station *Freedom* will provide more opportunity as well as the highest quality, longest duration reduced gravity laboratory. Within its instrument racks will be dedicated space, electrical power, and advanced diagnostic instrumentation for microgravity combustion experiments. Multi-user experiments will be conducted in experiment "modules" by scientific specialists. Principal investigators on Earth will have the capability of monitoring and modifying in real-time the performance of their experiments. This future facility, along with the means by which investigators' experiments will be selected for flight, are discussed elsewhere in this workshop.

MICROGRAVITY COMBUSTION EXPERIMENTS AND SPACECRAFT FIRE SAFETY

In this workshop, the currently supported microgravity combustion studies are reviewed; they are listed in Table 1, noting that this list does not include completed or nearly completed microgravity combustion studies such as those experiments which have flown on the Shuttle (Solid Surface Combustion Experiment; Smoldering Combustion in Microgravity; Wire Insulation Flammability; and Candle Flames in Microgravity). Also shown in the table are the current facilities for the currently supported experiments; the NASA HQ-selected candidates for space-based testing are listed with their likely carrier. The flight candidates were selected through a NASA Research Announcement (see Program Participation section below) and began their efforts in the ground-based facilities several years ago.

Substantial differences between normal and microgravity flames have been observed in combustion systems such as burning droplets, Burke-Schumann flames, laminar, transitional and turbulent gas-jet diffusion flames, flame spread over solids and liquid pools, cellular and freely propagating premixed gaseous flames, smoldering combustion, and candle flames. Normally considered weak, diffusional and radiative processes have been shown to have significant influence on low gravity flames. In addition to new examinations of classical problems, current areas of interest include soot formation and agglomeration and weak turbulence, as influenced by gravity. The next generation of experiments will likely include and may expand beyond these areas, into such endeavors as combustion synthesis of materials.

Currently NASA and international human-crew space missions incorporate various means of fire protection, emphasizing fire prevention but including provisions for fire detection and extinguishment. There are several reasons for ongoing scientific and engineering interest. Safety strategies are evolutionary processes and must be subject to periodic review and updating as the knowledge of microgravity combustion grows and new consensus standards in aircraft and related fields are developed. The complex missions and environment of future spacecraft, particularly the permanently orbiting Space Station *Freedom*, create a demand for unique and innovative approaches to fire safety. Improved knowledge can optimize safety factors and provide tradeoffs of minimal risk against greater utilization of spacecraft facilities. A series of experiments is underway examining fire detection methods, extinguishment methods, and combustion product evolution and dispersion.

MICROGRAVITY COMBUSTION DIAGNOSTICS DEVELOPMENT

Compared to normal gravity experiments, low-gravity instrumentation has been simple, consisting of movie films and intrusive temperature and velocity probes such as thermocouples and hot wire anemometers (calibration of the latter for low-gravity applications is a concern, especially for the low-velocities usually of interest). This was due to the forementioned constraints on reduced gravity experimentation. However, to better understand the unique results obtained in low-gravity combustion experiments, more sophisticated diagnostic systems are strongly needed. This has motivated an emphasis on developing small, low-power and lightweight optical techniques because they are non-perturbative, and suited to the acquisition of multi-dimensional data fields (e.g. two and three dimensional imaging) while being usable in flight hardware. As with all microgravity experiments, development proceeds from development and testing in a normal gravity laboratory to demonstration in the ground-based facilities to repackaging / design and use in space flight hardware.

Table 2 lists methods in active design, development, testing, or demonstration in the low gravity facilities. Intensified CCD array cameras with sensitivity below conventional detectors or photographic films have revealed heretofore unseen flame structures and behaviors, especially in dilute hydrogen mixtures aboard the KC-135. Platinum silicide arrays for imaging in the near and mid-infrared are now available with sensitivity permitting bandpass filtering to isolate weak spectral emissions. This allows two dimensional temperature field measurements of known emissivity radiators, such as soot or grids of thin (15 micron) ceramic fibers. Such fibers are already being used in the drop towers for the qualitative assessment of temperature distributions in droplet and gas jet diffusion flames. A more complete characterization of the IR spectrum may enable the determination of major species concentrations and temperatures.

Relative to phase-sensitive, interferometric methods, the rainbow schlieren method tends to be simpler, more tolerant to mechanical and thermal fluctuations, and readily adaptable to large fields of view. The present system with continuously graded color filters has achieved comparable sensitivity to conventional interferometry. A quantitative determination of the refractive index distribution has been completed and is in being prepared for publication. This system has been employed in normal gravity to measure refractive index distributions in and above liquid pools and in axially symmetric jet diffusion flames. A system of this type is being assembled in a rig for reduced gravity tests in the 2.2 second drop tower facility, and has flown successfully aboard the KC-135.

Soot measurements are being conducted using transmission, scattering, and sampling techniques to determine soot size and concentration. These techniques have been incorporated into a 2.2 sec drop tower rig with the initial configuration accommodating full-field absorption measurements using a low power laser source, and soot sampling using a thermophoretic probe. For the latter, small wire electron microscopy grids are rapidly inserted into the flame and withdrawn (total residence time of approximately 30 milliseconds) with the size distribution of the soot particles then determined from the analysis of scanning electron micrographs.

In the longer range, particle image and laser doppler velocimetry systems are in development for use in low-gravity facilities. Prototype hardware is available for these measurements. Instrumentation for the determination of temperature and species concentration via near-IR laser light absorption is also under development.

MULTI-USER SPACE FLIGHT HARDWARE

Multi-user hardware is planned, intended to reduce cost and development time for space-based experiments. Elements of the flight hardware must be compatible with experiments several years from conception, but predictions of need are difficult; it is recognized that most experiments will need some unique subsystems to be developed especially and individually. NASA has adopted an evolutionary approach to multi-user space flight hardware. Experiment payloads, such as the Solid Surface Combustion Experiment, dedicated to the requirements of a single investigator are to be followed by more advanced Shuttle payloads each of which can accommodate a class of experiments.

The next set of combustion flight hardware will attempt to utilize a common set of components and subsystems in required configurations for a first series of flight experiments. Carriers such as Getaway Special Canisters (GASCANs), sounding rockets and cargo-bay mounted systems will be analyzed by NASA engineers for potential use in the next generation of experiments. Table 1 includes the currently planned carrier for flight project candidates. The first complete multi-user facility where many of these components and subsystems will be permanently mounted will be the Combustion Module (CM-1) to fly on Space Station *Freedom* or possibly on Spacelab. Finally, a Modular Combustion Facility (MCF), evolving from CM-1, is planned for Space Station *Freedom*.

OPPORTUNITIES FOR PROGRAM PARTICIPATION

NASA provides financial and facility support, typically for a three year "definition study" period, to academic and industrial principal investigators. Their initial proposals and subsequent progress are evaluated via the peer review process which addresses the following types of questions:

•Is there a clear need for microgravity experimentation, particularly space-based experimentation?
•Is the effort likely to result in a significant advance to the state of understanding?
•Is the scientific problem being examined of sufficient intrinsic interest or practical application?
•Is the conceptual design and technology required to conduct the experiment sufficiently developed to ensure a high probability of success?

Principal investigators (P.I.'s) collaborate with a NASA technical monitor to conduct the necessary research. Work in the drop towers and aircraft is strongly encouraged in this period. If it is believed that, following the definition study, space flight experiments are justified, the P.I.'s propose through a competitive solicitation (described below) a shuttle flight experiment. If they win award through this solicitation, they become flight candidates. Soon thereafter, the P.I.'s present their detailed objectives, test requirements, and the conceptual hardware design to another independent review panel comprised of scientific and engineering peers who assess the ability of the proposed flight experiment to meet its objectives. If this "Conceptual Design Review" is successful, NASA assigns a team of engineers and scientists to the multi-year development of space flight hardware which meets the P.I.'s specifications. NASA continues to support the P.I.'s throughout this development to conduct further research, provide consultation, and support the design and safety reviews prior to space flight. The nominal timeframe from flight experiment candidacy to manifest on the shuttle is five years. The P.I.'s then monitor the conduct of the experiment in flight, and subsequently analyze and are obliged to publish the data in an archival journal.

The above scenario is "typical" for shuttle-based experiments, however NASA also supports theoretical and diagnostics research as well as microgravity experiments which can be completed in the drop towers or aircraft.

Proposals for either definition study or flight experiment candidacy are solicited via a NASA Research Announcement (NRA); the first NRA focussed on microgravity combustion science was issued in December, 1989. It resulted in 13 definition study awards and 6 flight experiment candidacy awards out of 65 proposals. *The only path to selection for flight project candidacy is through an NRA, i.e. through a competitive, peer-reviewed selection process.* It is planned that an NRA for microgravity combustion science will be issued every three years. It is planned that a multi-disciplinary NRA, which will permit proposals for ground-based studies in microgravity combustion science, will be issued in the three-year period between combustion-specific NRAs. Finally, NASA offers graduate students financial support through its Graduate Student Research Program, and post-doctorate fellowships through the National Research Council. More information about the details of these programs and the process of proposal submission, progress reviews and space flight project selection is available by writing to the Microgravity Combustion Branch, MS 500-217, NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135.

Table 1: Today's Microgravity Combustion Science and Spacecraft Fire Safety Projects

Nomenclature: DT -- 2.2 sec Drop Tower; HDT -- Hokkeido (Japan) Drop Tower; ZGF -- 5.18 sec Zero Gravity Facility; SR -- Sounding Rocket; GAS -- GASCan in cargo bay of Shuttle; SSF -- Space Station *Freedom*; Middeck -- Middeck of Shuttle

TITLE	INVESTIGATORS	FACILITIES
"Low-Velocity, Opposed-flow Flame Spread in a Transport-Controlled, Microgravity Experiment"	Robert A. Altenkirch Subrata Bhattacharjee Sandra L. Olson	DT; ZGF; Learjet; SR or Middeck
"Risk-Based Fire Safety Experiment"	George E. Apostolakis Ivan Catton	DT; Learjet
"An Experimental and Theoretical Study of Radiative Extinction of Diffusion Flames"	Arvind Atreya Indrek S. Wichman	DT
"Gravitational Effects on Turbulent Gas-Jet Diffusion Flames"	Yousef Bahadori Dennis Stocker Raymond Edelman	DT; ZGF; KC-135
"Ignition and Combustion of Bulk Metals in a Microgravity Environment"	Melvin C. Branch John Daily	KC-135
"Modeling of Microgravity Combustion Experiments"	John Buckmaster	
"Gravitational Effects on Premixed Turbulent Flames: Studies of Dynamics of Wrinkled Laminar Flames in Microgravity"	Robert K. Cheng	DT
"Combustion of Interacting Droplet Arrays in a Microgravity Environment"	Daniel L. Dietrich	DT
"Investigation of Laminar Jet Diffusion Flames in Microgravity: A Paradigm for Soot Processes in Turbulent Flames"	Gerard M. Faeth	KC-135; SSF
"A Fundamental Study of Smoldering Combustion in Microgravity"	A. Carlos Fernandez-Pello	Learjet; KC-135; GAS
"Combustion of Electrostatic Sprays of Liquid Fuels in Laminar and Turbulent Regimes"	Alessandro Gomez Mitchell Smooke Marshall Long	TBD
"Ignition and Subsequent Flame Spread in Microgravity"	Takashi Kashiwagi Howard Baum	DT
"Modelling of Premixed Gas Flames in Microgravity"	K. Kailasanath Gopal Patnaik	
"Measurements and Modeling of Sooting Turbulent Jet Diffusion Flames Under Normal and Reduced Gravity Conditions"	Jerry C. Ku Paul Greenberg	DT
"Studies of Flame Structure in Microgravity"	C. K. Law	DT

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"Spacecraft Material Flammability Testing with Radiative Self-Heating"	Thomas J. Ohlemiller	
"Laminar Premixed Gas Combustion Experiments in Space"	Paul D. Ronney	DT; KC-135; SSF
"Ignition and Flame Spread Across Liquid Pools"	Howard D. Ross William A. Sirignano	ZGF; SR
"The Structure of Particle Cloud Premixed Flames"	K. Seshadri Abraham L. Berlad	
"Combustion Experiments in Reduced Gravity with Two-Component Miscible Droplets"	Ben Shaw	DT
"Combustion of Solid Fuel in Very Low Speed Oxygen Streams"	James S. T'ien Kurt R. Sacksteder	DT; KC-135
"High-Pressure Combustion of Binary-Fuel Droplets"	Forman A. Williams Jun'ichi Sato T. Niioka	DT; HDT
"Droplet Combustion Experiment"	Forman A. Williams Frederick L. Dryer	DT; ZGF; Middeck
"Laser Diagnostics for Microgravity Droplet Combustion"	Michael Winter Gregory Dobbs	DT; Learjet

Table 2: Today's Microgravity Combustion Diagnostics

Nomenclature: x -- completed, i.e. developed and demonstrated; i -- testing is imminent; d -- active design or development

MEASUREMENT OR INSTRUMENT	1G	DT	ZGF	LEARJET	KC-135	SOUNDING ROCKET	SHUTTLE OR SSF
Cine Cameras	x	x	x	x	x		x
Thermocouples, Radiometers and Pressure Transducers	x	x	x	x	x	d	x
Soot Sampling via Thermophoretic Probing	x	x					d
Soot Volume Fraction via Light Attenuation and Scattering	x	i			i		d
Soot Temperature via Pyrometry	i						d
Rainbow Schlieren	x (liquid and gas phases)	i			x (gas phase)	d (liquid phase)	
Standard CCD Video	x	x	x	x	x	d	x
Intensified Array Video w/ Bandpass Filtering	x			x	x	d	d
UV Intensified Array Video w/ Bandpass Filtering	x			i		d	
IR Video w/ Bandpass Filtering	x					d	
Planar (2D) Temperature and CH and OH Concentrations via Rayleigh Scattering and LIF	d						
Light Sheet Flow Visualization or Velocimetry	x (liquid phase)	x (smoke)				d (liquid phase)	
Laser Doppler Velocimetry	d						
Reactive Mie Scattering	x						
Liquid Surface Temperature and Vapor Phase Concentration via Exciplex Fluorescence	d						
Thin Fiber Pyrometry	d	d					
CH_4, CO_2, H_2O Concentration via Line Absorption	x	d					
Stable Species Concentration via Miniature Gas Chromotography	i						d

COMMENTS

Question: (Clayton Meyers, NASA Lewis Research Center): (1) How does the fire safety program "interact" with the evaluation of materials listed in MSFC-HDBK-527? Could a materials test program evolve to evaluate new material proposed for space use critical for future mission(s) success?

(2) Could optical diagnostics initialized by other directorates (2000, 5000) be shared via some commonality program/conference or other structured mechanism? Combustion byproducts analysis. laser ignition, laser diagnostics, and seeding technologies are available.

Answer: (1) We have joint efforts with both MSFC and JSC on the exchange of information of fire safety and combustion science research findings. We all are interested in, and we at LeRC are developing hardware for evaluating the flammability of common materials in low-gravity to assess the degree of conservatism of the 1-g test methods in the handbook you cite.

(2) Again, collaboration between directorates at LeRC exists. We presently share laboratories and expensive instruments with the groups you cite, and attend each other's seminars. I assure you we do not suffer from the "Not Invented Here" syndrome-- we are all too busy to reinvent existing measurement methods.