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Microgravity Combustion Research: 1999 Program and Results

Robert Friedman, Suleyman A. Gokoglu, and David L. Urban, Editors
Glenn Research Center, Cleveland, Ohio

June 1999

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Space Administration

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Summary

The use of the microgravity environment of space to expand scientific knowledge and to enable the commercial development of space for enhancing the quality of life on Earth is particularly suitable to the field of combustion. This document reviews the current status of microgravity combustion research and derived information. It is the fourth in a series of timely surveys, all published as NASA Technical Memoranda, and it covers largely the period from 1995 to early 1999. The scope of the review covers three program areas: fundamental studies, applications to fire safety and other fields, and general measurements and diagnostics. The document also describes the opportunities for Principal Investigator participation through the NASA Research Announcement program and the NASA Glenn Research Center low-gravity facilities available to researchers.

Introduction

The purpose of this document is to summarize the status of NASA-sponsored and other microgravity-combustion research through descriptions of current projects and their significant findings and applications.

In the past several decades, the use of the nonconvective, microgravity environment of Earth-orbiting space vehicles as a laboratory for a variety of tests and processes has been an ever increasing contributor to scientific knowledge. Indeed, the results of this microgravity research promise information and benefits not only in fundamental science, but also in applied technology, commercial "spin-offs," and future extraterrestrial exploration.

The National Aeronautics and Space Administration (NASA) Microgravity Research Program encompasses a group of scientific disciplines wherein fundamental knowledge can be extended through studies conducted over a range of gravitational accelerations. Combustion is a key topic within the program. In itself, combustion is one of the most important processes in the worldwide economy. Combustion underlies nearly all of energy generation, domestic heating, and transportation propulsion, and it contributes to a large fraction of the unit operations for producing raw and manufactured materials and in industrial fabrication, construction, and assembly. In a negative sense, uncontrolled combustion leads to the continuing, costly toll from the effects of fires and atmospheric pollution.

The microgravity environment has several characteristics that are particularly useful for fundamental and applied research in combustion science. For example:

- Buoyancy-induced flow is nearly eliminated, simplifying the study of quiescent and low-flow combustion fields.
- Weaker forces and flows normally obscured by strong buoyant motions, for example, electrostatics, thermocapillarity, and diffusion, may be isolated.
- Gravitational settling is nearly eliminated, allowing the stabilization of free droplets, particles, bubbles, mists, and arrays for basic ignition and combustion studies.
- Expanded experimental time or length scales become feasible, due to the elimination of buoyancy-driven disturbances.

While microgravity is the operational environment associated with Earth-orbiting space laboratories, effective combustion studies can also be conducted in other short-time, low-gravity environments. Tests in suborbital sounding rockets, parabolic-trajectory airplanes, and free-fall drop towers supplement to a great extent the limited on-orbit test opportunities on the U.S. Shuttle Orbiter, its payload-bay laboratories, the Orbital Station *Mir*, and the in-assembly International Space Station. In fact, the contributions of research conducted in these so-called "ground-based" low-gravity and microgravity facilities have been essential to the acknowledged success of the microgravity-combustion program. Additional contributions of high value to microgravity combustion science come from "normal-gravity" reference ground tests and from analytical modeling.

NASA offers a Strategic Plan to advance the mission of the Agency. Among the primary business areas defined in the Plan is the enterprise of Human Exploration and Development of Space (HEDS). Two of the six near-term objectives of the HEDS enterprise are pertinent to the research reviewed herein, namely, to:

- Use the environment of space to expand scientific knowledge,
- Enable the commercial development of space and share HEDS knowledge, technologies, and assets that promise to enhance the quality of life on Earth.

In 1998, a program operating plan was adopted to guide the Microgravity Research Program and make it conform to the strategic objectives of the HEDS enterprise. The plan defined a set of nearly twenty performance goals for all the disciplines within the program. Of these goals, several are applicable to combustion, and two, in particular, serve as the justifications for the attention given to the microgravity-combustion program. These goals are to:

- Enable increased combustion-system efficiency, reduced pollution, and mitigation of fire risks through insights and databases obtainable only through microgravity experiments,
- Develop methods, databases, and validating tests for material flammability characterization, hazard reduction, and fire detection/suppression strategies for spacecraft and extraterrestrial habitats.

The primary purpose of this review is to present the status of microgravity-combustion research and derived knowledge (principally from NASA-supported programs), described in three general program areas: fundamental studies, applications to fire safety and other fields, and general measurements and diagnostics. The description of projects and their findings is categorized into topics within the three program areas, and it is confined largely to the progress made in the past four years. Topical reports are not intended to be comprehensive compilations of every investigation supported by the program; and, hence, they do not cite individual investigators. A bibliography following the program-area reviews covers the literature appearing during the time period of the reviews. The document is, to a large degree, an update of three previous timely reviews of microgravity-combustion science produced by the NASA Lewis Research Center (now the NASA Glenn Research Center). The most recent overview, Microgravity Combustion Science: 1995 Program Update, NASA TM–106858, is still in print.

A secondary purpose of this review is the encouragement of the participation of new Principal Investigators in analytical and experimental microgravity-combustion research through the frequent opportunities offered by open competitive solicitations, *i.e.,* the NASA Research Announcements. The document includes, therefore, information on the solicitation process and its response requirements and a description of the NASA Glenn low-gravity test facilities and the spacecraft experiment hardware and accommodations available to researchers.

This review has been written by members of the NASA Glenn Research Center Microgravity Combustion Science Branch. NASA Glenn is a supporting center in the Microgravity Research Program, and it is assigned the management of the discipline of combustion science. Members of the National Center for Microgravity Research on Fluids and Combustion at NASA Glenn and some of the outside Principal Investigators have also contributed to this document. This valuable assistance is greatly appreciated.

Program Status: Fundamental Studies

The primary purpose of microgravity-combustion research is in extending fundamental knowledge. Fresh insights and databases obtainable only through microgravity experiments can advance the basic understanding of flame phenomena, thereby enabling the development of quantitative process models. Industry can use such data for the beneficial control of combustion processes to yield increased efficiencies, reduced pollution, and mitigation of fire risks. Microgravity-combustion research can also contribute to the fundamental understanding of combustion-synthesized materials, which fosters the production of novel materials.

Currently, the Microgravity Combustion Science program is supporting 58 ground-based studies, 13 flight-definition studies, six flight programs, and three Glovebox investigations. The majority of these projects, 54 of the ground-based studies, ten of the flight-definition studies, and all of the flight programs and the Glovebox investigations, belongs to the program area of fundamental studies.

The program area of fundamental-combustion studies covers the following topics, which are taken from the description of the NASA Microgravity Research Program performance goals:

- Premixed gas combustion
- Nonpremixed gas combustion
- Droplet and particle combustion
- Spray and aerosol combustion
- Soot processes
- Combustion over liquid and solid fuel surfaces
- Smoldering
- Metal combustion
- Combustion synthesis

Premixed Gas Combustion

Premixed combustion occurs in a variety of practical situations ranging from laboratory burners to auto engines to explosions. Many of these phenomena have been investigated extensively in ground laboratories under the ever-present influence of normal gravity (the sea-level acceleration of 9.8 m/s^2). Certain features of the combustion processes are known to be masked or altered by the ever-present gravity. For instance, laminar flame speeds are difficult to measure in the presence of buoyant convection, especially for near-limit flames; and numerical models normally neglect gravity to focus on the chemical kinetics. Other flames, such as stationary premixed spherical flames (*i.e.*, flame balls) exist only in microgravity. Also, premixed gas flames can develop a variety of instabilities driven by hydrodynamic, thermal-diffusion, kinetic, or chemical mechanisms. Experiments in microgravity allow the isolation of these effects, which are often weak in normal gravity.

Flammability Limits and Flame Balls

Combustible gas mixtures will not burn if sufficiently diluted with excess fuel, oxidant, or inert gases. The compositions delineating flammable from nonflammable gas mixtures are referred to as flammability limits. Studies of flammability limits are important for assessment of fire safety in many environments and for estimation of the operating limits of combustion engines. In practice, many factors, such as hydrodynamic strain and flame-front curvature (collectively called “flame stretch”), preferential diffusion, conductive and radiative heat losses, and flame chemistry, interact to affect the flammability limits. The isolation of an individual factor and the determination of its influence on the limits are very difficult.

A class of stationary premixed spherical flames, or “flame balls,” observed uniquely in microgravity, is controlled exclusively by reaction, diffusion, and radiation (fig. 1). The lack of buoyant convection (because the mass-averaged velocity, *i.e.*, bulk velocity, vanishes everywhere) preserves the spherical symmetry of these flames. Since there are no external factors, such as heat losses to the burner or confining walls, flame balls provide a suitable configuration for the study of intrinsic flammability limits.

Theoretical analyses predict that stable flame balls occur only in a narrow range of compositions near the lean limit of mixtures with low Lewis number, such as a lean mixture of hydrogen in air. Experiments confirm the prediction. The nature of the instabilities that exist when these conditions are not met has also been identified by the analyses.

Flame-ball experiments, in a project called The Structure of Flame Balls at Low Lewis-number (SOFBALL), were successfully conducted in space on Shuttle Missions STS-83 and STS-94 in 1997. Mixtures of hydrogen, oxygen, and a third inert component (nitrogen, carbon dioxide, or sulfur hexafluoride) were burned in the Shuttle Combustion Module-1 facility (see appendix A). These mixtures were selected to cover a wide range of Lewis numbers. A total of eighteen mixtures ignited, and they generated 52 flame balls. Most of the mixtures burned for 500 sec until the experiment timeout extinguished the flames, more than enough time to verify the steadiness, stability, and

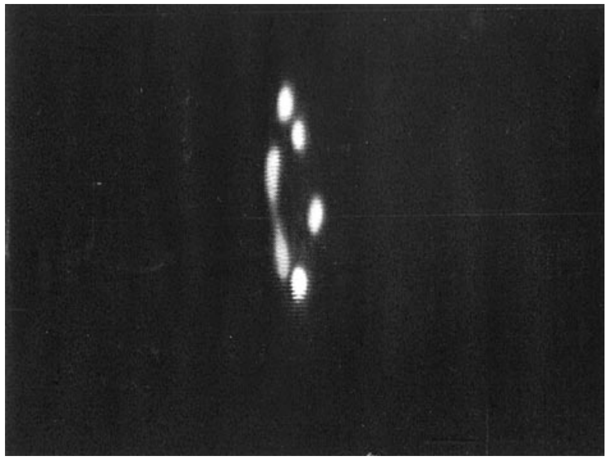

Figure 1.—Image of multiple flame balls formed in lean hydrogen-oxygen-diluent atmosphere.

longevity of flame balls. An interesting phenomenon—flame ball drift—was revealed when more than one flame ball was present in the combustion chamber. New theoretical work explains the motion as being due to enthalpy gradients imposed by one ball on its neighbors.

Comparisons of predicted flame-ball radii with experiments raise questions on the level of accuracy of the widely-accepted optically-thin radiation data used for model predictions. In addition, reabsorption of emitted radiation is found to be a dominant effect in mixtures diluted with CO_2 or SF_6; thus, the radiation model itself is of paramount importance. Flame-ball properties are computed both with and without inclusion of diluent radiation, to assess the effect of re-absorption of emitted radiation. For H_2-air mixtures, the computed radiative emission and lean-limit composition agree well with the flight-experiment data. The flame-ball radii predictions, however, do not agree with the data. For H_2-O_2-CO_2 mixtures, the numerical results with and without diluent radiation bracket the experimental flame-ball radii, total radiation, and lean-limit composition. These observations indicate that better radiation models, including re-absorption effects, are needed for accurate numerical simulation in these cases. For hydrogen-air flames, progress has been made in verifying the sensitivity of the flame-ball radius and the value of the lean and rich flammability limits through calculations based on the hydrogen-air chemistry, the transport model, the length of the computational domain, and the far-field radiation losses.

Asymptotic analyses show that near-field losses, at distances on the order of the flame-ball radius, are distinct from far-field losses, at distances large relative to the flame-ball radius. In practice, there is a continuum of losses covering the near and far fields, which can be represented by a very simple model. The model permits exact solutions, in which the relative magnitude of far-field and near-field losses can be changed by varying the concentration of water vapor in the far field.

In addition to the flame-ball modeling described above, various other simple systems have been studied analytically. A model has been developed to help explain the results of experiments performed in the Japanese Microgravity Center (JAMIC) drop tower on the flammability of twin counterflow flames. The model, assuming conditions representative of the experiments performed with methane-air and accounting for both strain rate and radiation loss, successfully captures the C-shaped quenching boundary found in the experiments. In particular, this model shows that, for an equivalence ratio greater than a minimum value, there exists a strong-strain limit and a weak-strain limit, which define the quenching boundaries.

Flame Stability and Propagation

In near-limit mixtures that have a large thermal diffusivity, and thus a large heat loss and large Lewis number, peculiar modes of flame propagation have been found to occur. Rotating spiral and target patterns have been observed experimentally on freely propagating premixed gas flames in large tubes at normal gravity. The patterns have also been observed when the conductive heat loss is large, such as on burner-stabilized flames at normal gravity using mixtures of methane-, propane- and butane-air, all of which have Lewis numbers close to one. However, buoyant flows strongly distort the flame curvature, hydrodynamics (thus stretch), and convective transport of species and heat; and this in turn complicates the patterns and underlying reactive-diffusive structure.

To isolate the mechanisms that drive the observed patterns, researchers are conducting normal-gravity and microgravity experiments to determine: (1) the structure and dynamics of the patterns, (2) the concentration bounds of the critical Lewis number and their influences on heat loss, (3) the relative significance of the chemical kinetics, and (4) the effects of curvature (local wave and global flame front) on wave propagation.

Using a flame-tube apparatus and two high-speed intensified video cameras, investigators have observed different fundamental modes of propagation, depending on the approach of the fuel concentration to the flammability limit. All the downward-propagating flames investigated support single target patterns, which are radially propagating, concentric-ring waves traveling at 2 to 3 m/s (fig. 2). Some tests have been done to see how the patterns evolve after contact with a barrier. In near-limit flames, multiple origin sites can develop simultaneously. If the wave frequencies are similar, a state is then established where the multiple sites and their target patterns coexist and continuously interact at their boundaries. In still leaner mixtures, rotating spiral waves develop (fig. 3). Once formed, the two free ends of the broken ring transform to two counter-propagating spiral waves. As the flammability limit is asymptotically approached (to within the experimental accuracy of the gas mixing system), the patterns often appear spatially disordered and temporally chaotic, a mode suggestive of "chemical" or "diffusion-induced" turbulence. A three-dimensional, unsteady numerical model has been developed to describe premixed combustion. To test the model, recent studies determined the effect of gravity on the three-dimensional cellular structure in the combustion of a mixture of 9.5 percent hydrogen-air. In flames that propagate downward, gravity has a stabilizing effect. In the absence of gravity, the flame initiates as a single, axisymmetric structure, which eventually grows and deforms in three dimensions, splitting into multiple distinct cells as time elapses. Flames that propagate upward display both Rayleigh-Taylor and thermal-diffusion instabilities in normal gravity, resulting in faster growth rates and loss of symmetry than in the microgravity case. These instability phenomena could be modeled if calculations are conducted in three dimensions rather than in two.

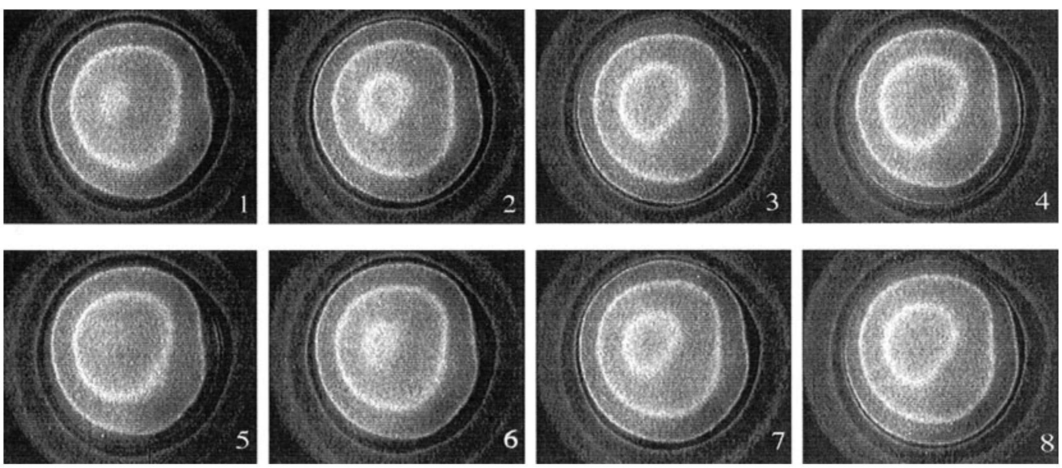

Figure 2.—Target pattern of downward-propagating flames in a lean mixture of butane-oxygen-helium. Time between oscillating images is 1/500 sec.

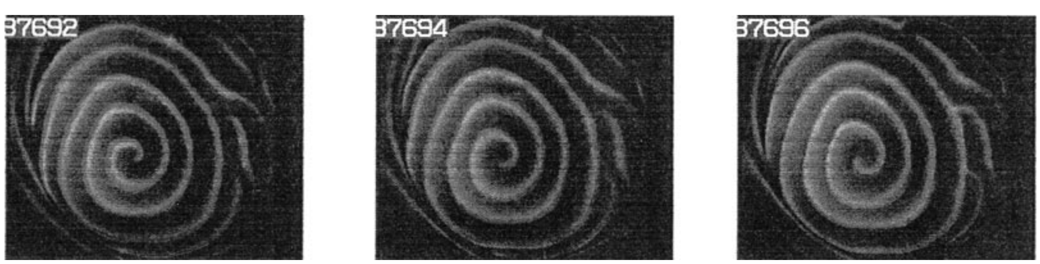

Figure 3.—Rotating spiral-wave pattern of downward-propagating flames in a very lean mixture of octane-oxygen-helium. Time between wave images is 1/500 sec.

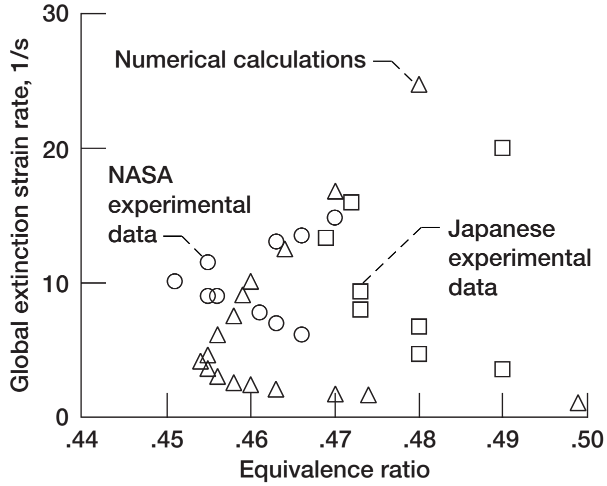

Figure 4.—Extinction limits for lean methane-air flames in microgravity from calculations, NASA and Japanese drop-tower data.

Experiments using a counterflow-combustion system in microgravity have been used to measure the extinction strain rates for very lean mixtures that cannot be studied in normal gravity. For methane-air flames, a turning-point behavior has been found in the global-extinction strain rate (fig. 4) that agrees with numerical models and data taken at the JAMIC drop tower.

Premixed flame experiments have been conducted in Hele-Shaw cells in different orientations corresponding to upward, downward, and horizontal propagation. The results have shown that Lewis-number effects alone cannot account for the flame-wrinkling spectrum, but that thermal expansion and viscous fingering dominate the properties for stability.

Aqueous autocatalytic chemical-reaction fronts have also been used in Hele-Shaw cells for the experimental simulation of combustion processes. These reactions exhibit very little density change across the front, have simple chemistry, are unaffected by heat losses since the front is nearly isothermal, and have high Schmidt numbers, allowing the front to remain “flamelet-like” even in the presence of very strong flow disturbances or turbulence. Analogous to the Saffman-Taylor instability, fingering-type instabilities are observed. Experiments have been carried out to measure the turbulent burning velocity and to determine the curvature of the front in these cells.

Flame Speeds

Laminar flame speeds are difficult to measure in the ideal sense, since it is not possible to set up a steady one-dimensional flame that is free from stretch and heat loss. However, a technique has been developed that, for the first time, can produce a stretch-free, one-dimensional, freely propagating flame for a short time period. This technique takes advantage of the fact that a stagnation flame is a positively strained (stretched) flame, and a Bunsen flame is a negatively strained one. When a flat, strained flame is established in a stagnation-flow configuration, and the distance between the stagnation plane and the nozzle exit is greater than roughly 1.5 nozzle diameters, a reduction of the flow rate (strain rate) results in a transition to a Bunsen flame, since the radial pressure gradients are too weak to sustain a stagnation flow field close to the nozzle exit. Thus, by obtaining a smooth and slow transition from positive strain rate (stagnation flame) to negative strain rate (Bunsen flame), one can achieve an interval in which the flame is one-dimensional, freely propagating, and stretch-free. This flame shape allows the direct determination of the true laminar flame speed.

Experiments were conducted in normal gravity using laser Doppler velocimetry to obtain real-time measurements of the flame centerline velocity. Flame speeds were determined, measurements not obtainable with the traditional stagnation-flow technique. Furthermore, these values coincide with the values derived by extrapolating the strained-flame measurements to ultra-low strain rates. Measurements in microgravity are scheduled in the near future to examine weak flames, which are more prone to be affected by buoyancy.

Turbulent premixed flames have been studied in planar and axisymmetric configurations. Results obtained in normal gravity show that the flame angles for rod-stabilized planar flames are different for +g and –g cases (downward and upward gravitational acceleration) and that the difference is a function of the equivalence ratio and the local Richardson number, defined as the ratio of buoyant to turbulent forces. For microgravity flames, the flame angle is accurately predicted by a linear extrapolation of the –g flame angles to a Richardson number of zero. Velocity measurements show a significantly higher divergence from microgravity for the +g case. Flame-surface wrinkling is also found to be a function of the gravity level, and this indicates a need to develop a new scaling parameter for its characterization.

Predictions of the effects of gravity on turbulent flame speed have been conducted for a turbulent planar Couette-flow problem, using both direct numerical simulation and large eddy simulation. In normal gravity, the density gradients caused by heat release tend to compress and expand the flame in upper and lower regions, respectively; whereas in microgravity, the mean flame propagation is radially symmetric. The normal-gravity flame has a greater positive stretch compared to the microgravity case. Initial experimental results show good agreement with these predictions.

Flame Spread in Nonhomogeneous Mixtures

In contrast to the flames discussed to this point in the section, which assume an initially uniform mixture of fuel and oxidizer, some flames spread through an initially nonuniform, although well-characterized, mixture. Sometimes called “layered systems” in the literature, such flammable mixtures occur typically in mines, over liquids that are above their flash points, or in lifted turbulent jet flames. In microgravity, they could occur following a flammable gas leak, propagated by slow ventilation flows or by diffusion.

Gravity can influence the rate of flame propagation in a layered system in at least three ways: through a hydrostatic pressure gradient, through buoyantly induced flows during spread, or through changes in the initial distribution of fuel vapor. Figure 5 shows a schematic of the model system under study. A layered, flammable mixture is formed by allowing a liquid to evaporate for a specified length of time. Flame-spread data have been obtained for two fuels, ethanol and methanol, at a variety of temperatures and diffusion times in normal gravity. Figure 6 shows a typical flame, which consists of two legs of a triple flame. The flame-spread rate has been shown to be a function of both fuel temperature and layer thickness (*i.e.,* diffusion time). A Michelson interferometer determined the fuel-vapor concentration ahead of the flame. An interferogram analysis technique based on Fourier image processing was developed to obtain iso-concentration lines of fuel vapor. Prior to the arrival of the flame, the lines are flat, and they predict the surface concentration well. As the flame approaches, the vapor-concentration lines are pushed up, making the flammable zone larger.

Also studied are edge flames, which are defined as flame sheets with edges that arise in nonuniform gases. A one-dimensional model has been developed that includes transverse flow of heat, oxidizer, and fuel. It accurately describes flame propagation along the flame length. Additionally, the model examines a premixed flame located in a planar counterflow of fresh cold fuel-oxidant mixture and hot inert. There are two stable, one-dimensional solutions: one characterized by vigorous combustion, and the other by weak combustion.

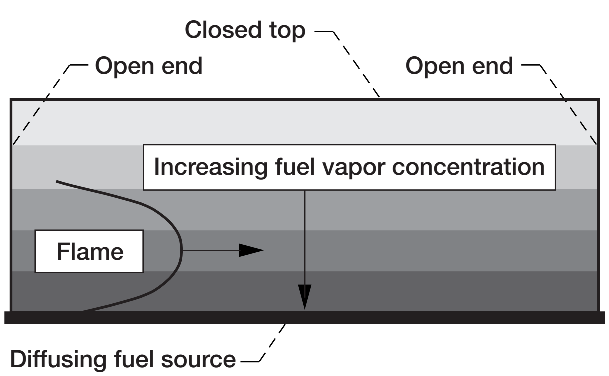

Figure 5.—Representation of flame propagation through a layered, non-homogeneous fuel-air mixture.

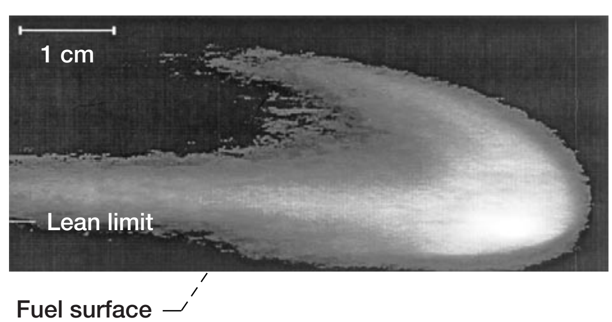

Figure 6.—Photograph of a flame propagating through a layered, non-homogeneous methanol-air mixture.

Low-Temperature Oxidation Reactions

The perturbing effects of buoyancy at normal gravity complicate nonisothermal studies of cool flames and low-temperature oxidation reactions in unstirred, closed vessels. While stirring offers the advantage of spatial uniformity of temperature and concentration, it necessarily destroys the structure that would otherwise occur naturally. Studies in microgravity are intended for clearer examination of this gradient structure.

Ground laboratory and reduced-gravity (airplane) tests have been conducted using a variety of hydrocarbons (*e.g.*, methane, propane, butane) diluted with oxygen at temperatures below 600 °C and pressures from 1.3 to 101 kPa (10 to 760 torr). Different regimes have been found corresponding to slow reaction, cool-flame development and propagation, steady glow, oscillatory glow, two-stage ignition, complete on-off ignition, and oscillatory ignition.

For both cool flames and "hot" ignitions, two major differences have been found to date between their microgravity and normal-gravity behavior. In microgravity, cool flames and hot ignitions propagate spherically from a centrally located reaction kernel; whereas, in normal gravity, cool flames and hot ignitions exclusively start at the top of the vessel. The induction time for cool-flame development is shorter in microgravity than in normal gravity, but the disparity decreases with increasing temperature, perhaps due to different temperature dependencies of the chemical and the transport times. A quantitative comparison between normal-gravity and microgravity results is currently underway, and a detailed numerical analysis incorporating both transport and chemical kinetics is being developed to explain the experimental observations.

Nonpremixed Gas Combustion

Laminar diffusion flames are essential to the fundamental understanding of combustion science. They also are pertinent to the turbulent diffusion flames of more practical interest via the laminar flamelet concept. The discussion below covers recent advances in the study of the two main classes of gas-fueled laminar diffusion flames of concern in microgravity, gas-jet flames and spherical flames, followed by topics in turbulent diffusion flames.

Gas-Jet Flames

Three U.S. spaceflight experiments involved laminar gas-jet diffusion flames: Laminar Soot Processes (LSP), Transitional and Turbulent Gas Jet Diffusion Flames (TGDF), and Enclosed Laminar Flames (ELF). LSP, flown aboard Shuttle missions STS-83 and STS-94 in 1997, allowed the first long-term observations (up to 200 sec) of gas-jet diffusion flames. Although its primary emphasis is soot formation, LSP also examines the structure of laminar diffusion flames. The observed flame lengths are greater than those in corresponding normal gravity, or even in the short-term low-gravity environments of drop towers and airplanes. The data provide simple expressions for luminous flame lengths and widths. The classical analysis of Spalding, with slight modifications, is found to yield excellent agreement with the luminous shapes of the closed-tip LSP flames.

The primary objective of the TGDF experiment, flown on STS-87 in 1997, is to characterize the processes of vortex-flame interaction in transitional and turbulent gas-jet diffusion flames. This experiment also measures shapes and temperatures of laminar diffusion flames and develops a numerical model of laminar gas-jet diffusion flames that includes radiation.

ELF, flown in the Glovebox facility (see appendix A) aboard STS-87, examines the effects of buoyant convection on the structure and stability of co-flowing diffusion flames. ELF data produce maps of flame stability in microgravity and in normal gravity. Higher velocities are found to be required for liftoff and blowout of nonbuoyant flames. The most stable fuel velocities are identified for buoyant and nonbuoyant flames. The experiment showed the presence of stable, lifted, nonbuoyant flames (at low fuel-flow rates), which is in conflict with theoretical predictions.

In ground-based experiments, nonbuoyant coflowing flames were studied aboard the KC-135A airplane. Measurements include CH and OH concentrations from excited-state emissions and gas density from Rayleigh scattering. In microgravity, the co-flowing flames are shorter and wider, with a higher flame-front curvature. The observations compare favorably with the results of an elliptic model covering 26 species. The microgravity environment enables the separation of fluid effects (buoyancy) from chemistry effects (atmospheric dilution) in modeling and verifying the ignition and flame lift-off predictions.

Laminar, hydrogen-jet diffusion flames were examined in the NASA 2.2-s drop tower using Rainbow-Schlieren deflectometry. This technique allows measurement of flame boundaries and temperatures. In another experiment for similar flames, temperatures were measured using shear-plate interferometry. For nonbuoyant gas jets of hydrocarbon fuels, flame shapes were determined in tests conducted in an environment that minimized interference from soot emissions. Flame lengths are found to be proportional to fuel mass-flow rate, but they are 40 percent longer than those of corresponding normal-gravity flames. Widths of most nonbuoyant flames are proportional to burner diameters.

Laminar, gas-jet flames were also studied in the 4.7-s drop tower in Bremen, Germany. The investigations measure shapes, oxygen concentrations, and temperatures. Results show that many nonbuoyant hydrocarbon diffusion flames are open-tipped, consistent with the observations of previous investigations.

Spherical Flames

Spherical flames are of fundamental importance, because they represent the only stationary, one-dimensional diffusion flames with infinite boundaries. Although extensive studies of unsteadily burning droplets have been conducted in the past, the investigation of gas-fueled, spherical diffusion flames is a recent development. Spherical flames require microgravity, but their one-dimensionality ameliorates some of the diagnostic limitations imposed by microgravity.

One spherical diffusion-flame study included the effects of radiation, including possible extinction, using ceramic spheres in drop-tower tests. The experiments measured temperatures, expansion rates, and radiative emissions, but results to date are unable to demonstrate radiative extinction.

Another project combined several buoyancy-reducing techniques to create a set of nearly-spherical diffusion flames in normal gravity. This study resulted in the discovery of a novel, double-concentric diffusion flame. Testing in the 2.2-s drop tower yielded flame-expansion rates and indicated that test times of at least 10 sec will be required to establish steady, spherical diffusion flames.

A modeling study investigating the effects of rotation on spherical diffusion flames predicts polar flame holes and total flame extinction at moderate and high rotational rates, respectively. Other theoretical analyses of the structure and dynamics of spherical diffusion flames, using activation-energy asymptotics, examine the consequences of low fuel-injection rates: leakage of fuel and/or oxidant, quenching, and surface flames.

Flame-Vortex Interactions

Turbulent flames exist in high Reynolds-number, reacting flows in terrestrial applications, and they contain scales of motion that range from the size of the device down to the microscopic. Buoyancy effects do not occur in many real devices on Earth because the relatively high speeds make the ratios of turbulent stresses to buoyancy-induced stresses large. The problem in normal gravity is one of observability of the range of scales. In order to conduct experiments, large, realistic size scales are desirable. When size scales are expanded, buoyancy must be considered because of the large temperature and density gradients across the various turbulent structures. Alternatively, if velocity scales are reduced, buoyancy again interferes because the large-scale turbulent stresses responsible for momentum transport become smaller than the buoyancy stresses. Consequently, it would be desirable to reduce speeds, while real turbulence and observable size scales are retained. This can be accomplished in microgravity environments.

Flame-vortex interaction is a fundamental characteristic of turbulent flames. Hence, a number of microgravity projects are in progress that study the interactions between imposed vortices and premixed and diffusion flames. Components of flame stretch, strain, and vorticity are being measured in an axisymmetric configuration, where a vortex ring interacts with a freely propagating premixed flame. Microgravity is found to significantly increase the amplitude of flame wrinkling and flame surface area (and, hence, burning rate).

Comparison of experimental results with direct numerical simulations shows good agreement. The results help delineate different regimes of premixed flame-vortex interactions, namely, weak, intermediate, and strong interactions, which can result in flame extinction. Numerical computations also help understand how gravity affects the interaction of a flame with a vortex, as might occur in many turbulent fields. In particular, the interaction between a one-dimensional methane-air flame and a vortex is modeled for three different vortex strengths.

For weak vortex strengths, the flame is pushed back, with the greatest effect seen on the axis where the fluid velocity induced by the vortex is highest. In microgravity, the flame remains wrinkled and has sharp cusps. In a downward-propagating flame, buoyancy provides a stabilizing effect; the flame destroys the vortex, and a planar flame is re-established. In an upward-propagating flame, buoyancy has the opposite effect and is destabilizing. The disturbance caused by the vortex is amplified by buoyancy, and a large finger of cold reactants falls into the products.

For intermediate vortex strengths, the flame is more distorted and is extended further along the axis. The vortex gets past the initial location of the flame intact and begins to entrain the hot products. Gravity does not alter the process significantly but does control the final flame shape.

For very strong vortex strengths, the fast moving vortex drags the flame, extending it greatly along the axis. The strong vortex causes sufficient strain at the axis that the flame is extinguished locally. The vortex then carries some unburned pockets of reactants into the burnt products, but the mixture is not hot enough to react due to radiative cooling. The vortex passes through the computational domain intact, and gravity has no effect. For the cases studied, computed flame shapes and interactions are similar to those observed in the experiments.

Interesting results have also been obtained by “turning off” radiation in the model during a vortex interaction. These lead to the conclusion that the role played by radiative losses in extinguishing this flame is essential. In all cases, irrespective of the vortex strength or the heat losses, a finite amount of time is required for flame extinguishment, a finding in disagreement with the results of steady-state flame-extinguishment studies.

Flame-vortex interactions have also been studied for diffusion-flame configurations. In a recently conducted flight experiment, a gas-jet flame was subjected to imposed, axisymmetric vortex rings. The experiment provides results on the energy interchange between the flame and the vortices, and on the vortex growth and damping processes in the presence of a sheared flow. Another experimental study is investigating the combustion of hydrocarbons in a vortex ring. The interactions are found to depend strongly on the vortex-ring circulation and fuel volume discharged in the ring-formation process.

Microgravity also offers the opportunity to study pulsed flames, for developing universal scaling relations and for exploring flame-control techniques. The obtained scaling relations provide information on degree of wrinkling, the probability of flame curvature, and the stretch distribution along the flame as the strength of the vortices vary.

Turbulent Diffusion Flames

Turbulent diffusion-flame research in microgravity is progressing in a number of areas. Global characteristics of gas-jet flames, such as flame-height variation with fuel dilution and nozzle size, have been reasonably established (fig. 7). Work is now underway in the understanding of the turbulence evolution and decay processes (scalar dissipation) in these flames. Results of numerical simulations indicate that the distribution of the scalar dissipation is symmetrical around the flame surface in the nonbuoyant flame but skewed towards the oxidant side in the buoyant, horizontal flame. The peak of the scalar dissipation, averaged in a horizontal plane, in the buoyant flame is about twice that in the nonbuoyant flame.

Elliptic nozzles have been used to investigate the three-dimensional flow fields of transitional diffusion flames. Active control of these flames by means of imposed acoustic excitation results in a split flame configuration that significantly reduces flame length and sooting. However, the pulsation-induced splitting phenomenon is different for microgravity, normal gravity, and inverted gravity configurations, indicating the importance of buoyant effects on the flame.

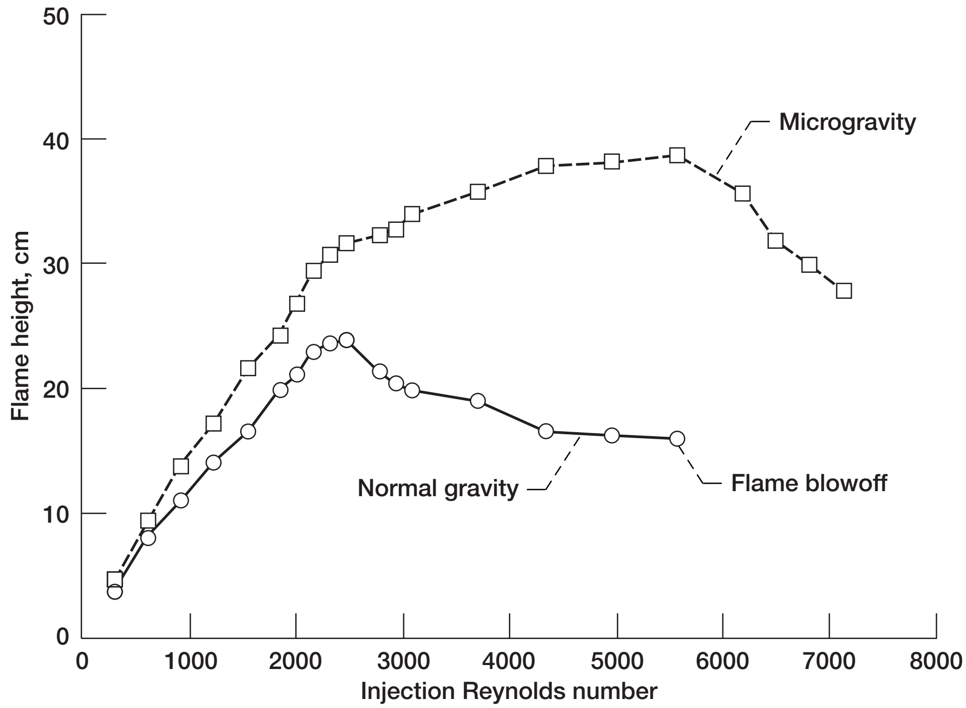

Figure 7.—Measured luminous flame heights for propane-oxygen-nitrogen combustion as a function of injection Reynolds number.

Droplet and Particle Combustion

Isolated Single-Component Droplets

The combustion of liquid hydrocarbon fuels is not only the major source for transportation and electrical-generation energy in the U.S., but it is also the major source of air pollution. In most applications, the liquid fuel is burned in the form of tiny droplets, in order to provide maximum surface area for a given volume of fuel burned. Therefore, a thorough understanding of the process of fuel-droplet combustion is of practical importance.

From a scientific point of view, isolated, spherically symmetric, single-droplet burning is the simplest example of nonpremixed combustion that involves the participation of a liquid phase (fuel) in the gas-phase diffusion flame. Investigation of the combustion of single, isolated liquid droplets affords the opportunity to study the interactions of physical and chemical processes in an idealized and simplified geometrical configuration. In practical sprays, typical droplet diameters are small, and consequently buoyant forces are small. The time scales associated with the combustion of these small droplets are also small, which, when coupled with the small size, makes their study in a normal-gravity environment difficult. The spherically symmetric burning configuration obtained in microgravity allows researchers to develop detailed theoretical models in a simplified, one-dimensional representation. Also, the larger length and time scales offered by microgravity droplet combustion allows both transient and quasi-steady liquid- and gas-phase and flame-extinction phenomena to be studied in detail.

Past experiments in the NASA Lewis (now NASA Glenn) drop towers have established the existence of unique phenomena related to small droplet combustion in microgravity. These findings include:

- A new slow-burning regime,
- Burning-rate influences of hydrocarbon fuels on soot formation,
- Disruptive burning of initially pure liquid-fuel droplets,
- A lower limiting-oxygen concentration for droplet combustion in microgravity than in normal gravity,
- Spark-droplet interactions in the ignition of the droplet, and
- The identification of product dissolution in the liquid phase of the droplet.

The generation of isolated, near-motionless droplets in a quiescent environment for combustion studies is accomplished by a standardized technique in facilities such as drop towers and parabolic-trajectory aircraft. The fuel is injected from two opposing hypodermic needles, which are then separated to a predetermined length to center the injected droplet between the needles and finally withdrawn rapidly. Shortly after deployment, the droplet is ignited using two symmetrically placed hot-wire igniters.

In the period of this review, the Droplet Combustion Experiment (DCE) was conducted successfully on the Shuttle Mission STS-94 in 1997. The experiment investigates large heptane droplets (1.5 to 5 mm in diameter) burned in a quiescent oxygen-helium environments over a range of oxygen concentrations and ambient pressures. Results of the experiment indicate that, under high-oxygen concentrations, the liquid droplet vaporizes completely and the surrounding flame first grows in size, then decreases to a very small diameter, and eventually extinguishes. This behavior is called diffusive extinction because the heat loss occurs by diffusion. Under low-oxygen concentrations, the flame grows and then extinguishes at a maximum size, leaving unburned fuel behind in the residual droplet. This behavior is called radiative extinction. Under intermediate-oxygen concentrations, initially smaller droplets exhibit diffusive extinction but larger droplets exhibit radiative extinction. A follow-on DCE, now in preparation, will incorporate a drop-retrieval mechanism for analysis of the residual, quenched droplets, along with improved diagnostics.

Isolated, Multicomponent Droplets

Most practical fuels used in boilers, gas turbines, diesel engines, rockets, and so on, are multicomponent mixtures. Typical hydrocarbon fuels consist of several hundreds or thousands of components, with a wide boiling range due to volatility differences, in contrast to a single-component fuel with a specific boiling point.

As a first step toward the understanding of multicomponent droplet combustion characteristics, researchers study the burning of droplets composed of only two components, but with greatly differing volatilities. Again, microgravity provides an ideal environment for the study of bi-component droplet combustion by enabling stable conditions with relatively large length and time scales. Two phenomena of interest in bicomponent droplet combustion are the droplet burning history and the possibility of disruptive burning. The burning history of the bi-component droplet may exhibit three stages, because of the dependence on the liquid-phase mass transport. In the initial stage of burning, if liquid-phase mass transport is diffusion-limited, the more volatile component will vaporize and burn preferentially. This results in a liquid-phase boundary layer in the droplet, because liquid-phase mass diffusion is typically slower than droplet regression. With the more volatile component depleted, the second burning stage follows, with the droplet heating to the boiling temperature of the less volatile component. This is followed by the third, quasi-steady burning stage. The phenomenon of disruptive combustion, or a “microexplosion,” occurs when a pocket of more volatile fuel is heated above its homogeneous nucleation temperature for bubble formation. For bi-component droplet combustion, disruptive burning can result if a higher concentration of the more volatile fuel is trapped at the core of a droplet surrounded by a shell of less volatile fuel and if there is sufficient volatility difference between the two fuels.

In the period of this review, two successful tests of single- and bi-component droplet combustion were conducted in space. The Fiber-Supported Droplet Combustion Experiment was operated in a glovebox on Shuttle missions STS-73, in 1995, and STS-94 in 1997. This study burns alcohol and alkane fuels and mixtures in air environments. The fuel droplets, ranging in initial diameter from 2 to 6 mm, are supported on 80- to 110-μm-diameter silicon-carbon fibers and ignited using spark electrodes. Results cover the histories of droplet and flame sizes and their extinction behavior. The most interesting observation in the experiment is that of the interaction of two droplets, initially about 1-cm apart, ignited simultaneously. The droplets are forced apart by the ignition process; but, as they burn, they eventually join as twins, due to the effect of the reduced vaporization in the gap between the droplets.

Spray and Aerosol Combustion

In practical fuel sprays, droplets do not burn individually but interact with one another during combustion. It is insufficient, then, to base models of fuel-spray combustion entirely on results from single-droplet combustion experiments. In addition to the limited tests of double droplets in the Fiber-Supported Droplet Combustion Experiment, three types of studies extend the results of single-droplet combustion studies to more practical fuel sprays.

Two of these studies deal with droplet arrays. Arrays are a collection of a small number of droplets in a controlled configuration that closely simulates an actual fuel spray but is amenable to detailed analytical treatment. Both studies use fiber-supported droplets (as in the Shuttle experiment cited above), where the separation distance of the droplets can easily be controlled. One study investigates the individual and merged flames over pure fuels in low-pressure environments. The second fiber-supported droplet study investigates arrays of pure fuels and bi-component mixtures in high pressures (above the critical pressure of both fuels), continuing a study of single-droplet combustion of bi-component fuels at high pressures.

A third study examines the combustion of laminar fuel sprays in normal gravity and microgravity in the NASA Glenn drop tower. Two spray generation techniques are being used. The first is an electrostatic spray, which allows self-dispersion of the spray due to coulombic repulsion and control of the droplet trajectories. The second is an ultrasonic spray, which allows studies of flame extinction and droplet interaction under low-slip conditions (more amenable to numerical modeling). The results from the first technique show an unexpected influence of buoyancy on the laminar counterflow diffusion flame. In a regime where buoyant effects are expected to be minimal, a laminar counter-diffusion flame is ignited and stabilized first in normal gravity and then exposed to microgravity (the free-fall). Instead of remaining flat, the flame curves in microgravity.

Solid, or dust-particle, combustion has important implications for practical processes and in fire and explosion prevention. Successful low-gravity experiments have been quite limited because of difficulties in stabilizing the relatively dense arrays. A ground-based experiment in progress seeds methane-air and propane-air opposed-jet flames with aluminum oxide particles. The purpose of the study is to determine the limits of extinguishment of the flame as influenced by the particle size (1 to 25 μm), particle seeding rate, and fuel equivalence ratio.

Recent drop-tower studies in Poland on the combustion of aluminum and cornstarch dust note that peak explosion pressures are greater and ignition delays are shorter in microgravity, due to the uniform composition of the arrays and the absence of dispersion-induced turbulence. Another ongoing study on the burning of sub-millimeter magnesium and zirconium particles in air is discussed in the later section of the review covering metal combustion.

Soot Processes

From an environmental and economic standpoint, soot is an important combustion intermediary and product. Soot is an aggregate of fine solid particles, comprised of a range of aromatic hydrocarbon species. Soot production is an important pathway for a significant fraction of the fuel in many practical flames; consequently, the soot processes must be defined in order to understand the chemistry and physical transport in these flames. Due to its high radiative emissivity, soot is a major contributor to the radiative heat loss from a flame; and, as a result, soot formation is a strong positive factor in energy extraction for large-scale boilers and furnaces and a negative factor enhancing flame spread in accidental fires. Soot is an intentional by-product in the manufacture of carbon black, an industrial product used in tires, plastics, inks, pigments, magnetic tapes, and carbon-fiber matrices.

Microgravity offers a means to improve the understanding of soot processes, because it enables the control of the combustion flow environment. For example, predictive modeling shows that, due to the lack of buoyant flow, the soot residence time in laminar gas-jet diffusion flames is of the order of 30 times longer in microgravity than in normal gravity. The movement of soot through the flame is also strongly affected by microgravity. In normal gravity, soot forms in the hottest regions on the outside of the buoyant flame and then moves radially inward toward cooler regions. The soot particles subsequently follow the buoyantly accelerating gas flow until they cross the flame near the flame tip. In microgravity, soot is formed in the coolest regions, and the particles follow a continuously decelerating flow path through zones of ever-increasing temperature. The longer residence times suggest that broad soot-containing volumes exist inside the microgravity flame.

Further insights on soot formation in nonbuoyant flames are now available from the Laminar Soot Processes (LSP) experiment, cited previously in the discussions of laminar gas-jet flames. The long-term, nonperturbed microgravity environment produces flames that are longer and sootier than those formed in short-term, ground-based (drop tower or airplane) tests. Observed flame shapes are open- or closed-tipped, depending on the fuel-flow rates. Tip opening is attributed to quenching of flame reactions due to radiative heat losses. This yields both unburned fuel and soot. LSP investigators propose that universal state relations can be derived for soot properties for all practical nonbuoyant diffusion flames.

Combustion over Liquid and Solid Fuel Surfaces

Spread Across Liquids

Many aspects of flame spread across flammable liquids are currently not well understood, especially in comparison to the state of knowledge of flame spread across solids. When a pool of flammable liquid is ignited, the flame-spread rate can vary widely depending on the initial liquid temperature, fuel geometry, ambient atmospheric conditions, and the level of gravitational acceleration. Several phenomena, such as flame-front pulsations, liquid-phase flow, and gas-phase recirculation are all unique to liquids. However, there is a scarcity of detailed thermal- and velocity-field data in both the liquid and gas phases and in either normal gravity or microgravity. Such data would enhance the understanding of these effects and provide “bench-marks” for numerical models. Furthermore, better understanding of the details of the flame-spread process should result in improved safety procedures and hazard assessment in the case of flammable liquid spills both in space and on earth.

Microgravity research on flammable liquid pools is being conducted in the NASA Glenn 5.2-second Zero-Gravity Facility and aboard a sounding rocket. Early drop tests showed that, in cases where the liquid temperature is high enough to be in the uniform spread regime, there is little difference in flame-spread rate or character between normal gravity and microgravity. In contrast, if the fuel temperature or ambient conditions (oxygen concentration or diluent) are such that the flame would pulsate in normal gravity, it extinguishes in microgravity unless a forced flow is present.

In 1994, the Spread Across Liquids (SAL) experiment became the first combustion experiment to fly aboard a sounding rocket, and it has now completed five flights. The first three SAL flights studied the effects of forced opposed airflow over a 2 cm wide × 30 cm long × 2.5 cm deep pool of 1-butanol in microgravity. Results of the tests show that the flame spread is much slower and steadier than in corresponding normal-gravity conditions (fig. 8). The microgravity flame lies closer to the surface, and it is dimmer and less sooty than the normal-gravity flame. Three-dimensional liquid-phase flow patterns that control the liquid preheating are noted in both normal and microgravity. A two-dimensional numerical model, with single-step chemistry and nonuniform moving grids in both the gas and liquid phases to track the flame, successfully resolves many of the phenomena seen experimentally, such as the liquid-phase vortex and the gas-phase recirculation cell. Interestingly, however, the model predicts faster, pulsating flame spread; and agreement between the model and the experiment can be obtained only by artificially turning off the gas thermal expansion in the model. This leads to the hypothesis that there is significant lateral gas thermal expansion in the experiment, which is not being properly modeled.

The subsequent SAL flights, therefore, focused on the visualization of gas-phase flow patterns using smoke traces. Indeed, the thermal expansion effect was observed. The presence of a recirculation cell predicted by the model has also been experimentally verified in front of a spreading flame for both normal gravity and microgravity (fig. 9). However, the flow patterns are found to be approximately the same regardless of gravitational level, and the aforementioned hypothesis remains unproven.

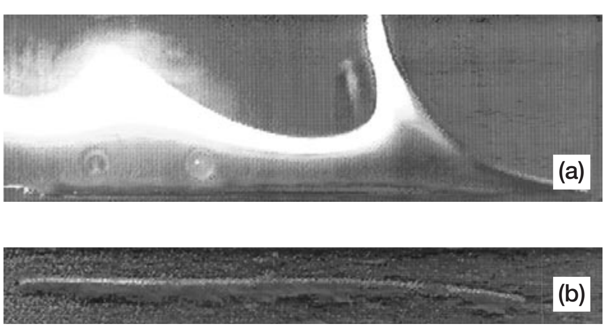

Figure 8.—Images of flame spread over 15-cm wide, I-butanol pool fire. (a) Normal gravity. (b) Microgravity.

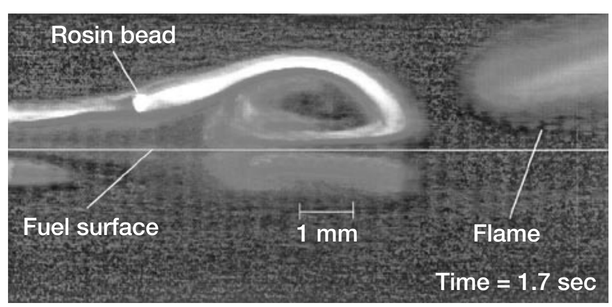

Figure 9.—Smoke-trace visualization of gas-phase recirculation cell ahead of flame in normal-gravity, 1-butanol pool fire.

Quiescent Flame Spread Across Solid Surfaces

Truly quiescent environments are achievable only in microgravity, which eliminates the appreciable buoyant flows always present in normal-gravity flames. Early studies on the combustion of thin-paper fuels under various oxygen concentrations in quiescent microgravity show that, for atmospheres with high oxygen concentrations, the flame-spread rate, V_f, is independent of the gravity level. This finding is consistent with a thermal theory of flame spread for thin fuels, where the flame-spread rate is controlled by gas-phase heat conduction. For oxygen concentrations below about 30 to 40 percent for the paper fuels, however, V_f is lower in microgravity than in normal gravity. Thus, the limiting-oxygen index (LOI, the lowest oxygen concentration in which a flame will self-propagate) is higher in microgravity than in normal gravity (*i.e.*, the flammability range is reduced).

The normal-gravity flame is extinguished by blow-off at low Damkohler number (Da, the ratio of the residence time in the reaction zone to the time required to complete the combustion reaction). In microgravity, however, since the residence time of the reactants is long, extinction must be due to another mechanism.

In order to study thicker solid materials, longer microgravity times than are available in ground-based facilities are necessary. The Solid Surface Combustion Experiment (SSCE) has flown successfully 11 times since 1990. In this experiment, ash-free filter paper or polymethylmethacrylate (PMMA) samples are burned in a quiescent microgravity environment to determine the effects of gravity, oxygen concentration, and pressure on the burning process. The parametric experimental data of flame spread, surface and flame temperatures, and chamber pressure rise provide a set of observations to benchmark flame-spread models over a wide set of conditions. Comparisons of the data to thermally thin combustion models show that radiative heat exchange between the pyrolyzing solid, the gas-phase flame, and the environment must be included to predict the observed trend of increasing flame-spread rate with pressure accurately. Furthermore, while a one-step, steady, fuel-pyrolysis model is adequate for normal-gravity flame spread, an unsteady, multistep pyrolysis model is needed to represent microgravity flame shape, spread, and extinction.

Other quiescent-microgravity experiments, conducted in a short-duration drop tower, examined the effects of oxygen concentration and atmospheric diluent (CO_2, He, Ar, or N_2) on quiescent flammability. The results of these experiments are presented in a following section.

Opposed-Flow Flame Spread Across Solid Surfaces

Thermally-thin fuels.—Flow-aided flame spread from a central ignition zone over thin cellulose fuel samples was studied in the Radiative Ignition and Transition to Flame Spread (RITSI) experiment conducted in a glovebox on the STS-75 Space Shuttle mission in 1996, and in three campaigns in the 10-sec JAMIC drop tower. A focused beam from a tungsten/halogen lamp ignites the center of a rectangular fuel sample, with an external air flow of 0 to 6.5 cm/s velocity present. The nonpiloted radiative ignition of the paper occurs more readily in microgravity than in normal gravity. Under all conditions studied, the sample ignites, and the transition to flame spread follows for all conditions except at the lowest oxygen concentrations and flows. For quiescent conditions (zero air velocity), the flame quickly extinguishes in air, a behavior already expected from results of previous drop-tower work. The ignition-delay time is linearly dependent on the gas-phase mixing time.

This experiment is also the first to demonstrate the flame-spread preferences of a centrally ignited flame in a weakly ventilated microgravity environment. After ignition, the flame spreads in a fan-shaped pattern in the upstream direction (towards the flow). The fan angle is directly related to the limiting-flow velocity normal to the flame front, and it increases with increasing external flow and oxygen concentration (fig. 10).

Downstream flame spread is observed only during the long test times available on the Shuttle tests, after the upstream flame spread is complete. Despite significant preheating by the upstream flame, the downstream flame is not simultaneously viable, due to the depletion of oxygen by the upstream flame, called an “oxygen shadow” by the RITSI investigators. Linear relationships between imposed flow, concurrent flame-spread rate, and opposed flame-spread rate are determined from the experiments (fig. 11). Note that the data of the figure show that the flame fails to propagate at very low flows for both upstream and downstream flame spread. This quench-extinction region extends from velocities just below 0.5 cm/s in opposed (upstream) flame spread and below ~1.5 cm/s in concurrent (downstream) flame spread.

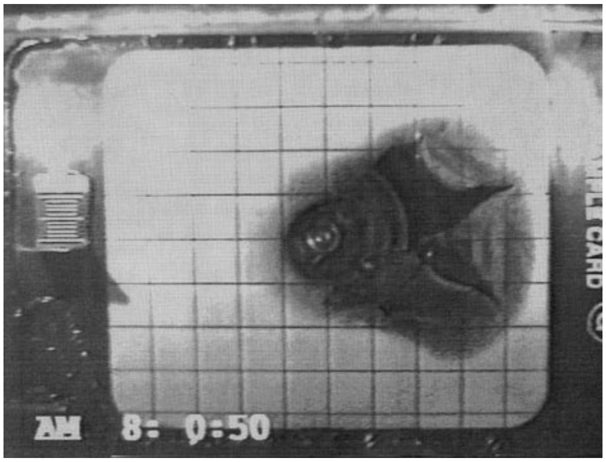

Figure 10.—Fan-shaped pattern of flame spread over thin paper from central ignition point in microgravity. Air flow of 2 cm/s is from right to left.

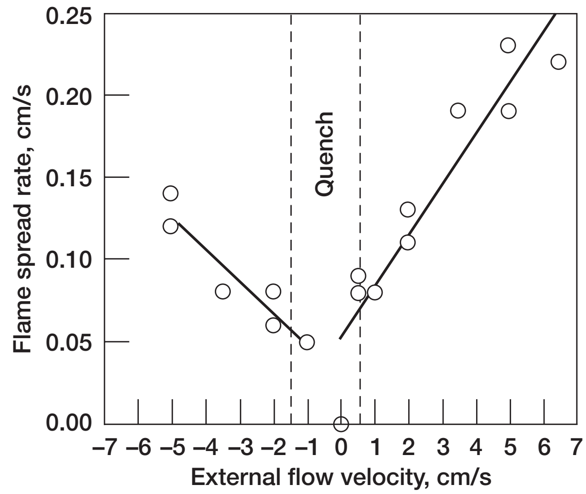

Figure 11.—Summary of flame-spread measurements for centrally ignited paper in microgravity with external air flow. Positive velocities are for upstream flame spread (opposed to the direction of the air flow); negative velocities are for downstream flame spread (in the direction of the air flow). In quench region, flame does not propagate.

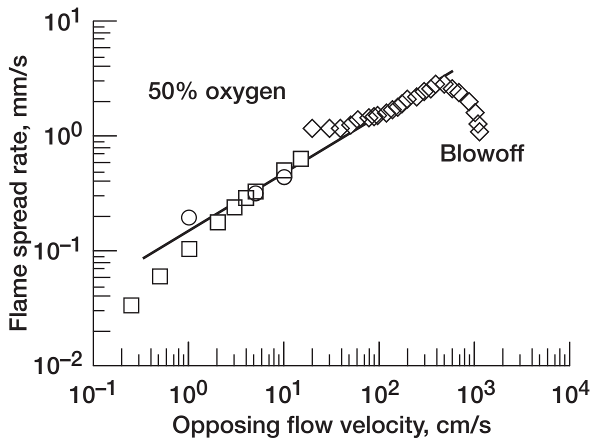

Figure 12.—Flame-spread rate over thermally thick PMMA slabs. Squares are calculations, diamonds are buoyant measurements, and circles are recent measurements in microgravity from DARTFire experiment.

Thermally-thick fuels.—Opposed-flow flame spread over thermally thick fuels was the focus of a sounding rocket experiment, Diffusive and Radiative Transport in Fires (DARTFire), which has had four launches to date, starting in 1996. Because radiative heat transfer is critical to these microgravity flame-spread experiments, the DARTFire tests impose an external radiant heat flux on the burning samples and also measure the radiant heat loss. DARTFire is the first attempt at such experimental control and measurement in microgravity.

Flame spread is very sensitive to low-velocity opposed flow. The effect of flow velocity on flame spread over the 1 to 15 cm/s range extends data previously reported at high opposed flows by almost two orders of magnitude. DARTFire results demonstrate that even a flow on the order of diffusive velocities (<2 cm/s) is sufficient to sustain combustion. In contrast, previous experiments show that, under absolutely quiescent conditions, flame spread does not occur. Flame extinction by flow cessation may not be a practical option for fire control, however, since inhabited, powered space vehicles may always retain some atmospheric flow due to crew motions, ventilation, and cooling systems. Flame-spread rates over more than three orders of magnitude show a power-law dependence on flow, where the exponent on the flow is ~0.5 for both the 50 and 70 percent oxygen data (fig. 12), suggesting a relation to boundary-layer thicknesses.

The effect of external heat flux, noted above in the description of the DARTFire tests, is also under review. Experiments select flux levels to offset approximately either the surface radiative loss alone or the surface plus flame radiative loss. Preliminary results indicate that the flame-spread process is linearly dependent on the net heat flux from the flame to the surface, which includes both the conductive and radiative contributions.

Concurrent-Flow Flame Spread Across Solid Surfaces

A study of upward flame spread over solid fuels was conducted to clarify the mechanisms of spread rates for concurrent-flow flame spread and, in particular, the effects of buoyancy. It is proposed that upward flame spread could be steady, because convective losses to the sides of the fuel samples, or surface radiative losses, or both, prevent the flame length and thus spread rate from growing indefinitely. These losses are argued to be unavoidable because the flame length will grow until these losses balance the heat-generation rate. Scaling relations are derived for the spread rates in the presence of convective and radiative losses, laminar and turbulent flow, buoyant and forced convection, and thin and thick fuels.

In the period of this review, the Forced Flow Flame Spreading Test (FFFT) was conducted successfully in a miniature combustion tunnel mounted in a glovebox on the Shuttle mission STS-75 in 1996. The investigation studies the effects of flow speed and thickness for flat paper fuels, and the effects of flow speed, flow direction, and initial fuel temperature for cylindrical molded-cellulose fuels. Results report the flame lengths as functions of time. Although the facility can deliver air flow with velocities up to 8 cm/s, the size of the tunnel limits the useful measurements of flame length for the flat fuels to velocities no greater than 3 cm/s. The cylindrical fuel tests yield quantitative results, indicating an increase in flame length with time for increasing air velocity and for increasing preheat temperature (75 to 135 °C). Consistent with results of other solid-surface tests, the flame extinguishes when the air flow is shut off.

A similar combustion-tunnel test, conducted on Mir, in 1998, observed the concurrent-flow flame spread across cylindrical samples of three plastic materials: high-density polyethylene, PMMA, and Delrin. The results, still under review, indicate that each material has a characterizing limiting-combustion velocity, that is, a minimum concurrent air flow necessary to maintain flame spread in microgravity.

An overall solid-surface-combustion experimental and analytical project, Solid Inflammability Boundary at Low Speed (SIBAL), is now in progress. The unique aspect of the experimental project is the use of a moving fuel surface dispensed from a roll at a rate to match the flame-spread rate. The fuel is a cotton fabric blended with a small amount of fiberglass. The model is established in terms of a seven-decade range of Grashof number, Gr_W, defined as gW^3/ν^2, where g is the gravitational acceleration, W the fuel-bed width, and ν the kinematic viscosity. Flames are found to achieve steady values of both spread rate (V_f) and flame length when the sample is sufficiently tall. Measured values of V_f, normalized by the opposed-flow (downward) spread rate for the same atmosphere and fuel bed ($V_{f,opp}$), are shown in Fig. 13. At low Gr_W, $V_f/V_{f,opp}$ is proportional to the first power of Gr_W, with the value of the proportionality constant being slightly different for different atmospheres. At high Gr_W, V_f is independent of Gr_W, indicating a transition to radiative-stabilized flame spread. At intermediate Gr_W, there is some indication of a region where $V_f/V_{f,opp} \sim Gr_W^{4/7}$ as would be characteristic of turbulent buoyant regime. The data deviate from $V_f/V_{f,opp} \sim Gr_W^1$ behavior towards $V_f/V_{f,opp} \sim Gr_W^{4/7}$ near a value of $Gr_W = 20{,}000$, which is analogous to a criterion for the transition from laminar to turbulent behavior.

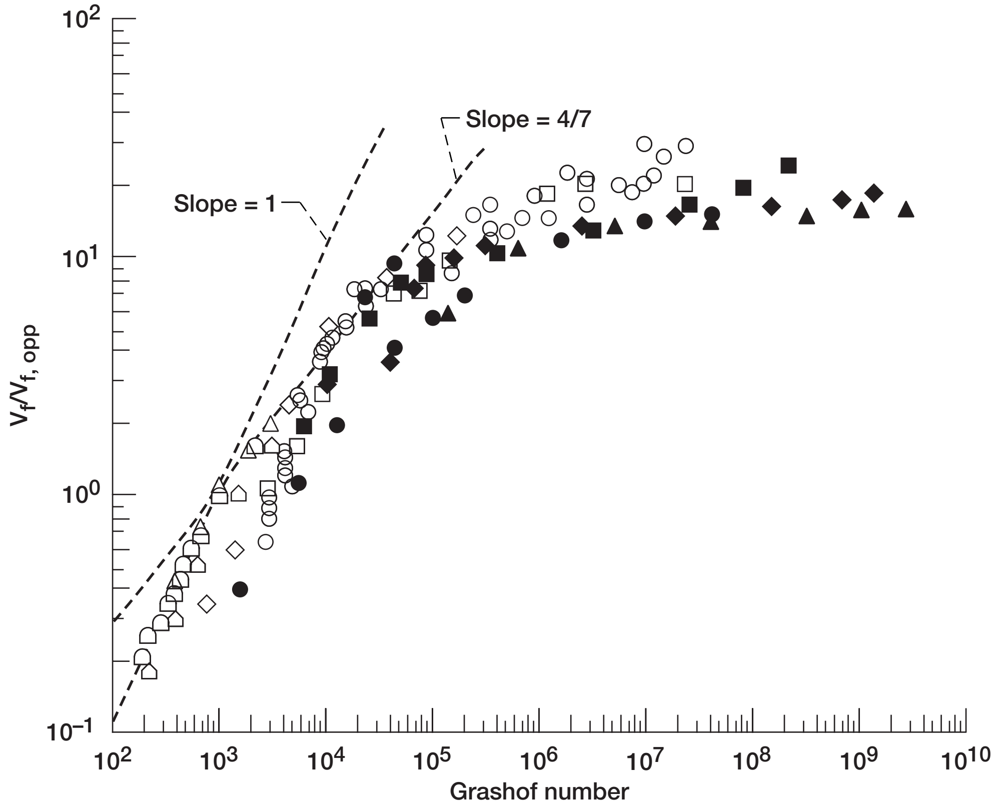

Figure 13.—Ratio of concurrent to opposed flame-spread for cotton-fabric fuel as a function of Grashof number, Gr_w, defined as gW^3/ν^2, where g is the gravitational acceleration, W the fuel-bed width, and ν the kinematic viscosity. Various symbols are for tests covering a range of total pressures, oxygen concentrations, and atmospheric diluents.

Diluent Effects on Flame Spread Over Solid Surfaces

The effects of diluent addition on flame spread over 5-cm wide Kimwipe sheets, 15-cm long, were studied in normal gravity and quiescent microgravity. In one case, the additives are the inert gases He, Ar, N_2, CO_2 and SF_6, since they provide a variety of radiative properties and Lewis numbers from about 0.3 to 1.4. In a second case, the additives are sub-flammability-limit concentrations of combustible gases such as CO and CH_4.

In the first studies, for He and N_2 and Ar dilution, the microgravity flame-spread rate, V_f, is always lower than the normal-gravity spread rate, and the minimum oxygen concentrations to support flame spread are greater in microgravity than in normal gravity. These results are entirely consistent with prior studies, which conclude that this behavior is due to the greater radiative heat losses in microgravity. In contrast, for CO_2 dilution, V_f is slightly lower in microgravity than in normal gravity, but the minimum oxygen concentration is lower in microgravity than in normal gravity (fig. 14(a)). For SF_6 dilution, V_f is substantially higher in microgravity than in normal gravity for all oxygen concentrations, and the minimum oxygen concentration is significantly lower in microgravity than in normal gravity (fig. 14(b)).

Only the H_2O and CO_2 combustion products produce significant thermal radiation at flame temperatures. At the conditions tested in this study, much of the radiation processed can be considered optically thin. However, for CO_2 and especially SF_6 diluents, re-absorption of emitted radiation cannot readily be neglected; and radiation emitted near the zones of peak temperature may not be lost to the surroundings, which can increase the spread rate above the rate without radiative transfer.

In the second studies, the additives for the thin-fuel, flame-spread experiments are sub-flammability-limit concentrations of gaseous fuels in O_2-diluent atmospheres. These conditions represent possible atmospheres encountered in under-ventilated fires, which can contain substantial concentrations of unburned fuel gases or intermediates, such as CO.

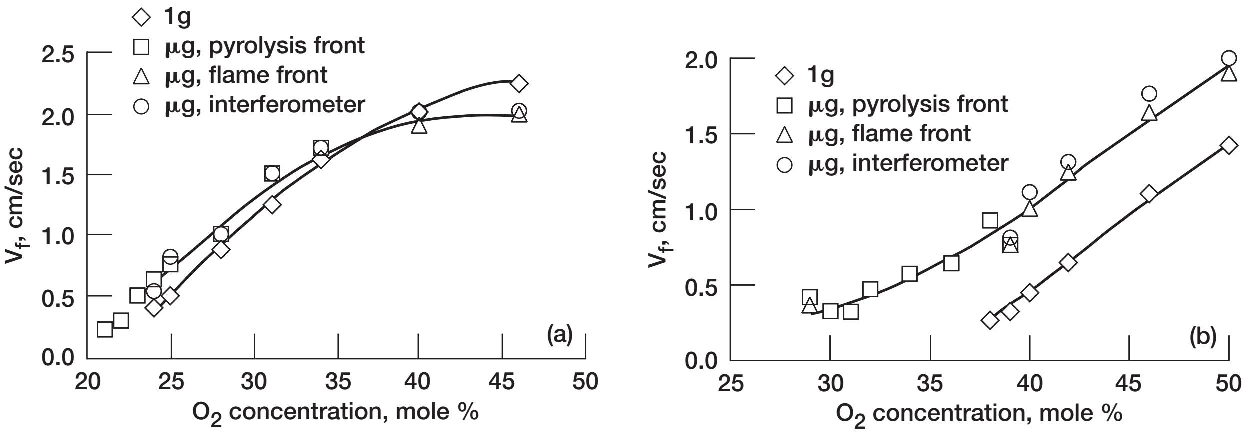

Figure 14.—Flame-spread velocities for thin paper in quiescent atmospheres with radiation-absorbing diluents. (a) Carbon dioxide diluent. (b) Sulfur hexafluoride diluent.

Initial normal-gravity tests show that, for some fuels such as CO and H_2, there is a strong effect of the fuel additive on V_f, whereas for other fuels such as NH_3, there is practically no effect. Remarkably, for CO fuel (a very important case for practical applications), it is found that V_f is higher and the minimum-oxygen concentration is lower when a given number of oxygen atoms in the ambient atmosphere is present in the form of CO rather than oxygen. In microgravity, the effect of adding gaseous fuel to the ambient atmosphere is qualitatively similar, but the effect is stronger in microgravity than in normal gravity. In fact, V_f is actually higher in microgravity than in normal gravity at high premixed fuel concentrations. Also, the effect of added gaseous fuel is found to be greater at higher oxygen concentration and with CO fuel. All of these results are consistent with a simple theoretical model that shows the effect of the premixed fuel is to cause a partially-premixed flame sheet to occur upstream of the conventional nonpremixed flame. This additional flame increases the total heat flux to the fuel bed and thus V_f.

For diluent-modified atmospheres, steady flame spread is obtainable over thick fuel beds at microgravity conditions even in short duration drop-tower experiments. The highest possible spread rates are found with fuels with low thermal conductivity and density; and drop-tower experiments on thick sheets of polystyrene, ignited in microgravity, show that combustion can continued for the entire 2.2-sec drop.

Low-Stretch Combustion of Solids

In spacecraft, low-velocity flows from ventilation equipment or small cooling fans for electronic hardware can impinge upon flammable surface materials and create low-stretch environments. To study flame structure and extinction characteristics of these unusual low-stretch flames, researchers generated diffusion flames over cylindrical polymethylmethacrylate (PMMA) samples of varying large radii. These experiments are the first conducted in normal gravity at such low stretch for a large-scale solid fuel. The results are consistent with characteristics of low-gravity, low-stretch flames. The only clear gravitational effect noted is fuel dripping, which is inconvenient but does not change the overall trends provided by the experiment.

The surface regression rates and nondimensional mass burning rates decrease monotonically with stretch rate in agreement with model predictions. The low-stretch surface regression rates extend the database for PMMA to quenching extinction, so data are now available from blowoff to quenching. A transition from the blowoff side of the flammability map to the quenching side of the flammability map is observed at stretch values of ~6 to 7 sec^{-1}, as determined by the nonmonotonic trends in peak temperatures, solid and gas-phase temperature gradients, and nondimensional standoff distances.

A local extinction limit beyond which a one-dimensional flame cannot exist is found as the stretch rate is reduced, or solid-phase heat loss is increased, or both. Beyond this limit, smaller, three-dimensional flamelets are stable. Quenching extinction of the flamelets is found to occur as heat loss increases.

An extensive layer of material above the glass-transition temperature is observed due to the extremely low burning rates obtained at these very low-stretch conditions. Unique phenomena associated with this extensive glass layer are substantial swelling of the burning surface, in-depth bubble formation, and migration or elongation of the bubbles toward the hot surface.

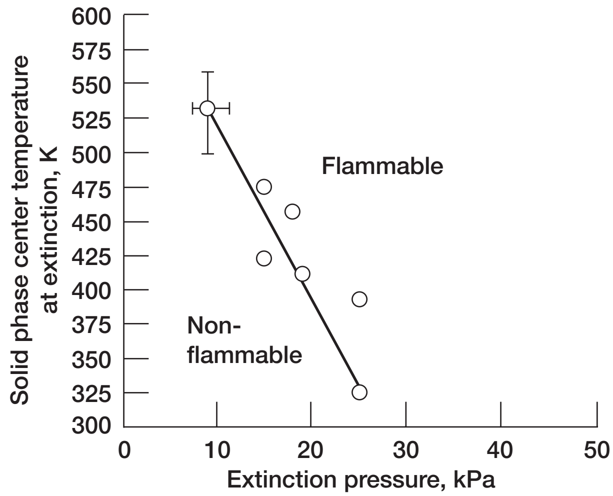

Figure 15.—Flammability map for low-pressure extinction of flames spreading radially across PMMA cylinders with 10 cm/s air cross-flow.

A time-dependent, three-dimensional numerical model is being developed to predict the temperature field, burning rate, and bubble-bursting characteristics of burning thermoplastic materials in microgravity. The numerical model includes the dynamics of bubble growth and migration, heat transfer through the condensed material, the chemistry of gasification, and coupling to the gas phase. The degradation characteristics from the model predictions are being compared with experimental results of the combustion of a PMMA sphere in low-gravity tests conducted on an airplane. Upon ignition, the sample swells, and the outermost surface layer of the burning sample bubbles. Violent sputtering and ejection of molten polymer from the burning sphere are observed as the gaseous fuel bubbles from the interior of the droplet reach the surface.

An important fire-safety issue that can be examined in a low-stretch environment is the effect of a forced flow on a diffusion flame at reduced pressure in low gravity. The phenomena is important for spacecraft fire safety since the last-resort option for fire control is the use of depressurization (venting) of the spacecraft atmosphere following abandonment by the crew. A set of recent experiments and numerical simulations examined the effects of reduced pressure on a low-stretch diffusion flame over small radius PMMA cylinders in a cross-flow (10 cm/s) in low gravity. During each test, both experimental and numerical, the pressure is slowly reduced until extinction occurred. A flammability map is created using the experimental extinction pressure and solid-phase centerline-temperature data at blow-off (fig. 15). The experimental results indicate that a hotter material requires a lower pressure to be extinguished. As the solid-phase centerline temperature increases, the extinction pressure decreases, and with a centerline temperature of 525 K, the flame is sustained to a pressure of 10 kPa (0.1 atm) before extinguishing.

Smoldering

Smoldering is a nonflaming combustion process that takes place in porous-solid combustible materials, and it is characterized by a heterogeneous surface reaction that propagates within the fuel material. Smoldering is important both as a fundamental combustion mechanism and as a fire precursor, since fires are often triggered by the transition from slow smoldering to rapid flaming. Smoldering transport and reaction processes are complex, and the removal of gravity offers substantial simplifications to their study.

Surface Smoldering

Microgravity smolder spread over a thin cellulosic fuel was studied in the Radiative Ignition and Transition to Spread Investigation (RITSI) experiment, already cited in the section on flame spread across solid surfaces. Radiative smoldering ignition is initiated by a focused beam from a tungsten/halogen lamp at the center of the smolder-

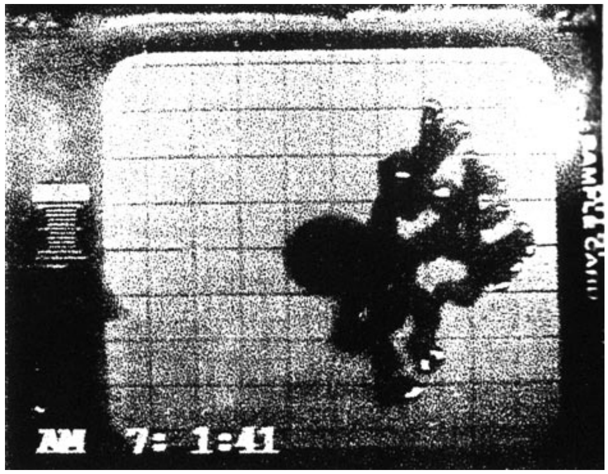

Figure 16.—Pattern of smolder-front spread over treated paper from central ignition point in microgravity. Air flow of 2 cm/s is from right to left.

promoted filter paper. The external air-flow velocity is varied from 0.5 to 6.5 cm/s. This experiment demonstrates for the first time nonpiloted smoldering ignition of the paper in microgravity by external thermal radiation.

Although smolder fronts are uniform in convective environments, a complex, finger-shaped char pattern forms in microgravity. Each “fingertip” has a glowing smolder front that propagates, frequently bifurcates, and occasionally extinguishes (fig. 16). Smolder fronts preferentially propagate upstream into fresh oxidizer. At low imposed flows, onset of downstream smolder is delayed until completion of upstream smolder, analogous to the RITSI observations on the combustion of nonsmolder-promoted paper. Normalized smolder area, a ratio of the area smoldered to the total available area, linearly increases and smolder-front spacing decreases with imposed flow, approaching unity (uniform front) at velocities of 9 to 10 cm/s. Average smolder-front width (“fingertip”) is independent of flow velocity. The smolder fronts exhibit bifurcation, merging, and extinction rates that are directly proportional to the semicircular circumference available for smolder.

Analysis of oxygen transport reveals that each smolder front casts an “oxygen shadow” that influences the oxygen mass flux to adjacent smolder fronts. The oxygen mass flux to each smolder front depends strongly on the proximity of other smolder fronts and weakly on the nondimensional smolder-spot size.

In-Depth Smoldering

Smoldering combustion has been investigated in three space-flight campaigns. The original study, Smoldering Combustion in Microgravity, was a Glovebox experiment on Shuttle mission STS-50 in 1992, and it was reported in the previous microgravity-combustion overview.

A second space experiment, Microgravity Smoldering Combustion (MSC), was flown twice. First, it was operated in a GASCAN carrier (see appendix A) on Shuttle mission STS-69 in 1995. Next, it was operated in a rack on the Spacehab-4 Laboratory on Shuttle mission STS-77 in 1996. Tests in the MSC are conducted with cylindrical polyurethane fuels, 12-cm diameter by 14-cm long, in quiescent and opposed-flow environments, compared to the 8-cm-long by 5-cm-diameter samples of the first flight experiment.

The MSC tests show that the effect of gravity on smolder is most pronounced under limiting flow conditions, namely, low flow velocities and oxygen concentrations, and in transitional processes, such as ignition, extinction, and flaming combustion. In quiescent conditions, the smolder front does not progress beyond the influence of the igniter. With forced flow, the nonbuoyant smolder propagation becomes stronger than upward smolder in normal gravity but still weaker than downward smolder.

A significant observation in MSC is that the generation of CO and other light gases is relatively minor. This finding is in contradiction to the results of the 1992 space experiment, which reported the generation of possibly hazardous quantities of the light gases. The MSC researchers conclude that the larger sample sizes and more uniform air flow through the sample for the later tests reduce heat losses and igniter influences. The MSC results are considered more representative of spacecraft smolder scenarios.

Metal Combustion

Metal combustion processes are of considerable interest for applications to such varied fields as solid-rocket propulsion, oxygen-handling systems, ceramic syntheses, and metal cutting. Metals generally have high boiling temperatures and heats of combustion. Their oxide products also have high boiling temperatures. Hence, while some metals burn in the vapor phase similar to conventional organic fuels, many metals burn in the solid or liquid phases. For metals burning in the liquid phase (iron for example), the predominant gravity-induced motion is downward, *i.e.*, dripping or sedimentation. This is in contrast to the upward buoyant motion of combustion products in vapor-phase combustion. It is reasonable to expect that the suppression of sedimentation in a microgravity environment will strongly influence the physical characteristics of metal combustion.

Investigations of metal combustion are conducted with three general types of fuel configurations, (1) bulk wires, ribbons, and pellets, (2) individual particles, and (3) dispersed-particle arrays.

For bulk-metal configurations, microgravity tests have been conducted on metal rods ignited at the bottom by a chemical promoter and on 4-mm-sized pellets ignited at the top and side by exposure to lamp radiation. It is not surprising that the combustion behavior of the two setups is not consistent. Iron-rod tests, carried out in a 100 percent-oxygen atmosphere over a pressure range from 0.1 to 6.9 MPa, show that the solid regression rate, used as an indication of flame spread, increases with increasing pressure and with decreasing gravity. In microgravity, the melting fuel forms a spherical ball adhering to the unburned metal with an elliptical attachment area. The metal-pellet tests, conducted on titanium and magnesium fuels, established complete spherically symmetric combustion. For this setup, both the flame-spread and fuel-regression rates are significantly less in low gravity, compared to normal gravity.

In the symmetric-combustion metal-pellet studies, the application of advanced diagnostics reveals novel features of metal combustion. For example, high-speed cinematography shows new regimes of combustion in which the accumulation of metal-oxide particles in the reaction zone induces a pulsating combustion process. The enhanced radiation from the particles increases the heating and expands the fuel and flame size, until the rapid evolution of metal vapor collapses the flame zone. This cycle is followed by a continuing series of buildups and collapses.
For metal-particle combustion, one study uses an electric arc to generate and ignite a series of particles, typically of the order of 100 mm in diameter, from a metal ribbon or wire source. Tests with aluminum, titanium, zirconium, and boron fuels were conducted in a low-gravity airplane laboratory and in normal gravity under air. The combustion lifetime of these particles is several hundred milliseconds. The apparatus permits the observation of the combustion process and the collection of quenched particles at any time during the combustion process, for surface and interior analyses. Two distinct stages are noted in metal-droplet combustion. The first stage is the physical process of the formation of a liquid metal-oxygen (and in some cases, metal-nitrogen) solution within the burning droplet. The second stage is the chemical process of the reaction to form the stoichiometric metal oxide. These stages account, at least in part, for the brightness variations and "microexplosions" typically observed during the course of metal combustion.

The minimization of convection flows in low gravity influences the composition and homogeneity of the reacting and quenched droplets. The experimental combustion times showed reasonable agreement with calculated times, which are derived from evaporation constants based on the initial particle and atmospheric thermal properties. For dispersed-particle metal combustion, the microgravity environment is essential. Not only does microgravity enable the stabilization and control of the particle array for research, but the environment strongly influences the combustion behavior.

A systematic microgravity study is underway on the physical interaction and combustion behavior of arrays of relatively large metal particles, 50 to 300 mm in diameter. Since the combustion process itself is very rapid for the three metals tested, magnesium, zirconium, and titanium, the drop-tower exposure time of 2.2 sec is long enough to stabilize the array, permit a variable preignition delay time, and complete the combustion process. For magnesium, the flame-front position in the aerosol indicates that flame speed varies directly with the general motion of the particles, *i.e.*, it decreases as delay time increases. The recovered burnt particles are slightly larger, on the average, than the original fuel particles, due to the accumulation of an oxide coating. For zirconium, the recovered burnt particles are, on the average, two to three times greater in diameter than the unburned particles. Scanning electron-microscope images of the product zirconia particles show them to be of the form of large agglomerates of multiple joined spheres. The study of the combustion characteristics and burnt-particle morphology of titanium is now in process.

Combustion Synthesis

The use of combustion to synthesize improved and novel materials is expanding. Self-propagating high-temperature synthesis (SHS) is being investigated as a means of preparing a wide range of advanced materials, *e.g.*, ceramics, intermetallics, metal-matrix composites, and ceramic-matrix composites. Parameters such as green (reactant) density, reaction stoichiometry, particle size, heating rate, and mode of combustion, coupled with the effect of gravity, have been found to affect the exothermic SHS reaction and the resulting microstructure and properties of the synthesized product significantly. Microgravity also offers an opportunity to isolate the coupled effects of pressure and buoyancy in the flame production of fullerenes and other nanostructures.

Experimental Syntheses of Bulk Materials

In early studies of syntheses in low gravity (airplane facilities), investigators controlled the generation of (1) porous ceramic composites by using gasifying agents that lead to "foamed" structures, and (2) dense metal-matrix composites by using excess metal that melts during the SHS reaction and fills residual pores. For dense metal-matrix composites, ceramic reinforcing particles have been used that are either lighter or heavier than the metal matrix, to study the effects of nonuniform distribution of reinforcing particles in the matrix. SHS reactions conducted in low gravity show the following differences from those conducted under normal gravity or slightly elevated (twice normal) gravity conditions:

- A decrease in segregation of components in metal-matrix composites,
- An increase in porosity in "foamed" ceramic composites, and
- A wide range of possible microstructures because of the greater control of combustion temperature.

Recent work on the SHS production of a porous B_4C-Al_2O_3 ceramic, using B_2O_3 as a gasifying agent, investigated the control of porosity through variations of pressure, gravity level, and stoichiometry. The strength of the composite is optimized by the quantity of molten aluminum used to infiltrate the porous ceramic structure. However, the formation of aluminum oxide at the metal-ceramic interface reduces the ability of the Al metal to wet and fill the pores. The alternative of infiltrating the porous ceramic structure with polymers, such as PMMA, shows considerable promise. Polymer infiltration of the SHS product decreases its total porosity, but it increases the average pore size by preferentially filling smaller pores, resulting in a composite material with increased strength. Since the polymers used for infiltration are bio-compatible, the product may have a significant application as a bone-replacement material. The porosity of this material has been successfully controlled to a range between 40 to 60 percent, with pore sizes of 200 to 500 μm. Such properties are required in order to allow significant blood flow through the structure to facilitate high bone-growth rates. The products of this research are found to be competitive with currently used materials by a commercial company that specializes in the synthesis of bone-growth proteins. Recent research has also included the synthesis of porous Ti-TiB_x composites that are expected to provide an additional range of bone-replacement materials with substantially higher mechanical properties.

Several classes of heterogeneous-reaction systems were studied in microgravity, using the NASA Glenn 2.2-sec drop-tower facility. These combustion syntheses systems ignite metal-powder reactants by a heated filament under inert-gas atmospheres. Results indicate that composite products produced in microgravity have a uniform distribution of the refractory phase with fine grain sizes. For example, Ni-Al-Ti-B systems yield TiB_2 grains dispersed in a Ni_3Al intermetallic matrix that are ~50 percent smaller than those formed in normal-gravity conditions. Experimental results shown in figure 17 demonstrate the quantitative evolution of grain-size growth, where quenching distance was controlled by enclosing the reactants in a wedge-shaped space embedded in a brass heat-sink mass. In other experiments conducted in the same facility, synthesis of freely expanding Ni_3Al yielded intermetallic foams with porosities of up to 90 percent, without the need for gasifying additives, as used in earlier syntheses.

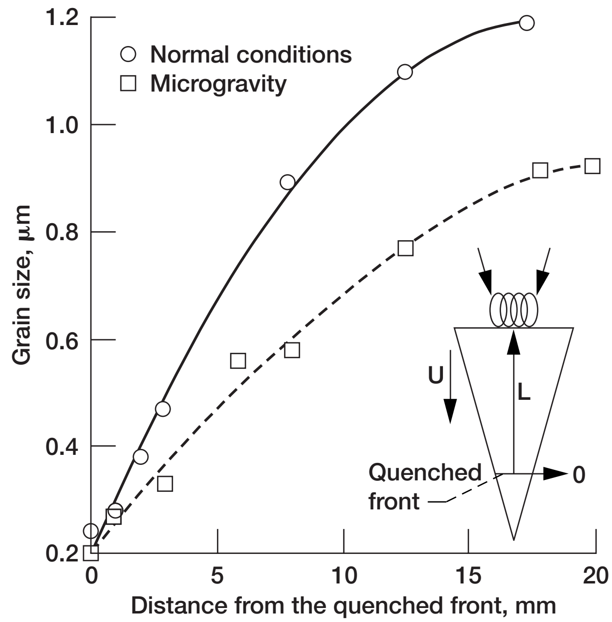

Figure 17.—Evolution of TiB_2 grain size in quenched sample from reacting (3Ni + Al) + (Ti + 2B) synthesis mixture.

Modeling

Theoretical models are being developed and analyzed to describe the fundamental mechanisms in the SHS and smoldering processes. Both processes are governed by the same mathematical model, involving multiphase heterogeneous combustion in porous media and differing only in scale and in the intended goal of combustion. Smoldering combustion waves are undesirable, whereas SHS waves are desirable. The analytical and numerical studies focus on (1) filtration combustion (FC), in which a gas containing oxidizer flows through a porous medium to the reaction site, where it reacts with the solid porous reactant, and (2) “liquid flames”, which arise, *e.g.*, in high heat-capacity mixtures, when the porous matrix melts, forming a liquid suspension containing solid particles and gas bubbles.

One modeling result describes a possible fingering instability in FC, in which the interface between the burned and unburned portions of the sample takes the shape of a propagating finger that occupies only the interior of the sample and not its surface. Such a combustion wave is more dangerous, from the point of view of fire safety, in that its combustion velocity exceeds that of the flat interface and the burning is concealed and not easily detected. Another result describes a new type of FC wave, driven by convection rather than diffusion, which arises due to the imbalance between the temperatures of the solid and gas phases. These waves propagate much more rapidly than diffusion-driven FC waves, and they may occur even in mixtures with very low thermal conductivity.

Another model describes the ignition, propagation and stability of “liquid flames”. New ignition criteria are derived, which account for gravity-induced relative motion between the phases and depend on the relative time scales of reaction and relative motion. In addition, investigators find (1) ”shock-like” structures for the reactant concentrations, (2) a new mechanism of quenching due to significant buoyant compression of the reaction zone, and (3) a new mechanism of instability due to gravity-induced separation.

Nanostructures

The flame production of both metal and ceramic nanoparticles is being investigated by a process that holds promise for commercial scale-up. The synthesis involves the encapsulation of extremely fine, reactive nanoparticles in a protective coating that can be readily removed during subsequent processing. This novel step yields purer and less-agglomerated materials than can presently be obtained. The flame and encapsulation process is being studied in microgravity in order to simulate actual conditions realized during spray combustion. Normal-gravity results so far demonstrate that metal (*e.g.*, aluminum, titanium, tungsten and iron) and ceramic (*e.g.*, aluminum nitride, titanium boride and silicon carbide) nanoparticles can be produced with flame technologies and that the encapsulation process is effective in maintaining the purity of the powders. A novel computer code developed to model the particle-encapsulation process demonstrates that encapsulation in flames is basically a two-step process where, first, a small number of particles are coated and grow very rapidly. Then, these particles act as scavengers impacting the metal or ceramic particles and resulting in the encapsulated products.

Recent studies of laminar premixed and diffusion flames under normal and reduced gravity in variable-pressure environments clarify the chemistry of the fullerenes and other carbon nanostructures. This research is also expected to benefit the knowledge of soot formation, because high-molecular-weight growth reactions involving polycyclic aromatic hydrocarbons and acetylene are integral to both soot and carbon nanostructure synthesis.

Program Status: Applications to Fire Safety and Other Fields

The primary purpose of microgravity-combustion research is the advancement of fundamental knowledge. The pursuit of information in basic science, however, is often justified by its potential benefits in future applications. Because combustion is such an important process in a wide variety of essential activities, microgravity-combustion research should lead eventually to many process and product innovations, improvements, and efficiencies. This section continues the presentation of the status of microgravity-combustion research and derived knowledge, by extension to the program area of practical applications. Measurements and diagnostics for basic and applied combustion studies are considered a separate program area, and discussions of progress in these fields are reserved for a later section.

The program area of applications covers the following topics:

- Spacecraft fire safety
- Combustion, processing, and fire safety in future extraterrestrial missions
- Aircraft and terrestrial fire safety
- Commercialization and “spin-offs”

Spacecraft Fire Safety

Spacecraft fire safety must be founded upon design and operational analyses that identify fire risks and consequences in advance. Since absolute (zero-risk) safety is impractical, risk assessments operate with the objective of limiting a worst-case scenario to a fire event that may cause the suspension of some operations temporarily but no human injury nor permanent spacecraft damage. The implementation of this goal is primarily through fire prevention, which aims simply to eliminate at least one leg of the familiar fire triangle of fuel, ignition, and oxygen. Fire prevention, however, is never guaranteed. Provisions must also be in place to respond to fire events if they do occur. All current and proposed human-crew spacecraft are equipped with automated detectors and hand-operated fire extinguishers.

Spacecraft Experience

Five fire-causing incidents involving component overheating or electrical short circuits have been reported in the 19 years of operation of the Shuttle Transportation System, which covers a span of more than 90 missions. In all these incidents, the crew observed the problem and acted to eliminate potential fires by removal of power, without using the extinguishers. About 15 other anomalies, such as false alarms or detector faults (failure of the built-in test circuits), have also been recorded in the Shuttle operations. It is generally agreed that the probability of such incidents will increase in the longer and more complex orbital-station (the International Space Station, ISS) and extraterrestrial missions. It is already known that several small fires have occurred in the ten-year span of Mir orbital-station missions, although documentation of these incidents is sketchy.

The February 1997 fire originating in an oxygen-generating system on *Mir*, however, was well publicized because of the international crew onboard. The *Mir* fire is an unusual fire scenario that is highly threatening. The fire propagated in a highly convective local environment at an elevated oxygen concentration, all of which are conditions that are conducive to fire spread in any gravitational environment. The fire persisted for a number of minutes (the exact time of the fire is contradictory in various reports) and rapidly filled the orbital-station atmosphere with smoke. The crew contained the fire by applying the contents of several aqueous-foam extinguishers, but no doubt the fire extinguished only when the generated oxygen was depleted. The crew spent more than a day to clean up the *Mir* interior of the residues of the fire, smoke, and excess suppressant; but, fortunately, the fire caused no permanent damage.

Risk Assessments

In a quantitative risk-assessment project completed just prior to the reporting period of this review, a study team established the probabilities of scenarios consistent with Shuttle experience, *i.e.,* electrical-wiring overloads. The analytical models calculated heat release, mass-burning rate, and smoke and gas evolution for the defined scenarios. Results of microgravity drop-tower tests showed that strongly overloaded wire insulations readily ignite and pyrolyze in microgravity, but the wire-insulation temperatures and the nature of the soot and gaseous-product evolution all differ from those expected in corresponding normal-gravity conditions. The effects of long-term but moderate overload levels could not be determined since the experimental phase of the project was not continued into spaceflight testing.

Another project, while not directly aimed at fire-risk assessments, is relevant to the scenario of wire-insulation degradation in microgravity. A simple experiment examines the quantity, composition, and morphology of the particles released by overheated wires with fluorocarbon insulations. The results show that, as expected, normal-gravity overheating tends to produce small-size, individual particles, and low-gravity overheating tends to produce large-size, agglomerated particles. The unexpected finding of this research is that the particle sizes and morphology generated in both low gravity and normal gravity by the degradation of the polymers investigated are strong functions of the color of the insulation, presumably because of the influence of the different dyes in the polymers, even in trace quantities.

Material Flammability Testing for Fire Prevention

The selection of materials for use in U.S. and European human-crew spacecraft is based largely on test methods defined in the NASA Handbook NHB 8060.1C. Normal-gravity tests are necessary because the expense and time for microgravity tests of the thousands of potential spacecraft materials are prohibitive. The principal NASA test (Test 1), which has been in use for over 25 years, determines material acceptability by its resistance to upward flame spread following chemical ignition. This is obviously a severe test because buoyancy naturally promotes the fire spread. A similar test (Test 4) is used to determine the acceptability of electrical-wire insulation in a sample holder that maintains wires or wire bundles at 15 degrees from vertical with ignition at the bottom.

Certainly, some items that cannot meet the fire-performance standards are necessary and commonly used in space. Examples are paper, cotton clothing and towels, minor plastic parts, and data films. Some necessary “off-the-shelf” appliances with components that cannot be verified for fire resistance have no practical substitutes. These articles are precisely inventoried for each mission. Techniques to reduce the fire risk of these materials include limitation of quantity and spacing, elimination of fire-propagation paths between articles, and storage in nonflammable containers or under nonflammable covers.

The upward-flammability test offers advantages for the routine screening of materials. It is a severe “worst-case” test in terms of ignition energy, means of edge ignition, direction of buoyancy-assisted flame spread, sample thickness, and oxygen concentration. Results are rarely ambiguous; samples clearly pass or fail. Designers assume that the normal-gravity acceptance testing provides a margin of safety over the expected diminished fire spread and flammability of the qualified materials in microgravity. Research in microgravity confirms that this safety factor exists under quiescent, near-air, microgravity environments. On the other hand, materials under conditions of forced air flow, such as induced by a ventilation system or crew movement, show increased flammability and flame-spread rates in microgravity. In general, microgravity flames intensify with increased air velocity, but they tend to extinction with time as the flow is cut off.

Several forced-air combustion-tunnel facilities are now available for material-flammability testing in microgravity with imposed atmospheric flows, such as the flight projects discussed in the section on concurrent-flow effects on combustion over solid surfaces. Among these, the DARTFire project incorporates imposed flow, atmospheric control, and radiant heat flux as variables in flammability measurements. Results on the combustion of thick PMMA sheets confirm the strong influence of velocity on flame spread (note fig. 12), although the tests were conducted, for fundamental understanding, at oxygen concentrations considerably higher (35 to 70 percent) than those in current human-crew spacecraft atmospheres.

The Lateral Ignition and Flame Spread Test (LIFT, ASTM E-1321) is a standard terrestrial method to provide key information about the ignition and flame-spread characteristics of materials. LIFT differs from the NASA test methods in that it imposes an external radiant flux on a sample until that sample produces fuel vapors in sufficient quantity to sustain ignition. The LIFT apparatus, however, relies on gravity for the transport of heat and mass, and consequently cannot be used in microgravity. A flammability-test apparatus, Flammability, Ignition, and Spread Tests (FIST), is now in development as a test bed to represent the ambient conditions in space-based environments. FIST tests will provide information about the ignition delay and the flame spread rate of sheet materials as a function of an externally applied radiant flux, oxidizer velocity, and oxygen concentration.

Smoke Detection

Automated early warning of fire events in current spacecraft is achieved through smoke detectors. The Shuttle has nine detector units that sense smoke as a “fire signature” through ionization-current interruption. The U.S., European, Japanese, and Italian operational segments of the ISS will have one or more detector units in each module that sense smoke through photoelectric light-beam obscuration and scattering (fig. 18). The photoelectric detector has recognized advantages over the Shuttle ionization type in its much lower power requirement, slightly lower mass, and lack of moving parts. The Russian operational segment will have fire-response systems that differ from those of the other segments. The Russian modules were designed independently and in some cases prior to those of the balance of the ISS. For example, the Functional Cargo Block (*Zarya*), placed in orbit November 1998, has ten ionization smoke detectors, which are similar in principle to those on the Shuttle. The Service Module, the primary Russian element to be launched in late 1999, will have photoelectric detectors (*Mir* designs), which are closer in design to the types found on the other ISS segments.

The results of the completed phase of the Shuttle Solid Surface Combustion Experiment (SSCE) on thin-paper flames now provide new insights on low-gravity flammability and “fire signatures” for detection. Experiment images show that the flames are nearly undetectable under quiescent, “near-air” conditions, but they become brighter and yellow at higher oxygen concentrations and total pressures. The SSCE setup did not make it possible to compare microgravity fire properties to corresponding normal-gravity behavior. Independent low-gravity airplane tests conducted by the European Space Agency (ESA) show that flames over paper and thin plastic sheets propagate poorly in quiescent low-gravity air atmospheres, and the resulting flames are nearly invisible with little smoke. With forced air flows of the order of 10 cm/s, or with increased atmospheric-oxygen concentrations, the flames are bright and yellow, and they propagate readily.

A practical investigation of microgravity smoke detection was one of the objectives of the Comparative Smoke Diagnostics (CSD) project, conducted on the Shuttle mission STS-75, in 1996. The CSD experiment examined the particulate emissions from typical, well-established pyrolysis or fire events in microgravity. The sources include a burning candle and four overheated materials, namely, paper (flaming in some tests), silicone rubber, polytetrafluoroethylene-insulated wires, and polyimide-insulated wires. In the near field (*i.e.*, within the same chamber as the smoke generators), smoke particulates are collected on thermophoretic grids for later analysis, and total smoke density is measured by laser-light extinction. In the far field (*i.e.*, in a separate chamber connected by a pumped hose line), smoke-detector response is determined by the responses of a Shuttle detector and a prototype ISS detector in parallel.

The visible smoke appearance and smoke-particle size distribution in the microgravity tests vary considerably from those observed in normal gravity. This suggests that the relative response of the spacecraft smoke detectors may differ considerably between the two environments. Table I is a selected summary of response time to reach an arbitrary fraction of full scale for each detector in space. It shows that, despite changes in the nature of the smoke signatures in microgravity, both detectors show adequate, if not entirely optimal, response to most of the fire events. (The ISS detector is set at a higher sensitivity for the test than will be used in service, however, because it is a preliminary prototype.)

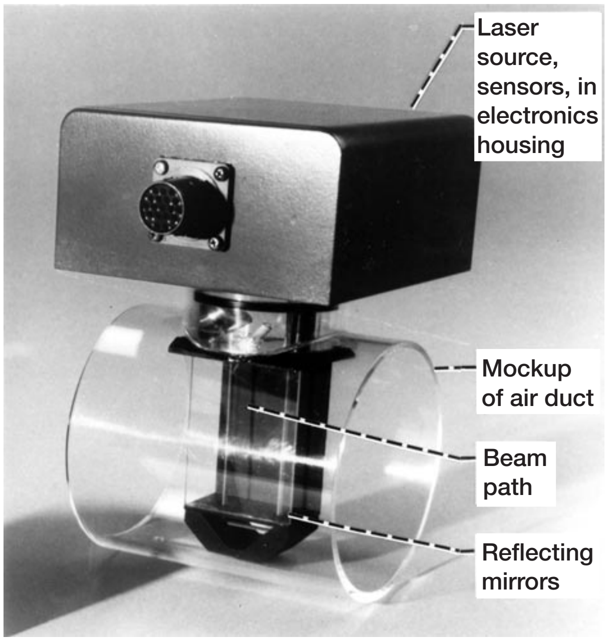

Figure 18.—Model of prototype photoelectric smoke detector for the U.S. and other operational segments on the International Space Station.

TABLE I.—SELECTED RESPONSES OF SHUTTLE AND ISS SMOKE DETECTORS IN MICROGRAVITY, FROM THE COMPARATIVE SOOT DIAGNOSTICS EXPERIMENT

Fuel	Condition	Time to respond at arbitrary set point, sec	
		Shuttle detector	Space Station detector
Candle	Flaming	40	56
Paper	Flaming	54	20
Silicone rubber	Smoking	40	20
PTFE wire	Pyrolyzing	39	30
Polyimide wire	Pyrolyzing	25	14

Extinguishment

The prescribed response to a fire event detected by crew senses or a smoke detector is through steps of isolation, local power shutoff, and air-flow cessation. These actions have been adequate to combat all U.S. fire situations to date. Nevertheless, all current spacecraft are also equipped with fire extinguishers.

The Shuttle has portable fire extinguishers charged with Halon 1301 (bromotrifluoromethane). The manufacture of this agent, a stratospheric ozone-layer depleter, is now prohibited by international protocol, but existing suppression systems may be retained. The Shuttle fire extinguishers are supplemented by a fixed, remotely operated system also charged with Halon 1301, for use during critical periods, such as reentry, when the mobility of the crew is limited. The nonRussian segments of the ISS will have portable fire extinguishers charged with carbon dioxide. No centralized, fixed system is planned. The Russian segments of the ISS will have water-foam extinguishers, equipment already in service in other Russian spacecraft.

The ISS extinguishers are sized to release sufficient carbon dioxide to reduce the local ambient oxygen (in a rack, for example) to half its original concentration within 60 sec. The ISS has the option of abandoning a module, closing its hatches, and venting the module, as a means to control a difficult or inaccessible fire. Proposed venting capability is the attainment of a total pressure of 30 kPa or less within 10 min.

The determination of the completion of fire extinguishment in spacecraft is by no means straightforward. Since burned material remains hot in the nonconvective environment, embers may reignite if prematurely exposed to fresh air. Both the SSCE space-flight and ESA airplane tests demonstrated that, in low gravity, paper fuels are not completely consumed as flame passes, hence reignition after apparent suppression is a possibility. SSCE tests with thick PMMA fuels also show that the flame-propagation rate under quiescent conditions decreases with time, and self-extinguishment is apparently approached; but the fire may persist for a long period of time.

Considerable cleanup will be required after all fire events, minor or major. Atmospheric revitalization to remove even trace quantities of fire and extinguishment contamination may tax the environmental controls and require the use of portable crew-breathing equipment for periods of time. On a longer time scale, the subtle toxic and corrosive aftereffects of the fire on equipment, systems, and payloads must be recognized and appropriately controlled.

Research information applicable to the suppression of fires in microgravity, to predict the effectiveness and dispersion of practical agents, is scarce. One set of findings of promise is the interpretation of the results of microgravity studies on atmospheric-diluent effects on thin-sheet fuel flammability. These studies are discussed in an earlier section of this document on combustion over solid surfaces.

Additional pertinent information, in this case on fire extinguishment through depressurization, is also discussed in the previous section. These tests on the flammability of a PMMA cylinder ignited along the axis with atmospheric crossflow of nominally 10 cm/s determine the low-pressure limit for flame extinction. The experimental extinction boundary is a unique function of the fuel temperature, regardless of gravity level. As fuel temperature increases, the necessary extinction pressure decreases (that is, extinction becomes more difficult). The investigators note that, for practical venting in operating spacecraft, rapid venting to a specified final pressure would limit the potential fuel heating and aid extinguishment. On the other hand, an excessive rate of depressurization may cause substantial atmospheric flows to intensify the fire.

Earlier ESA airplane tests also investigated the behavior of mixed-phase foams for fire suppression (analogous to the Russian system on the ISS). Although the foam penetration is different in low gravity compared to normal gravity, the foam does stick to surfaces, and it successfully suppresses fires by oxygen exclusion.

Extraterrestrial Combustion and Processing

The objective of planned extraterrestrial missions is to establish long-duration, human-occupied bases on the Moon and Mars. These bases will support diverse operations, such as exploration, planetary science, and propellant manufacture. A typical mission to Mars requires at least 180 days in transit, and the crew will remain at the Martian base for over 500 days before returning to Earth. The return vehicle will use methane or carbon monoxide and oxygen propellants, which are manufactured on the planetary surface (*in situ*). For the planned extraterrestrial missions, research on performance and fire safety in extraterrestrial processing, such as oxidation of habitat/transit solid waste, *in-situ* propellant production (ISPP), and combustion processes, are critical concerns.

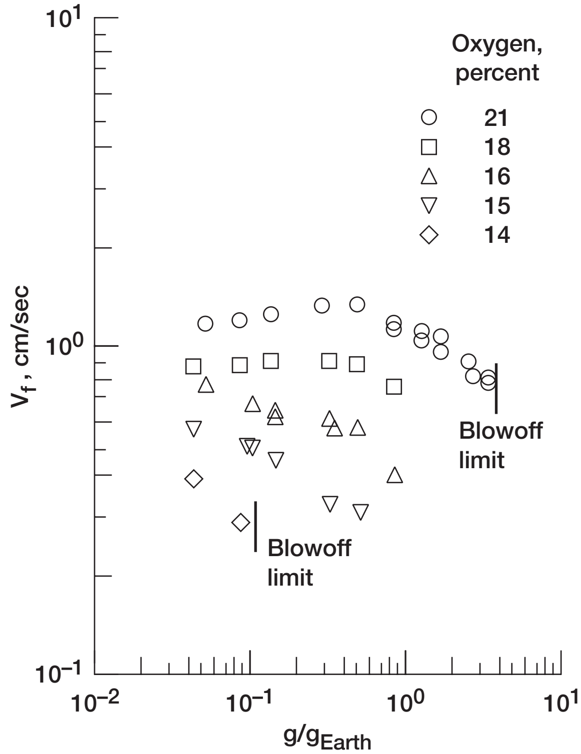

Figure 19.—Experimental flame-spread velocities for downward burning, thin cellulosic sheets over a range of oxygen concentrations (in nitrogen) and gravitational accelerations (g_{Earth} = 9.8 m/s^2). Blowoff limits are indicated from theoretical predictions.

There are various technologies available for propellant production and life support on Mars. The most common technique studied for ISPP provides a very cost-effective supply of propellants by converting carbon dioxide, which is ~95.3 percent of the Martian atmosphere, to usable propellants. The two most developed concepts for utilizing Martian carbon dioxide are the Sabatier/Electrolysis (S/E) process and the Zirconia Solid-State Electrolyte process. The S/E process converts carbon dioxide to methane and water by reacting CO_2 with hydrogen ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$). In a separate step, the water that is produced can be electrolyzed to release oxygen ($2H_2O \rightarrow 2H_2 + O_2$). The sum of these reactions converts carbon dioxide and hydrogen into methane and oxygen ($CO_2 + 2H_2 \rightarrow CH_4 + O_2$). Oxygen and methane are subsequently liquefied and stored for future use as propellants. The Zirconia process acquires and compresses the Martian atmosphere and converts it in a reactor to oxygen and carbon monoxide to be liquefied and stored for future use. The direct conversion of carbon dioxide and hydrogen into methane and oxygen within a Zirconia cell is also possible, and additional oxygen can also be generated by decomposition of carbon dioxide. Earlier work at NASA Glenn on liquid carbon monoxide/liquid oxygen propellant combinations has successfully demonstrated steady combustion in a sub-scale rocket engine, with small amounts of hydrogen present initially to aid ignition.

Recent studies have provided important information pertinent to fire safety in the extraterrestrial surface operations. Downward, opposed-flow flame-spread rates over thin-paper fuels as a function of gravitational accelerations (fig. 19) show that the maximum flame-spread rate occurs near the Martian-surface gravity level (about 0.38 of normal gravity). The flame-spread rate is lower near the lunar gravity level (about 0.17 of normal gravity), but it still exceeds the rate at normal gravity. A flammability map of oxygen mole fraction as a function of gravity level is shown in figure 20. Also shown is the U-shaped flammability boundary predicted by a modeling study (dotted line). It is seen that for downward burning, there is a minimum in the flammability boundary occurring at gravity near the Lunar- and Martian-surface gravity levels. The most important finding is that flame spread and flammability in gravity levels of a fraction of normal gravity (here referred to as partial gravity) cannot be predicted simply through interpolation between measurements obtained in normal gravity and in microgravity.

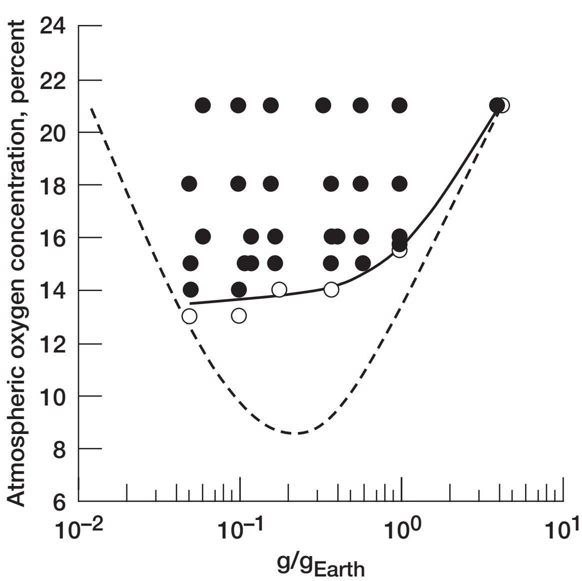

Figure 20.—Experimental flammability map for downward burning, thin cellulosic sheets over a range of gravitational accelerations. Solid points are flammable conditions for stated levels of oxygen concentration; open points are non-flammable conditions. Dotted line is predicted flammability boundary.

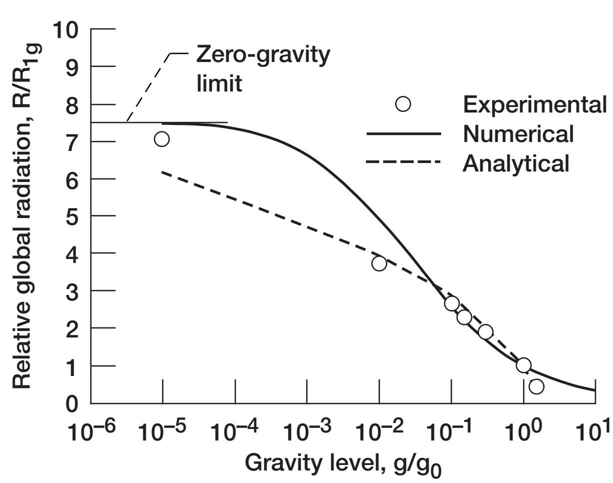

Figure 21.—Experimental and calculated ratios of radiation heat losses at stated gravity levels (referenced to radiation at $g_0 = 9.8$ m/s^2 for non-premixed gas-jet flames.

Another research study covering a range of gravitation levels is that of laminar gas-jet diffusion flames in quiescent air. Radiative heat transfer has been found to be significantly related to the level of gravitational acceleration (fig. 21). Radiative losses in the Lunar/Martian gravity are almost twice those in normal gravity and approximately seven times those in microgravity. This can be explained as the competition among such factors as longer residence times and accumulated combustion products in microgravity, leading to higher radiative losses and lower overall temperatures, and the presence of different levels of convective effects in partial and normal gravity, removing the hot, radiating gases from the flames. It is also found that the buoyancy-dominated flame-flicker in Lunar/Martian gravity is only a fraction that in normal gravity. The measured flame radiation and flame-flicker are "fire signatures" useful for radiation detectors.

Aircraft Fire Safety

In 1997, NASA, in cooperation with the FAA and other air-transport organizations, announced the initiation of a seven-year aircraft accident-rate-reduction program. One element of the program is accident mitigation, where the goal is to reduce the accident toll in terms of injuries and fatalities (independently of the reduction in accident rates). Fire prevention and response are key factors in the mitigation element.

There is a well-recognized synergy among microgravity combustion science, spacecraft fire safety, and aircraft fire safety. First, spacecraft fire protection is based, to a large extent, on established aircraft standards and practices, since the transportation modes share features of confined space, hostile external environments, and limited space and mass allowances for fire-protection resources. In turn, aircraft and terrestrial fire safety can benefit from innovations and improvements from controlled experiments and idealized analyses in microgravity that permit a simplified representation of the combustion field.

An immediate concern of aircraft fire safety is that of the hazards of the onboard aviation fuel. Two fire scenarios are possible: in-flight fuel-tank fires and post-crash spilled-fuel fires. These are very rare fire events, but they are extremely feared and well publicized when they do occur. Research contemplated or in progress to address the first scenario includes a variety of basic studies of fuel flammability properties, such as minimum ignition energy, flammability limits, and flash point, as functions of fuel properties and aircraft tank designs and dynamic conditions. Research proposed to address the second scenario includes basic studies of so-called "fire-safe" fuels, achieved through modification of fuels as supplied, modification of fuels upon demand, or automatically actuated suppression at impact.

Other opportunities for spacecraft fire-safety research applications to aircraft fire safety are seen in such areas as the improvement of rate-of-heat-release and flame-resistance testing of sheet and insulation materials, in sensitivity and false-alarm tradeoffs of photoelectric smoke detectors (proposed for aircraft cargo compartments), and in the evaluation of gaseous and aerosol replacements for Halon fire suppressants.

Terrestrial Applications and "Spin-offs"

While practical benefits on Earth have always been a strong selling points for a variety of space experiments, applications from combustion studies have been rare. A major step that promises to expand the opportunities for "spin-offs" from microgravity-combustion research has been the establishment of the Center for the Commercial Application of Combustion in Space (CCACS) in 1996. The Center is operated by the Colorado School of Mines and supported by NASA and academic, research, and industrial partners.

There are currently seven projects underway at the CCACS, aimed at commercial products in combustion-synthesized materials, sensors, space-furnace facilities, and catalytic combustors. A project of strong interest to the microgravity-combustion community is that of water-mist evaluation for space and terrestrial fire suppression. An experiment package, called Water Mist, is being developed for inclusion in the CM-2 facility (see appendix A) on Shuttle mission STS-107, scheduled for late 2000. The objective of the experiment is the microgravity stabilization of the generated mist, which permits the study of the effects of droplet size and concentration on the extinguishment of model propane-air flames.

A study in progress, while strictly computational, holds great promise for practical application to improvements in booster and upper-stage space propulsion. The analysis calculates the physical characteristics and the time-related instabilities at the liquid/gas interface of a liquid-propellant combustion system. The study defines regions of stability, cellular (classical) instability, and pulsating (a new concept) instability. The innovations in the model are the incorporation of mass-burning rate dependence on the local pressure and temperature fields and the inclusion of surface tension, viscosity, and gravity vectors as variables.

Program Status: General Measurements and Diagnostics

The extent of scientific returns from microgravity-combustion experiments is directly related to quantitative measurement capabilities of meaningful variables. Instrumentation and measurement techniques available for terrestrial applications must be adaptable to endure the unique and severe operational constraints of microgravity experimentation. Improved understanding of chemical kinetic mechanisms in combustion environments requires accurate and nonperturbing determinations of flow, temperature and species concentration fields. In concert with other aspects of microgravity experimentation, the development of diagnostic instrumentation proceeds from basic requirements of the normal-gravity laboratory through those of ground-based facilities to those of spacecraft accommodations.

The program area of measurements and diagnostics covers the following topics:

- Velocity
- Refractive index
- Temperature
- Chemical species
- Soot volume fraction and size

Velocity

Measurement of velocity fields in combusting flows provides information on such quantities as residence time, mixing rates, and the turbulent structure of the flow field. Two complementary techniques for velocity-field determination under current development at NASA Glenn are those of particle image velocimetry (PIV) and laser Doppler velocimetry (LDV).

PIV provides instantaneous, full-field velocity measurements. Small seed particles are introduced into the flow stream, then illuminated with a two-dimensional light sheet several centimeters wide and a few hundred micrometers thick. A series of images obtained by recording the light scattered from these particles is then analyzed to determine the time-dependent particle trajectories. While this type of planar illumination generally provides information on the two components of velocity lying in the plane of the light sheet, the use of suitably displaced, calibrated cameras can offer three-dimensional measurements. Computer-based techniques for extracting velocity field information from particle-image sequences have developed along two general trends. Sub-image correlation analyses, usually employing densely-seeded flows, demonstrate improved accuracy in determining the mean velocity over the subregion, whereas direct trajectory analyses yield more accurate spatial resolution. Recently, a hybrid approach has been developed, using the results of the correlation analyses to initiate a structured trajectory search. The inclusion of fuzzy inference techniques results in an efficient algorithm providing both enhanced accuracy and spatial resolution. Current efforts involve the design of systems employing relatively compact, low-power light sources to provide measurement capabilities not only for ground-based facilities, but for eventual use on the International Space Station laboratories.

While PIV affords instantaneous, full-field capabilities, LDV provides the ability to probe the finer spatial scales (order of 10 mm) and rapid temporal changes associated with turbulent flows. Similar to PIV, small seed particles entrained in the flow serve as scattering centers, but for LDV the Doppler shift of the scattered radiation is utilized to determine the velocity. Because individual particle velocities can be acquired and processed in intervals as small as 10 ms, line or area scans on time scales that are small in comparison to the temporal evolution of many flow fields are possible.

Significant efforts have been directed at realizing optical systems of suitable compactness and power efficiency. In this regard, solid-state coherent laser sources and avalanche photodiode detectors are utilized to construct assemblies that are only a fraction of the size of their conventional counterparts and consume only a few watts of electrical power. Systems to date are configured in dual beam, or heterodyne, configurations, thereby suppressing the high-frequency optical carrier so that scattered signals on the order of 10^5 to 10^6 Hz/m/sec are detected and processed. Multicomponent systems have been demonstrated, and the implementation of directionally resolved capabilities is also in progress. A novel signal processor has also been constructed, taking advantage of recent advances in high-speed digital signal-processing capabilities. The entire system resides on two 16-bit personal-computer cards, and it is capable of acquiring, processing, and archiving 10^5 velocity realizations/sec. A series of graphical user interfaces provides real-time evaluation of triggering levels, processing bandwidths, signal-to-noise ratios, and velocity as functions of time. Direct memory access also permits on-line data storage for subsequent post-processing, a feature of significant utility for use in drop towers and reduced-gravity aircraft.

Refractive Index

The determination of refractive-index fields has long been used for both qualitative visualization and quantitative measurement of temperature and density in combustion reactions, or for species concentrations in nonreacting flows. Interferometric methods are often used for this purpose, but they can be problematic in microgravity-combustion science applications, since their phase-sensitive nature requires strict thermal and mechanical stability. In contrast, deflectometric methods (*i.e.,* methods that measure the bending of light due to first and second order refractive-index gradients) can be implemented with reduced complexity, tolerance to dimensional instability, and adaptation to large fields of view.

A system of this type has been developed at the NASA Glenn Research Center, employing continuously-graded color filters in a Schlieren configuration. A collimated noncoherent, broad-band light source is used to illuminate the test section. After passing through the combustion field of interest, the decollimated output is focused onto a filter possessing a spatially-dependent color-transmission function. Gradients in the refractive index distribution arising from nonuniformities in temperature or species concentration deflect the incident rays of light, altering the position in which they are intercepted by the color filter. The distribution of hues manifest in the qualitative appearance of the resulting images affords great detail, owing to the ability of the eye to resolve subtle differences in color. In addition, the continuous nature of the “rainbow” filter avoids truncation and diffraction effects associated with conventional knife-edges or stops, thereby improving the spatial resolution of the optical system. A simple image-digitizing and processing system has been developed to quantify the color attributes of the observed images, and, hence, the ray deflections that produced them. Once quantified, these ray deflections can, in turn, be related to the aforementioned physical quantities of interest. This approach is demonstrated to provide a measurement sensitivity comparable to that achieved with interferometric methods in determining temperature and species concentrations in a variety of applications.

Refinements of interferometric flame-visualization methods for low-gravity combustion studies are worth noting. A lateral-shearing interferometer is now in use in drop-tower tests. An additional consideration for combustion experiments is the very high refractive-index gradient, due to the rapid change of temperature at flame front, which makes data processing via conventional techniques difficult. A modified Fourier transform method for fringe processing is developed that relaxes some of the assumptions of the conventional Fourier method, making it suitable for processing data with large refractive-index gradients.

Temperature

Nonintrusive optical methods of temperature measurement fall into three distinct classes: emission measurements, implicit methods, and spectral methods. Advanced emission pyrometry employs thin (15 µm) silicon-carbide fibers introduced into the flame front. These fibers have well-characterized emissivity and rapid thermal response, with minimal disturbance of the phenomena under study. An array of fibers can be constructed to yield two-dimensional temperature data; the fibers are imaged using conventional coupled-charge cameras or infrared arrays, depending on the temperature range or spectral interference that may be present. For the Laminar Soot Processes

Shuttle experiment, a two-wave-length ratio measurement in the visible spectrum is used for soot temperatures, based on verified assumptions of the spectral dependence of the emissivity from soot.

Implicit measurements of temperature are based on gas density or refractive index. Gas density uses elastic Rayleigh scattering. Under isobaric conditions, the proportionality relationship of the scattered intensity to the local gas-phase temperature can be exploited to infer temperature. Refractive-index measurements are currently made by the Rainbow Schlieren (continuous-color filtering) technique described in a previous section. The line-of-sight nature of this technique relegates quantitative application to simpler systems possessing symmetric geometry.

Spectral methods encompass a number of approaches. One example is a tunable, pulsed titanium: sapphire laser that determines temperature via laser-induced fluorescence (LIF). LIF is utilized in this context by scanning the laser over several transitions originating from different rotational levels having temperature-dependent populations. Another example is the rapid scanning of a near-IR solid-state laser diode over a pair of absorption lines exhibiting well-characterized temperature dependence. Liquid-phase thermometry also uses fluorescence of a dopant introduced into the liquid. Ultraviolet light from a small nitrogen laser is used to excite the ground-state molecules of the dopant causing fluorescence. Under controlled conditions, one can calibrate the ratio of fluorescence intensities between the ground and excited states to ascertain the dependence on temperature.

Conventional methods for the determination of temperatures, such as thermocouples and broad-band point radiometers, are also of great value for combustion diagnostics. A rapid-temporal-response (~200 ms) thermocouple technique has been developed for the measurement of spatially resolved gas-phase temperatures. This method is implemented by bonding fine-gauge, 25 to 75-µm, Type R junctions to a probe apparatus originally devised for thermophoretic soot sampling. The fine-gauge junctions are supported in 1.5-mm-diameter ceramic tubing to achieve structural rigidity, low mass, and minimal thermal conductivity. The tubing has a pair of internal passages, serving to support and insulate the thermocouple leads. By freely suspending the junction 10 mm beyond the free end of the tube, the operator can position the thermocouple in different locations of the turbulent diffusion flames without penetrating the flame front with the ceramic support. Initial analysis indicates that the temperature measurements are repeatable and consistent with model predictions in a turbulent diffusion flame. In tests on turbulent acetylene flames, some temporal variation in response was observed in the first several insertions, attributed to soot deposition on the thermocouple junction. For subsequent insertions, corrections for the radiation loss due to soot resulted in temperature determinations consistent within 5 °C (fig. 22).

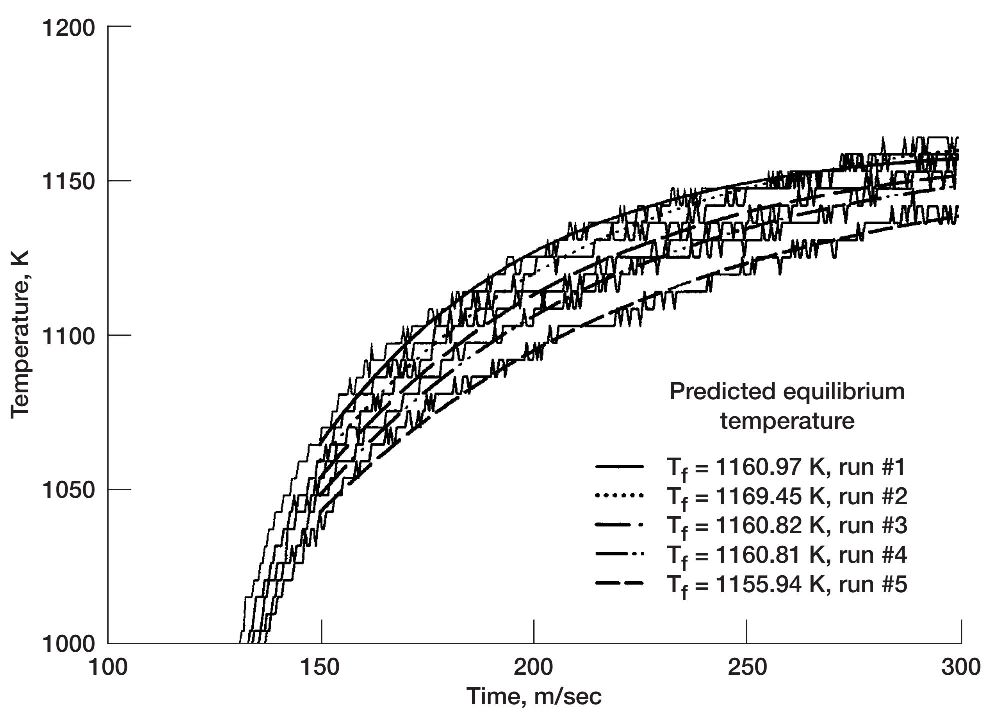

Figure 22.—Variation and stabilization of thermocouple response with multiple insertions into acetylene-oxygen-nitrogen gas-jet flame. Heavy lines are curve fits.

Conventional methods for determining solid-phase surface temperatures are also improving in accuracy and precision. As a solid burns, it undergoes pyrolysis, char formation, and volatile production. Each process influences the fuel surface emissivity, which, for a given fuel, is a function of temperature, wave length, and viewing angle. Infrared surface measurements are usually made using a constant value of emissivity measured at a single temperature and wave length, an approach that may lead to errors of 10 to 15 percent in the measured surface temperature. One method measures the temperature and wave-length dependence of the emissivity of solid fuels, such as paper. This technique involves heating the fuel in a vacuum with an electrical hot plate and imaging its surface with an infrared camera operating in the 1.8- to 5-μm region. Independent temperature measurements are made using surface thermocouples. Half of the plate has a high emissivity surface, while the other half has a low emissivity. Comparison of the radiation from the fuel as it is heated by these two different surfaces gives an estimate of the transmittance of the fuel, thus allowing the determination of the fuel emissivity, transmissivity, and reflectivity. At temperatures above 600 K, where the fuel undergoes a structural change corresponding to the pyrolysis process, the results show a sharp drop in the emissivity from roughly 1.0 to 0.75 and an increase in the transmissivity.

For liquid-pool fires, improved surface-temperature measurements use infrared imaging. In one example, an infrared camera with a spectral range of 8 to 12 μm viewed the liquid-surface temperature field ahead of the flame over the liquid fuel to provide a quantitative view of the preheating phenomena during flame spread over a range of air-flow velocities, directions, and gravity levels. The temperature field is also used as a qualitative indicator of liquid flow patterns. The infrared images show that the liquid-surface temperature has a large region of asymmetrical preheated fluid in the rectangular test channel. The images also show significant side-flow processes in both normal gravity and microgravity that cannot be revealed in line-of-sight, refractive-index methods, or in thermocouple measurements. Although a flat flame front is often taken to indicate that flame spread over condensed-phase fuels is two-dimensional, the infrared images show that this is not necessarily the case.

Chemical Species

A detailed understanding of the combustion process requires a knowledge of the chemical kinetics, energetics, and equilibria occurring in this complex reactive system. This knowledge must ultimately be grounded in accurate, spatially and temporally precise measurements of the species present, including reactants, products, and reactive intermediates. Ideally, the internal energy states of these species should be measured quantitatively as well, as the molecular internal energy states underlie the energetics and radiative environment that characterize combustion. This goal, challenging enough in a normal-gravity research laboratory, becomes ever more so with the constraints of the microgravity environment.

The most detailed results in combustion diagnostics come from spectroscopic measurements. The NASA Glenn Research Center has a long-standing program in development of diode-laser-based absorption spectroscopy for quantitative, spatially and temporally resolved detection of important combustion species. The original system that was developed for drop tower use is configured for water and methane. A recent NASA contract with a commercial company extends the technique to oxygen through an improved optical layout. The final hardware delivered to NASA under this contract is now designed for detection of carbon dioxide, as well as for oxygen and other species. Eventually, improvements will add the detection of the OH radical in the near infrared to this capability, along with reduction in the size and power draw of the hardware.

NASA research is also improving the technique of video imaging. Spectral filters in the visible, ultraviolet, and infrared allow line-of-sight averaged images of excited states of radicals such as OH and CH, and stable species such as H_2O and CO_2. Some recent developments involve electronically-tunable filters, which can be rapidly switched to permit measurements of several species closely spaced in time. The imaging techniques probe excited states, showing reactive zones for the radicals and the radiative environment due to the stable species. The absorption measurements noted above probe ground electronic states and vibrational states of the molecules. Combining the two measurements of ground and excited states gives more information on flame energetics than is possible by either technique independently.

The NASA Glenn diagnostics program uses a variety of spectrometers, including a Fourier Transform Infrared (FTIR) instrument suitable for simultaneous transmission and emission studies of flame species. The combustion laboratories have an assortment of small spectrometers, including “spectrometer on a chip” devices in the visible, near UV, and mid-IR. These small devices are generally rugged and are compatible with both drop-tower and space-flight design requirements.

Gas chromatography has long been a useful laboratory tool for detailed species measurements. The combustion-module (CM-1) diagnostics package (appendix A) flown on the STS-94 mission in 1997, carried a modified gas chromatograph. In current development are fiber-optic chemical sensors for a variety of combustion species. The fiber sensors are very small and lightweight, they use little to no power, and they are vibration-, g-load-, and electro-magnetic-interference-tolerant. The most mature sensor to date is an oxygen sensor based on quenching of the fluorescence from a dye molecule; this process is quantitative and selective for oxygen. Sensors for other species, including hydrocarbons, are under development in the laboratory. Many of these techniques are expected to be valuable as well for multi-sensor fire-detection systems for early warning of the onset of a fire in spacecraft.

Interferometric techniques have also been utilized for the determination of refractive-index fields, most notably a common-path configuration employing local reference-beam generation. This arrangement reduces the requirement for mechanical stability, since both object and reference beams effectively trace identical paths. A system of this type has been used to determine quantitative temperature fields in methanol flames, using conventional gray-scale techniques to perform image-plane phase deconvolution.

Soot

Soot Volume Fraction

For decades, soot volume fractions in combustion applications were determined through optical-extinction methods. Current techniques benefit from the use of coherent, monochromatic sources (lasers). These sources offer advantages of well defined spectral characteristics, critical to the resolution of the spectrally dependent properties of carbonaceous soot, and precise optical-beam manipulation. Two methods developed for and demonstrated in microgravity combustion-science applications at NASA Glenn are those of extinction tomography and laser-induced incandescence (LII).

The application of the principles of tomography to two-dimensional optical-extinction measurements can replace conventional, time-consuming sequential point imaging that is unsuitable for short-term microgravity tests. In a single scan, extinction tomography provides a full-field absorbance at video framing rates. For example, past studies on laminar acetylene-nitrogen jet-diffusion flames in microgravity show that the soot volume fractions are higher and extend further spatially, compared to those in normal gravity. Soot particles escape from the tip of the flame in microgravity, but they are confined to the nonluminous flame in normal gravity.

LII uses an intense source energy to heat soot to temperatures far above the background. For submicrosecond laser pulses, the energy-addition rate greatly exceeds the loss rate from thermal conduction, vaporization, or radiation; and it rapidly heats the soot particles. In accordance with the Planck radiation law, the particle thermal emission at elevated temperatures increases and shifts to the blue compared to nonheated soot and flame gases. The resultant blue-shifted emission from the laser-heated soot is a function of soot volume fraction, and measurements show that the LII signal is linearly proportional to the soot volume fraction. Absolute calibration of the technique is made by *in-situ* comparison of the LII signal to a system with a known soot volume fraction. Point measurements use a photomultiplier tube with spectral and temporal discrimination against natural flame luminosity. One- and two-dimensional measurements use a gated intensified-array camera.

Figure 23 shows both natural flame and corresponding (simultaneous) LII images of laminar atmospheric-pressure diffusion flames of a 50 percent acetylene in oxygen-nitrogen fuel mixture in both normal and microgravity. The volumetric fuel flow rate through the 1.1-mm I.D. nozzle is 1.2 cm^3/s. Each LII image is obtained with a single laser shot, and the image in microgravity image is obtained after ~1 sec of flame development. In contrast to the closed-tipped normal-gravity flame, the microgravity flame is open-tipped, emitting soot. In agreement with the full-field extinction measurement, soot volume-fraction levels are larger in microgravity than in normal gravity. The soot volume fraction in microgravity reflects a competition between flame temperature and residence time. Lower flame temperatures result in decreased fuel pyrolysis rates in gas-jet diffusion flames. Absence of buoyancy-induced convection in microgravity, however, enhances the residence time for fuel pyrolysis and soot inception/growth reactions.

Since LII is not a line-of-sight technique, it possesses geometric versatility, enabling studies involving heterogeneous combustion of liquids or solids. LII also has high temporal resolution because signals are induced by a single laser pulse. Even in steady-state gas-jet diffusion flames, LII provides a measure of the soot volume fraction, independent of unknown contributions from scattering by soot aggregates and absorption by polycyclic aromatic hydrocarbons.

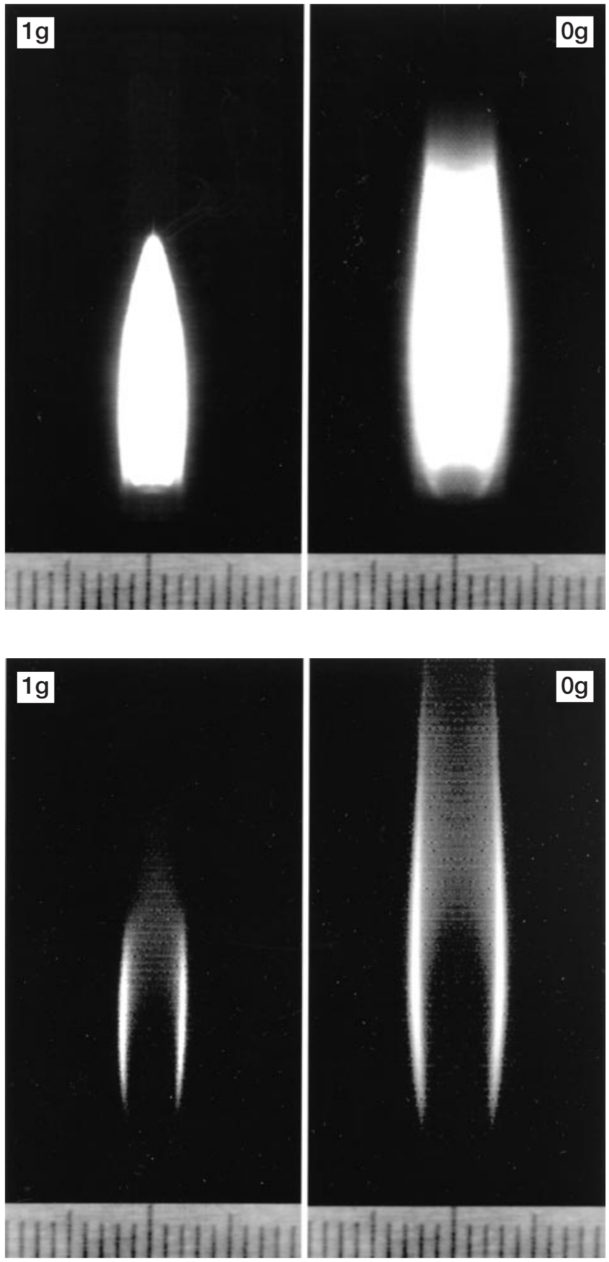

Figure 23.—Natural images and corresponding laser-intensified images of acetylene jet flames in normal gravity, 1g and microgravity, 0g.

Soot Size

Detailed interpretation of laser-induced incandescence and other optical measurements of soot depends upon both the number and size of primary particles composing soot aggregates. Each of these properties also affects the radiation from flames, often a major energy-loss mechanism in microgravity. Such information also aids in the understanding of soot nucleation and aggregation processes.

To measure these physical features of soot accurately, one must recover samples of soot. The technique of thermophoretic sampling utilizes the temperature difference between soot at flame temperatures and a transmission electron microscopy (TEM) grid, to drive soot to adhere to the grid. In this technique, a sampling grid supported by a thin probe is rapidly inserted into a flame via air-actuated pneumatic cylinders, where it remains resident for 10 to 500 ms. TEM analysis of the recovered grids is used to visualize the soot aggregates and primary particles and quantify the primary-particle size, aggregate size, and fractal character. In the absence of buoyancy-induced convection to remove the soot from the flame environment, soot residence times are greatly extended, allowing for continued growth and aggregation processes. For the simplified flame-transport processes in microgravity, interpretation of TEM data can serve as input to model the kinetics of soot nucleation and growth processes in flames.

Microgravity-Combustion Program Participation

NASA provides financial and facility support to Principal Investigators (P.I.) in the field of microgravity-combustion science. Initial proposals for definition studies and subsequent progress are evaluated by 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 advancement 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, who may be associated with small and large industrial concerns, nonprofit research organizations, and U.S. Government agencies, as well as academic institutions, collaborate with a NASA technical monitor to conduct the necessary research associated with the initial proposals. Preliminary testing in the NASA Glenn (formerly NASA Lewis) ground-based facilities (drop towers and aircraft) is strongly encouraged in the "definition-study" phase. If spaceflight experiments are justified, based on the definition study, the P.I. proposes a sounding rocket, Shuttle, or International Space Station flight experiment in response to a competitive solicitation (described below). If the P.I. wins a project award through this solicitation, the project becomes a flight candidate. Soon thereafter, the P.I. presents the detailed objectives, test requirements, and conceptual designs to an independent peer-review panel, who assess the likelihood of the proposed flight experiment to meet its objectives. If this "Science Concept Review" is successful, NASA assigns a team of engineers and scientists to the multi-year development of space-flight hardware to meet the specifications of the P.I. NASA continues to support the P.I. throughout this development period in assisting further research, providing consultation, and guiding the design and safety reviews prior to spaceflight. The P.I. continues to monitor the experiment during spaceflight, performs the subsequent analyses, and publishes the results (an obligation) in archival journals.

In addition to these spaceflight projects, NASA also supports independent analytical modeling, applied technology, and diagnostics research, as well as microgravity experiments that can be completed in the ground-based test phase in drop towers or in aircraft.

Proposals for either definition (ground-based) study or flight-experiment candidacy are solicited via a NASA Research Announcement (NRA). The first NRA focusing on microgravity-combustion science was issued in late 1989. It resulted in 13 ground-based and six flight-definition awards out of 65 proposals. The most recent microgravity-combustion NRA was released in 1997, and it resulted in 41 ground-based and 8 flight-definition studies. Depending on funding availability, NASA plans to issue an NRA solicitation for microgravity-combustion science about every two years.

More information about the details of the NASA microgravity support programs and the processes of proposal submission, progress reviews, and spaceflight project selection is available on the web at http://www.grc.nasa.gov or by writing to the Microgravity Combustion Science Branch, MS 500-115, NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135.

Concluding Remarks

Advancement in combustion-science knowledge is commonly achieved through inference, since the specific quantities of interest, *e.g.*, various forces, transport rates, and chemical-species concentrations, are rarely measured directly. Parametric experiments in which the initial pressure, oxygen concentration, diluent type, flow rate, material thickness, and geometry are varied seek to improve the level of understanding of controlling mechanisms, chemical kinetics, and fluid dynamics of flame systems. Microgravity offers an environment wherein the combustion process can be isolated and simplified in order to control its phenomena and promote its basic study.

The justification of the growing efforts in microgravity-combustion research is given by two objectives of the NASA strategic plan paraphrased as (1) the expansion of scientific knowledge, and (2) the applications to technologies and assets that promise to enhance the quality of life on earth.

In scientific knowledge, advantage can be made of the predominant feature of microgravity combustion, which is the near-elimination of buoyancy-induced flows. A new range of velocities between those associated with diffusive and buoyant convective transport (of the order of 1 to 30 cm/sec) is made available for study by imposing a known flow in microgravity or by subjecting the system to partial gravity. Several interacting transport processes have been identified repeatedly and form common themes to be accounted for in microgravity-flame models and simulations, for example, diffusional transport of oxygen and products over large spatial scales, radiative heat transfer even in small-sized flames, and hot-gas expansion. The microgravity environment now offers the means for a straightforward comparison between theory and experiment.

In technology applications, microgravity-combustion research is approaching its goal of developing methods, databases, and validating tests for enabling increased combustion-system efficiency, reduced pollution, mitigation of fire risks, and other benefits. Terrestrial interest includes areas such as turbulent combustion, soot processes, spray combustion, and flame-based synthesis of high-value materials. Further motivation to perform combustion experiments in space is in the necessity to maintain and improve fire safety aboard human-crewed spacecraft. Many findings from microgravity combustion research are of direct relevance to the NASA material-flammability and toxicological-screening test procedures and to the identification of fire signatures, *i.e.*, heat release, smoke production, flame visibility, and radiation. Finally, the microgravity program is devising and developing a broad range of nonintrusive instruments to meet the restrictions of volume, weight, and power, and the high vibratory and shock loads imposed in all microgravity facilities, from drop towers to the International Space Station.

The progress in microgravity combustion science will be expected to have a major impact on our society.

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The compilers of this review have chosen not to include citations to the literature in the body of the review. Instead, a comprehensive bibliography of the technical literature appropriate to microgravity combustion follows, limited to publications from late 1994 to the time of writing (early 1999). The bibliography is grouped into combustion topics, based on the judged primary subject of each reference. To keep the bibliography reasonably compact, each work is cited only once, with no cross-references. This does cause some problems in organization, particularly for publications on measurements and diagnostics, which could be appropriate to more than one topic. The reader will find it worthwhile to search through more than one topic for citations of interest in these cases.

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APPENDIX A
Facilities

A variety of space-flight and ground-based low-gravity facilities is available to researchers. Each has specific capabilities and characteristics that must be considered by an investigator when selecting the one best suited to a particular type of experiment.

Ground-Based Facilities

Most experimental microgravity combustion studies to date have been conducted in ground-based facilities. The principal venues are the two free-fall drop towers at the NASA Lewis Research Center (now the NASA Glenn Research Center). The smaller facility offers 2.2 sec of microgravity test time for experiment packages with up to 150 kg of hardware mass. A schematic diagram of the 2.2-Sec Drop Tower is shown in figure 24. The drop height is ~24 m with a chamber cross-section of 1.5 by 2.75 m. The experiment package is enclosed in a drag shield, which has a high ratio of mass to frontal area, hence a low drag coefficient. The drag shield/experiment assembly is hoisted to the top of the building and suspended there by single wire. Release of the wire initiates the drop. As the drag shield/experiment assembly falls, the experiment package is free to move within the drag-shield enclosure, and the drag forces are negligible. Residual acceleration is estimated to be of the order of 10^{-5} g. The assembly is decelerated at the bottom by compression of an air bag, limiting the deceleration loads to peak levels ranging from 15 to 25 g. Although the microgravity time is limited to 2.2 sec, the facility offers advantages of rapid turnaround time between experiments and low-cost operations. It is often used for proof-of-concept or preliminary experimentation. The 5.2-Sec Zero Gravity Facility (fig. 25) offers expanded experiment and diagnostic capabilities compared to those available in the 2.2-Sec Drop Tower. The facility is a 6.1-m-diameter steel-walled vacuum chamber, with a 132-m drop distance. Experiment packages with up to 450 kg in total mass are mounted in 1-m-diameter carriers

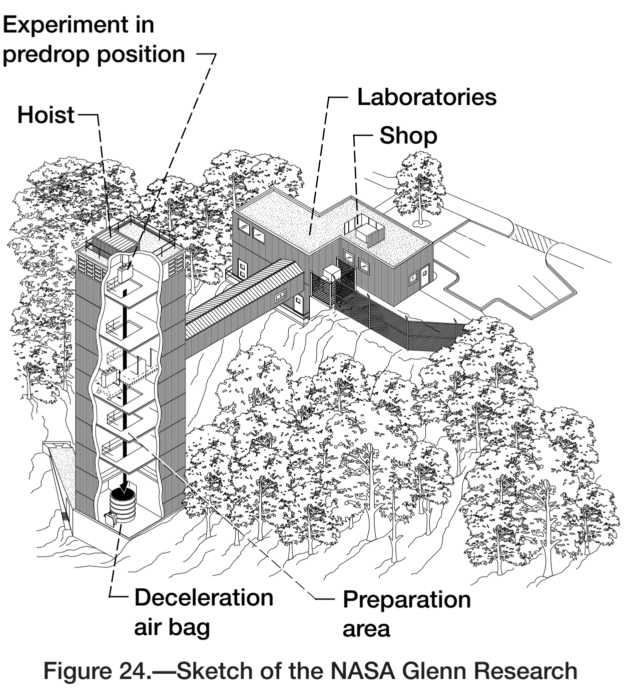

Figure 24.—Sketch of the NASA Glenn Research Center 2.2-Second Drop Tower.

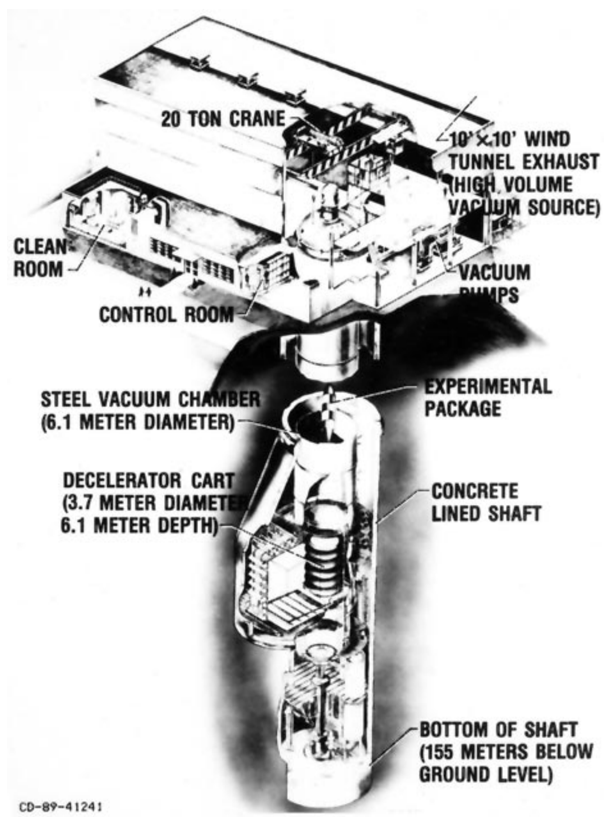

Figure 25.—Sketch of NASA Glenn Research Center 5.2 Second Zero Gravity Facility.

Figure 26.—Photograph of typical experiment vehicle (with combustion-chamber assembly) for use in the NASA Glenn Zero Gravity Facility.

(fig. 26). Prior to each test, the free-fall chamber is evacuated to a final pressure of about 1 Pa (10^{-2} torr) to eliminate air drag and allow residual accelerations as low as 10^{-6} g. The experiment drop is initiated by shearing a bolt in the release mechanism that suspends the carrier assembly. The carrier falls in the vacuum chamber, and it is decelerated at the chamber bottom by impact into a 6.1-m deep container containing small pellets of expanded polystyrene.

Dedicated jet aircraft flying parabolic (Keplerian) trajectories can provide significant increases in low-gravity experiment time compared to drop towers, with a penalty of higher residual-gravity levels. For an experiment firmly mounted to an aircraft bulkhead, accelerations in the range of 10^{-2} g can be obtained for up to 20 sec. During a single daily flight sequence, 40 or more sequential parabolic trajectories are possible. While the aircraft trajectories do not provide true microgravity, they do offer a research venue at low gravity with some advantages over the conditions in drop towers. Aircraft facilities permit operator interactions, allowing researchers to monitor their experiments in real-time and to reconfigure them between trajectories. Aircraft also allow researchers to utilize a wide variety of diagnostic equipment, since delicate equipment is not exposed to the severe shock loadings experienced in drop towers.

The NASA KC-135A research aircraft is shared for testing, with flights originating from both the NASA Glenn and Johnson centers. While experiment mounts are usually fixed, the large cabin volume, with a floor space of ~15.8 by 2.78 m, permits the free-floating of experiments to reduce residual accelerations to the level of 10^{-3} g for time periods of 5 to 10 sec, depending on the experiment size. Intermediate acceleration levels of less than 0.1 to 0.5 of normal gravity (partial gravity) can also be achieved in this aircraft by flying modified trajectories.

Sounding rockets offer advantages of even longer exposures to microgravity. A variety of sounding-rocket carriers that can attain altitudes of 30 to 1200 km are available for science payloads. These flights achieve acceleration environments of the order of 10^{-4} g for 5 to 15 min or longer. Payloads may vary in length, but their diameter is generally limited to 44 cm (56 cm in a few large rocket assemblies). For payload recovery, parachute systems impose landing loads equivalent to 30 to 50 g.

Most sounding-rocket experiments operate autonomously. Because the sounding-rocket flight lasts on the order of minutes, it is possible to uplink commands for operation and control and to downlink data, all in real-time. This capability can provide much flexibility in the design and operation of the experiment.

To date, combustion payloads on sounding rockets have included five in the Spread Across Liquids (SAL) series and four in the Diffusive and Radiative Transport in Fires (DARTFire) series.

Spaceflight Facilities

While the ground-based facilities of drop towers and aircraft are essential for microgravity experiments in combustion science, the longer-duration microgravity laboratories of the U.S. Shuttle Transportation System and the International Space Station, now in assembly, greatly expand the capabilities for investigations. The Shuttle flight duration for science missions is 7 to 13 days. In Shuttle operations, the drag and gravity-gradient forces limit the background acceleration to a level of around 10^{-4} g. In the future, the ISS will provide a similar-quality microgravity environment with test durations of months.

Available and proposed accommodations on the orbital facilities cover a great variety. This review will describe the range of facilities briefly for the information of the reader. To date, 31 combustion experiments have been conducted on the orbital venues. The leading project, in terms of the number of successful missions, is the Solid Surface Combustion Experiment (SSCE), which has had eleven flights. The SSCE is a self-contained apparatus, usually mounted and operated in the Shuttle crew compartment, using a mid-deck locker space. Each SSCE flight is dedicated to the measurement of the flame spread over a strip or cylindrical sample at a single condition of atmospheric oxygen concentration and total pressure.

Most of other combustion flight experiments have been carried in Shuttle payload-bay laboratories. The laboratories are pressurized modules connected by an airlock tunnel to the Shuttle cabin. Over 15 payload-bay laboratories have been flown in Shuttle missions. Most of the experiment space on these laboratories is assigned to biological, medical, material, and fluid experiments. Since 1992, however, combustion experiments have been conducted within the United States Microgravity Laboratories (USML-1 and USML-2), the United States Microgravity Payload (USMP-3), the SPACEHAB-4, and the Microgravity Science Laboratory (MSL-1). The latter laboratory was flown originally on Shuttle mission STS-83 in April 1997. The mission was terminated early, prior to the initiation of most of the experiments. It was then reflown, with the same crew and the same experiments, as Shuttle mission STS-94 in July 1997. The reflight, which was successful in all its objectives, is unique in the Shuttle program. It is an indication of the importance of the science contribution to the Shuttle program.

An additional venue for combustion research in space was the Russian *Mir Priroda* module. As part of the now-concluded ISS Phase I program, which involved cooperative U.S. testing on the *Mir* complex, two combustion projects were included in the suite of experiments brought to *Mir* during March to September 1996.

Space Accommodations

Several of the orbital accommodations for combustion experiments are worth noting, particularly for their versatility and their utility for the future. Unique to the Shuttle are the Getaway Special carriers (GASCAN). These are standardized, sealed volumes used as ballast in the Shuttle payload bay or on attached carriers, sharing available space with major payloads. The GASCAN experiments are not accessible to the crew, and they must be automated and software-controlled. GASCAN space is offered for the most part to student research, but it has been used to date for two Principal Investigator combustion-science projects, Microgravity Smoldering Combustion in 1995 and Turbulent Gas-Jet Diffusion in 1997. For the combustion-science experiments, the GASCAN accommodations had small, sealed chambers, flow systems, self-contained power, visual and environmental diagnostics, and data acquisition.

Ten combustion experiments have operated in glovebox facilities, located on several payload-bay laboratories, the Shuttle cabin, and the *Priroda.* The most recent glovebox experiment is Enclosed Laminar Flames (ELF), conducted on Shuttle Mission STS-87 in November 1998. The glovebox provides a sealed working volume in which small-scale experiments may be conducted (fig. 27). It offers connections for experiment power, video, and multiple-view still photography and for gas cleanup and filtration systems. The glovebox permits the implementation of several experiments in the same flight by interchanging experiment packages. Clever design of experiment packages also offers the opportunity to conduct multiple-point tests through the protected manipulation by the crew member. Advanced glovebox designs are now under development for inclusion in several of the ISS modules.

More complex multiuser facilities are also available for microgravity combustion research. The concept of common subsystems in hardware development avoids the high cost of repeatedly developing flight-qualified hardware and extends the useful life of such hardware. For example, The Combustion Module, CM–1, is a multi-user facility that accommodated two experiments, Laminar Soot Processes (LSP), and Structure of Flame Balls at Low Lewis Number (SOFBALL) in the noted MSL-1 Shuttle mission with its reflight. The CM–1 components are housed in

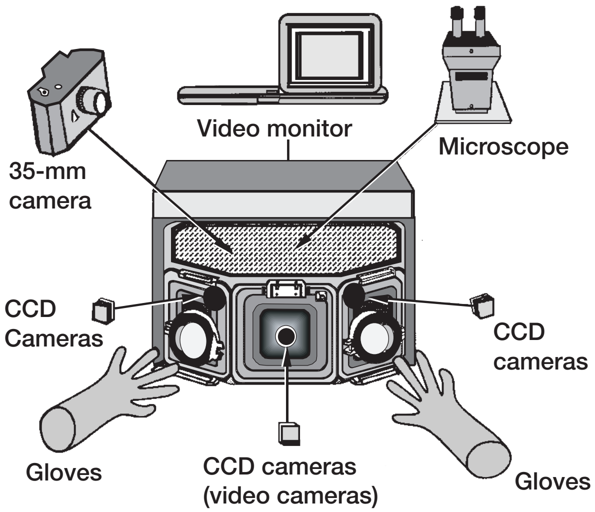

Figure 27.—Sketch of typical glovebox layout, showing diagnostics and operator access.

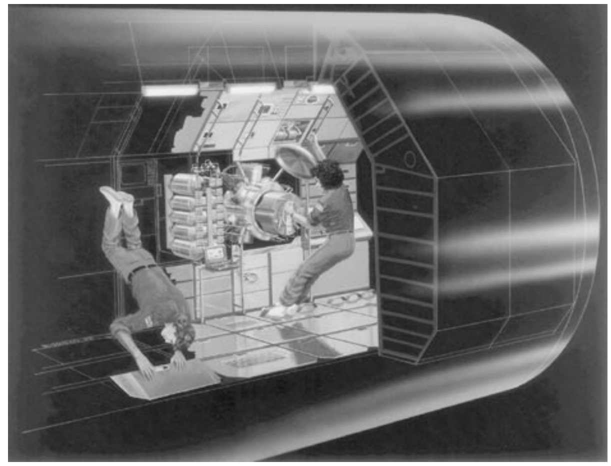

Figure 28.—Sketch of Combustion Module, CM-1 with experiment package being interchanged during spaceflight.

two adjoining racks. The single rack, shown to the left of the upright researcher in Fig. 28, contains the fluid-supply package to store and meter fuels, oxidizers, and diluents, and the video-recording equipment. The main double rack has the experimental combustion chamber, power supplies, experiment processor, diagnostics, and exhaust system. The flexibility required to perform multiple experiments is provided by mounting each set of experiment-specific hardware on a structure that can be interchanged and remounted within the double rack during the orbital operations, as also illustrated in figure 28.

The next version of a shared combustion accommodation will be CM-2, planned for flight on the Shuttle payload-bay laboratory, SPACEHAB Research Double Module, in late 2000. The two experiments operated on CM-1 above, LSP and SOFBALL, are designated for installation on CM-2 also. Both these experiments take advantage of ground-based testing to define new experiment requirements and to develop improved test hardware and diagnostics. For example, LSP-2 will have new cameras and filters for investigation of bright, nonsoot-emitting flames. SOFBALL-2 will extend its investigation to leaner gas mixtures, requiring improved gas-mixture control, spark igniters, and exhaust sampling. The SOFBALL-2 diagnostics will include the use of a new color camera, specified to meet the needs of both SOFBALL-2 and LSP-2.

CM-2 will also accommodate the first flight of Water Mist, a cooperative science and commercial experiment, aimed at the understanding of water-mist fire extinguishment for eventual ground and aircraft service. The Water Mist investigation requirements and hardware concepts are not complete at this writing, but the plans are to share the new CM-2 color camera and other components.

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13. ABSTRACT *(Maximum 200 words)*

The use of the microgravity environment of space to expand scientific knowledge and to enable the commercial development of space for enhancing the quality of life on Earth is particularly suitable to the field of combustion. This document reviews the current status of microgravity combustion research and derived information. It is the fourth in a series of timely surveys, all published as NASA Technical Memoranda, and it covers largely the period from 1995 to early 1999. The scope of the review covers three program areas: fundamental studies, applications to fire safety and other fields, and general measurements and diagnostics. The document also describes the opportunities for Principal Investigator participation through the NASA Research Announcement program and the NASA Glenn Research Center low-gravity facilities available to researchers.

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