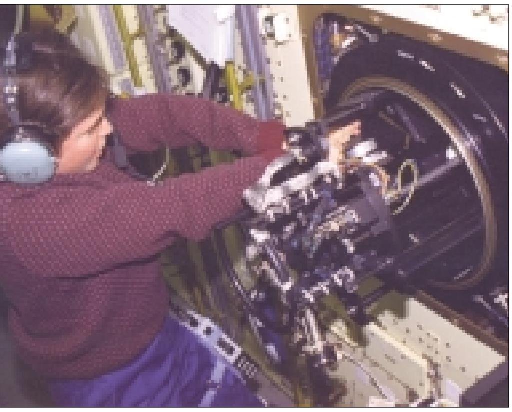
Microgravity studies offer insights into combustion

Combustion accounts for about 85% of the world's energy production and is a key element of many critical technologies. But while vital to our standard of living, combustion poses great challenges to the environment. Pollutants, atmospheric change and global warming, unwanted fires and explosions, and hazardous wastes are problem areas that would benefit from improved understanding of combustion.

The effects of gravity seriously impede combustion studies. Combustion involves the production of high-temperature gases whose low density triggers buoyant motion, complicating experimentation. Buoyancy effects are so ubiquitous that we often do not appreciate their enormous negative impact on these studies.

Perversely, the effects are strongest in the highest temperature regions of flames, where most chemical reactions occur, causing these reaction zones to collapse into very thin regions not resolvable by our instruments. Buoyant motion also triggers turbulence, yielding unsteady effects as an added complication. Finally, buoyancy causes particles and drops to settle, inhibiting the study of heterogeneous flames.

A Laminar Soot Processes Experiment Package was installed in Combustion Module-1.



Microgravity helps in overcoming these problems by allowing us to establish the flow environment rather than having it be dominated by uncontrollable buoyancy effects, and through this control, extending the available range of test conditions.

A major goal of microgravity combustion research is the generation of fundamental knowledge that can be used in developing accurate simulations of complex processes. The most fruitful approach is to concentrate on developing better understanding of the processes involved. With a full grasp of the physics and chemistry, physically accurate computer simulations can be developed for parametric exploration of new combustion domains. This, in turn, may allow us to develop radically different approaches to achieving various goals.

Space Shuttle studies

A fire or explosion aboard a spacecraft could be devastating to international efforts to expand the human presence in space. Testing has shown that ignition and flame propagation behave quite differently under partial- and microgravity conditions. In addition, fire signatures (heat release, smoke, flame, radiation) are known to change in reduced gravity. Research has provided data to improve the effectiveness of fire prevention practices, smoke and fire detectors, and fire extinguishers. The more we can apply our understanding to potential fire behavior in reduced gravity, the safer those whose lives depend on the environment aboard spacecraft will be.

In April and July 1997, a major suite of microgravity combustion experiments was carried out on Microgravity Science Laboratory (MSL-1) on the Shuttle, including studies of the structure of flame balls at low Lewis numbers (SOFBALL), laminar soot processes (LSP), droplet combustion experiments (DCE), and the fiber-supported droplet combustion (FSDC-2) series. The first two were carried out in Combustion Module-1 (using interchangeable experiment packages), the third in a middeck facility, and the last in the Middeck Glovebox (MGBX).

- SOFBALL. In 1944, Russian physicist Yakov Zel'dovich predicted a phenomenon in which the flame resulting from burning a fuel-oxygen mixture might burn indefinitely in a spherical shape without changing radius. This activity is unusual because flames tend to propagate into an unburned fuel mixture; in the case of flame balls, the unburned mixture is predicted to be drawn to the flame. Zel'dovich theorized that flame balls would be unstable, and thus no one would ever see them experimentally.

But Paul Ronney, a professor at the University of Southern California, observed them while investigating weakly combustible hydrogen-air mixtures during limited duration tests in drop towers and parabolic aircraft. In both cases, however, the flame balls were moving during the tests.

The SOFBALL experiments gave Ronney the opportunity to confirm his finding. "On the live downlink monitor I saw these three little flame balls perfectly motionless on the screen. I was just totally stunned. I never expected them to be that stable," he says. Comparison of experimental results to computational predictions revealed limitations in current models of hydrogen-oxygen chemistry for very lean mixtures. Refining these models is important for enabling improvements in lean-burning internal combustion engines, and could lead to increased conversion of chemical energy to work and reduced pollutant emissions.

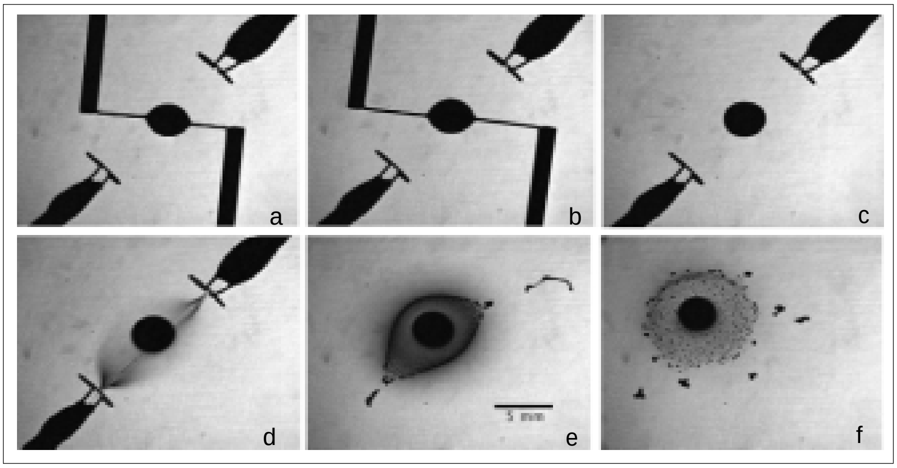
•LSP. At the University of Michigan, Gerard Faeth’s laminar flames experiment shows the growing sophistication of microgravity combustion research. A laminar flame is relatively steady, making it ideal for study. Ground-based studies of flames are limited to 1-2-in. flames, making it difficult to make measurements without disturbing the flame. In microgravity, Faeth was able to study soot processes in laminar flames 6-10 in. long. He explains that most flames produce soot; to describe them in detail, you must understand how this soot is made.

For Faeth’s LSP experiment, various diagnostics were used to gather data that, in conjunction with theories on radiation, determined soot temperatures. In addition, a pneumatically activated probe for soot sampling and a diode laser beam for determining soot concentration distributions were used to characterize the soot produced. Measurements were also made of flame radiation.

From these data, a complex picture of soot production has begun to emerge. Understanding soot production is of practical importance, since radiation from soot is the main heat load for many combustion devices and is the dominant mechanism for the growth and spread of unwanted fires.

•DCE. This experiment, directed by Forman Williams at the University of California at San Diego, is one of the most complicated combustion experiments ever flown. Using normal heptane, Williams tested theories that predict burning rates and the ratio of flame diameter to droplet diameter.

“People were afraid the experiment wouldn’t work because there were a lot of things you have to do,” explains Williams. “You have to make the droplet; then you have to somehow deploy it so it’s there rather than being held on something; then you have to ignite it. All this requires a lot of small-scale moving parts. When it burns, it has to be in the field of view of the instrumentation and not float away where you can’t find it.”



The deployment, ignition, and combustion sequence for an n-heptane droplet in the Droplet Combustion Experiment shows: a) growth, b) stretch, c) deployment, d) ignition, e) premixed/diffusion flame transition, and f) quasisteady burning.

The importance of microgravity here lies in the fact that spherical burning of large droplets cannot be achieved in normal gravity, because of flame distortion by buoyancy forces. Using microgravity to achieve spherical symmetry permits use of one-dimensional equations for analytical modeling, allowing testing of much more complete models of droplet combustion.

The results demonstrated both radiative and diffusive flame extinction during droplet burning, providing exacting tests of complex models. Better understanding of droplet combustion mechanisms is of practical import in that burning of fuel droplets is an important part of many operations.

•FSDC-2. Droplet combustion experiments covering a much wider range of fuels, and also examining the effects of controlled convection on droplet burning and the interactions in the burning of droplet pairs, were carried out in this experiment. Droplets were tethered to a thin-diameter fiber, and flame and droplet images were recorded by video camera.

These experiments demonstrated that fuel droplets as large as 5 mm in diameter burned largely as predicted by droplet theory. Qualitative agreement was found between theoretical and numerical predictions and experimental data regarding extinction diameters for methanol and methanol/water mixtures. This agreement improved when radiative heat loss from the flame was included in the model.

Many other combustion experiments have been and are being carried out in various flight facilities, including middeck locker facilities; Get-Away Special canisters, in which fully automated experiments with relatively simple diagnostics are carried out; an MGBX facility; and sounding rockets. The Black Brant sounding rockets provide approximately 6 min of high-quality microgravity time.

In addition to the MSL-1 experiments, numerous space-based combustion experiments encompassing various combustion processes have been carried out to date, with even morestill in the development stage. These include five studies in the area of gas-eous flames, three in droplet combustion, seven in ignition and spread of flames across liquid or solid fuel surfaces, two in smoldering combustion, and one for characterization of smoke detector response under microgravity conditions. In addition, there are 11 other microgravity combustion flight studies in early development phases, five on gaseous combustion, two on droplet combustion, and four on ignition/combustion of solid fuel surfaces.

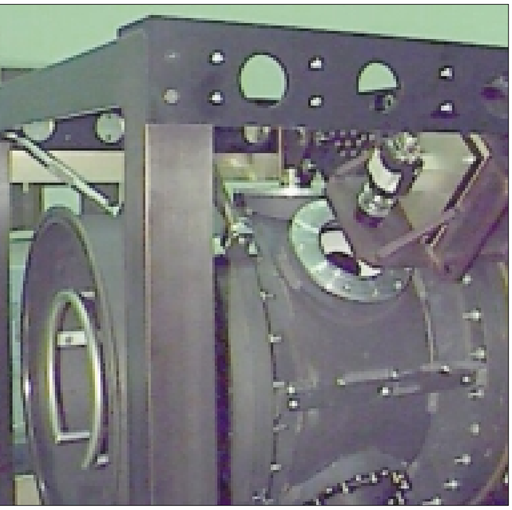
Ground-based studies

Flight investigators in the NASA Microgravity Combustion Program often must conduct low-gravity experiments in ground-based facilities during experiment definition phases. In addition, the amount of microgravity time available in those facilities is adequate to complete some studies at much reduced cost. These reduced-gravity facilities include two drop towers at NASA-Glenn (formerly Lewis) and a KC-135 aircraft based at Johnson. In addition, NASA researchers have used a Japanese drop shaft in Hokkaido capable of providing 10 sec of high-quality microgravity time.

One drop tower provides 2.2 sec of test time for experiment packages of up to 125 kg. The package is enclosed in a drag shield that provides accelerations of less than 10^{-5} *g* as the package free-falls. In one day, 8-12 tests can be performed, with data acquired by high-speed video cameras and by on-board systems that record data supplied by thermocouples, pressure transducers, and flow meters.

A second drop tube, evacuated to a final pressure of 1 Pascal to minimize drag, provides 5.18 sec of microgravity; hardware weighing up to 450 kg can be accommodated in a drop bus. Visual data are acquired via high-speed video cameras; pressures, temperatures, and accelerations are recorded on board or transmitted to a control room. Due to the complexity of drop chamber operations and chamber pump-down time, only one test is typically performed per day.

A combustion-integrated rack is being built for the ISS. This front right view shows the optics plate with combustion chamber and one diagnostic package installed.



The KC-135 can provide periods of low gravity for up to 23-sec intervals by flying parabolic trajectories, accommodating a variety of experiments. The brief pushover at the top of the parabola produces less than 1% of Earth's gravity. Qualified observers or operators may fly with their experiments, and several experiments can be integrated in a single flight.

As of this January, NASA was supporting 20 flight or flight definition investigations and 58 ground-based programs, including several that are purely theoretical in nature and several more dedicated to development of sophisticated low-weight, low-power diagnostic tools for use in future experiments.

ISS facilities

Microgravity combustion experiments on the International Space Station (ISS) will be carried out in either a dedicated combustion integrated rack (CIR) with experiment-unique inserts, or in the Microgravity Science Glovebox (MSG), a major upgrade to the MGBX. The station will offer the opportunity to conduct many more experiments per year; regular access to a laboratory in space should bring flight-based research more closely in line with experimentation on Earth.

The CIR is one part of the larger Fluids and Combustion Facility (FCF) planned for ISS. The facility includes three racks of on-orbit hardware/software, nine racks of ground-based hardware/software, training, operations, and virtually all other items needed to support fluids and combustion experimentation. The CIR will support an average of five combustion projects per year; if resources are increased, it should be capable of supporting up to 15 per year. Over its life cycle, the CIR should be capable of supporting 80% of proposed combustion experiments.

In designing the CIR, the Microgravity Combustion Program developed 11 basis experiments and defined their requirements. They span the scope of experiments likely to be proposed, and the FCF is required to accommodate them.

Central to giving the FCF the required flexibility is the use of principal investigator (PI)-unique hardware/software to customize the CIR to meet the PI's requirements. The CIR infrastructure contains items common to many or all experiments, including a combustion chamber, optical and other diagnostics, fuel and oxidizer management, on-orbit and on-Earth data reduction and analysis, communications with Earth, Internet-based communications to distribute near-real-time data to PIs at their home institutions, and other commonly required features. Each PI hardware team will develop unique equipment to manage the geometry of the combustion event, lenses to customize light sources and cameras, occasionally a unique illumination or camera system, and any other equipment and software needed.

The CIR will be the first of three FCF racks deployed to ISS. It is scheduled for launch in October 2002 and will begin its work immediately. Seventeen combustion experiments are tentatively planned during the first three years of operation. The rest of the facility, including the fluids integrated rack and shared accommodations rack, is currently scheduled for June 2003 and June 2004 launch. Several experiment-specific inserts are also currently under development.

The MSG is designed to support a wide range of microgravity science investigations. In the sealed mode, the MSG serves as a single level of containment by providing a physical barrier to the surroundings. In the air circulation mode, it serves as a one-failure-tolerant containment by providing a physical barrier and a negative pressure relative to the cabin.

It is envisioned that MSG experiments will be conducted in the areas of fluid physics, combustion science, materials science, and biotechnology. The MSG is being developed by the European Space Agency and will be available for use soon after the deployment of the U.S. Lab Module.

Benefits of microgravity studies Microgravity combustion studies have demonstrated major differences in structures of various types of flames from those seen in normal gravity. These studies will enable advances in many areas:

- Reduction of combustion-generated pollutants. Barriers to progress include a lack of understanding of reaction, pyrolysis, and devolatilization kinetics; soot nucleation, growth, and oxidation processes; flame stabilization mechanisms; and kinetic-transport interactions. Microgravity research provides increased spatial resolution through the use of larger length scales that cannot be achieved at normal gravity.
- Reduction of fire and explosion hazards. Technological barriers include lack of understanding of flammability limit mechanisms, ignition mechanisms, smolder-to-fire transition, and fire growth processes. Microgravity studies eliminate the intrusion of buoyancy effects that obscure these phenomena in normal gravity.
- Improved hazardous waste incineration processes. These efforts are currently hindered by lack of understanding of reaction pathways leading to pollutants and toxic products. Microgravity helps by providing improved spatial resolution, long controllable residence times, and elimination of settling of condensed phase species.
- Increased efficiency in conversion of fuel chemical energy to useful heat and work in practical combustion devices. Progress is hampered at normal gravity by lack of understanding of soot production processes, turbulence, flame interactions, droplet vaporization, near-critical behavior, and very fuel-rich or fuel-lean combustion. Microgravity provides controllable residence times, reduced turbulence scales to allow direct model comparison, truly one-dimensional geometries (allowing meaningful comparison of model predictions and data), and generally simplified experiments.
- Improved materials via combustion synthesis. Barriers to progress include a lack of understanding of heterogeneous kinetics and processes leading to improved structural ordering and infiltration of materials in composites. Microgravity eliminates sedimentation (which leads to particle agglomeration) and gravity-induced flow through pores in the developing structure.

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