NASA MICROGRAVITY COMBUSTION SCIENCE PROGRAM

MERRILL K. KING
NASA Headquarters, Code UG
Washington, DC 20546

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Introduction

Combustion is a key element of many critical technologies used by contemporary society. For example, electric power production, home heating, surface and air transportation, space propulsion, and materials synthesis all utilize combustion as a source of energy. Yet, although combustion technology is vital to our standard of living, it poses great challenges to maintaining a habitable environment. For example, pollutants, atmospheric change and global warming, unwanted fires and explosions, and the incineration of hazardous wastes are major problem areas which would benefit from improved understanding of combustion. Effects of gravitational forces impede combustion studies more than most other areas of science since combustion involves production of high-temperature gases whose low density results in buoyant motion, vastly complicating the execution and interpretation of experiments. Effects of buoyancy are so ubiquitous that their enormous negative impact on the rational development of combustion science is generally not recognized. Buoyant motion also triggers the onset of turbulence, yielding complicating unsteady effects. Finally, gravity forces cause particles and drops to settle, inhibiting deconvoluted studies of heterogeneous flames important to furnace, incineration and power generation technologies. Thus, effects of buoyancy have seriously limited our capabilities to carry out "clean" experiments needed for fundamental understanding of flame phenomena. Combustion scientists can use microgravity to simplify the study of many combustion processes, allowing fresh insights into important problems via a deeper understanding of elemental phenomena also found in Earth-based combustion processes and to additionally provide valuable information concerning how fires behave in microgravity and how fire safety on spacecraft can be enhanced.

Promising Microgravity Combustion Program Research Thrusts

(1) Turbulence and Combustion. Virtually all practical combustion devices are turbulent. The wide range of turbulence length and time scales generally precludes exact numerical simulation and also presents a significant challenge to experimental investigations. Microgravity uniquely limits the range of length and time scales to those large enough to be tractable experimentally and more readily simulated. Preliminary μg experiments reveal that buoyancy plays a role in the turbulence characteristics in regimes where it had been previously assumed that the flow field and flame behavior was independent of gravitational influence. One particularly powerful approach for treating the coupling between fluid motion and combustion chemistry based on studies of laminar flames is currently under development; this approach, referred to as laminar flamelet theory, shows promise as a tractable representation of turbulent combustion. The extension of laminar flamelet theories to predict fully turbulent flames cannot presently be exploited, however, due to limitations of our current knowledge base caused by the interferences of buoyancy during laminar flame studies. Microgravity combustion studies provide an opportunity to eliminate these interferences and, thus, markedly advance our capability to address turbulent combustion phenomena.

(2) Transient Processes in Gaseous Flames. Numerous types of instabilities are possible in combustion of flowing gases, some of these being gravity-dependent and others not. Such phenomena as ignition, extinction, and unsteady response of flames to externally imposed perturbations (e.g., pressure oscillations) are also of major importance as regards fire safety, production of pollutants, and combustion efficiency. Research studies in a microgravity environment provide for examination of fundamental phenomena involved in these transient phenomena without the confounding effects of buoyancy-induced flows which will, under normal gravity conditions, also respond in an unsteady manner to such imposed perturbations, often masking fundamental phenomena of interest. With understanding of these phenomena, strategies for controlling ignition, extinction, and responses of flames to externally imposed perturbations in practical combustion devices can better be devised.

(3) Soot Processes. Soot is a critical element in many combustion systems, strongly affecting combustor lifetime, efficiency, peak power output, and pollution generation. The short time scales and small spatial volumes affecting soot formation and destruction processes under normal gravity conditions preclude experimental probing. Furthermore, buoyancy accelerates, in an uncontrolled fashion, the flow field in which soot is formed and oxidized; this too inhibits scientific investigations. Microgravity offers a unique opportunity for controlling the flow environment and through this control extending the range of conditions involving soot processes. The lack of buoyantly-induced, accelerated flow results in longer residence times for primary soot formation, clustering, cluster-cluster agglomeration, and oxidation in a variety of flames. In addition, soot particle pathlines are strongly altered under microgravity conditions, resulting in major changes in the environmental history seen by the soot precursors and particles. From the perspective of practical benefit, the fundamental understanding of the processes controlling soot formation, aggregation, and oxidation is of vital importance since such understanding would allow us to develop methods to predict and control sooting associated with combustion processes under a wide variety of circumstances.

(4) Measurement (Species, Velocity, Temperature) Technology. A historic (and valid) criticism of microgravity experimental research is lack of quantification of meaningful variables (e.g. species concentrations). Advancement in understanding of chemical kinetic mechanisms is inhibited by an inability to measure progress of reactions and to quantify the detailed temperature and flow fields in which those reactions take place. Improved measurement methods in both 1g and μg are a growing focus of terrestrial research. Technological improvements in measurement capabilities will lead directly to improved kinetic and flow field modeling leading to enhanced capability for design of combustors with reduced pollutant generation and improved fuel efficiency. Spinoffs of these technologies can and are being used not only in laboratories distant from the inventor's own, but also in the monitoring of pollutant emissions from various sources. In the future these technologies will be used to evaluate fuel consumption, product generation, heat transfer efficiency, and pollutant control in manufacturing processes, and to serve as insitu engine performance and emission levels monitors. The resulting combination of diagnostic sensors and computational algorithms will allow electronic controls to play a larger part in practical combustion systems, enabling so-called "intelligent combustors".

(5) Droplet/Particle Combustion at Pressures Up to Supercritical. Microgravity is of particular benefit in studies of particle and liquid droplet ignition and combustion inasmuch as it permits elimination of settling effects and of buoyancy-induced flows around the droplets, thus leading to truly symmetrical (and hence one-dimensional) geometry and allowing droplets to be restrained within the field-of-view of various diagnostics. Currently, high pressure and supercritical fluid operation of combustion devices is being examined for increased efficiency. Unfortunately, pollutant (e.g., soot and oxides of nitrogen) generation increases with increasing pressure; hence military and NASA aeropropulsion research is heavily populated with studies aimed at realization of the theoretical efficiency improvements with simultaneous minimization of pollutants. Another application of this technology is in the area of hazardous waste disposal: supercritical water oxidation of hazardous wastes has been predicted as an important technology of the future, hopefully yielding only benign products (carbon dioxide and water). Much of our detailed knowledge in the area of combustion of droplets and particles has been obtained at low pressure; extension of studies to high pressure is required. For example, soot studies have mostly been performed near ambient pressures with flame temperatures of less than 2000K; diesel engines operate at over 50 atm and 2800K. Much of our knowledge of soot kinetics may not be applicable to these high temperature, high pressure regimes. High pressure operation is accompanied by increased buoyant flow effects; microgravity experiments will enable, as in other situations, an isolation of the effects of the buoyancy on flame structure, flammability, and flame speeds.

(6) Classical Model Validation/Benchmark Data. Combustion textbooks are replete with theories which are incompletely tested though widely accepted (through historical precedent). These theories often neglect buoyancy effects and utilize simplified transport processes and/or assume one-dimensional behavior in situations where buoyant effects preclude it. Microgravity continues to offer the unique ability to test, via ideal truly one-dimensional experiments, the accuracy of specific aspects of theories and to provide a benchmark data base against which extensions to existing theories and altogether new theories can be tested.

(7) Flame Structure/Elementary Mechanisms. A fruitful approach to achieving meaningful technology gains in combustion processes must be centered on development of better understanding of the fundamentals of the unit processes involved. Without such an understanding, the approach taken to improving combustion devices tends to involve incremental trial-and-error perturbations around current state-of-the-art designs, with opportunities to achieve possible major improvements with radically different approaches being missed. However, if one fully understands the physics and chemistry involved in a given combustion process, including detailed understanding of the unit subprocesses and how they interact, this understanding can be combined into physically accurate models which can then be used for parametric exploration of new combustion domains via computer simulation, with possible definition of radically different approaches to accomplishment of various combustion goals. Accordingly, emphasis should be placed on studies of combustion fundamentals which are not currently well understood; gravitational effects associated with normal earthbound combustion studies have prevented study of many elementary processes which tend to be overshadowed by gravitation-induced processes such as buoyancy or settling.

(8) Direct Numerical Simulation, Large Eddy Simulation. DNS and LES are being widely pursued for definition of detailed features of the flame structure and transport processes (and their interactions) associated with combustion. Due to the large range of length and time scales, however, direct numerical simulation of practical or even idealized devices is considered to be a technology of the future, at best. DNS modeling to date has, however, shown the need to account for preferential mass diffusion even in turbulent flame environments. Microgravity experiments again lessen the range of scales and may make the problem tractable at least for model validation of laboratory-scale experiments, a first step toward DNS validation. DNS is expected to ultimately play a major role in the design of practical combustion systems and obviate the need for the expensive construction and modification of a wide range of breadboards, prototypes, and experimental models of combustion devices; it may also be used for optimization of design elements, subsystems, controls, and overall system performance at reduced cost/time.

(9) Spray and Aerosol Combustion. Realistic sprays include a liquid breakup region, dispersed multiphase flow, turbulent mixing processes, and various levels of flame interactions through the spray. Idealization of spray configurations in a quiescent environment (the starting point for models) has been impossible in 1g due to settling of large droplets and buoyant pluming of post-combustion gases. Microgravity offers the promise of such idealization, but has just begun to provide experimental data on ignition, fire spread, and interactions in idealized linear and planar arrays of monosized droplets. Spray and aerosol cloud combustion accounts for 25% of the world's energy use, yet remains poorly understood from both a fundamental and practical perspective. Improved understanding of the flammability and flame interactions of sprays can be expected to yield improved combustion efficiency in practical devices; this will only occur with an improved detailed theoretical description. In the area of combustion safety, dust clouds contribute to accidental fires and explosions (grain elevators, underground mines). Finally, improved spray technology can be applied to improvements in hazardous waste incineration.

(10) Combustion Synthesis. The use of flames to synthesize materials is expanding rapidly. Products include valuable vapors (e.g. acetylene), ultrafine particles (fullerenes, silicon oxides, titanium oxides), coatings (diamonds) or monolithic solids (boron carbide, titanium boride). Fullerene production is being investigated extensively, but the product yields of fullerenes are currently typically less than 1%, leaving tremendous potential for improvement. Sedimentation and buoyant plumes yielding limited critical residence times again interfere with present investigations into both the scientific mechanisms of material production and the quality of the actual industrial product. For example, pressure and buoyancy effects on soot-filled flames are not understood sufficiently to determine the ideal operating conditions to maximize fullerene generation in either premixed or diffusion flames. Microgravity offers the promise of isolating the effects of pressure by removing the influence of buoyancy on the material production process. A major difficulty in self-propagating, high-temperature synthesis (SHS) of materials is the control of porosity and the microstructure of the products. SHS reactions generating gaseous, liquid, or combined phases are prone to gravity-induced fluid flows, leading to non-uniform microstructure and undesirable properties of the product material due to segregation and density gradient effects. Gravitational forces have been shown to play a dominant role in controlling both the combustion-synthesis reactions and the morphologies of the synthesis products. Current research is geared towards interpreting the differences between normal- and low-gravity processing.

(11) Partial Gravity Studies. The utilization of partial gravity environments enables systematic scientific testing of effects of this parameter on fundamental processes as well as tying directly to the nation's desire for space exploration. Both the Moon and Mars are in NASA's future; microgravity and normal gravity studies have already shown that combustion processes are distinctly affected by reductions in gravity, with a conclusion that the partial gravitational levels on the Moon and Mars may yield increased flammability. In addition, partial gravity environments may have strong effects on insitu propellant production processes as well as on utilization of these products.

(12) Surface Flame Spread <----> Large-Scale Fires. Anyone who has observed the combustion of solid fuels, particularly flame spread across and burning of vertical walls, is well aware of the dominant effects of buoyancy on such processes under normal gravity conditions, a dominance which makes understanding of other phenomena involved very difficult (an example of how buoyancy can "mask" such phenomena). Accordingly, microgravity studies of flame spread across solid fuels and liquid pools are of considerable interest from a fundamental point of view as well as being very important in terms of fire safety on various space platforms. On Earth, the fluid mechanics of large-scale fires are complicated by buoyancy-fed turbulent processes and thermal radiative interactions with surrounding materials, terrain, and building structure. Current models are still somewhat primitive, with little elucidation of the role of thermal radiation in almost any aspect of fires. Investigations of large-scale fires under microgravity conditions have yet to begin, but it has been shown that radiation takes on heightened importance in small-scale fires in microgravity, indicating that results from laboratory-scale experiments in microgravity might be utilized in modeling of large-scale fires. In terms of NASA's own direct interests, ongoing investigations of material flammability and fire behavior in microgravity have yielded vital guidance to improved fire safety aboard orbiting spacecraft. There does remain, however, a need for 1g - μg correlations of ignition, flame spread, flammability, and extinction conditions.

Current NASA Microgravity Combustion Program Content

As stated in NASA's Microgravity Research Program Strategic Management Handbook, the Microgravity Research Program mission is "To use the microgravity environment of space as a tool to advance knowledge; to use space as a laboratory to explore the nature of physical phenomena, contributing to progress in science and technology on Earth; and to study the role of gravity in technological processes, building a scientific foundation for understanding the consequences of gravitational environments beyond Earth's boundaries". For accomplishment of this mission, both a ground-based program and a flight experiments program are employed; in addition, development of facilities and experiment modules for conduct of multiple experiments is supported. The ground-based program has two major objectives: (1) nurturing and development of ideas and concepts that may be later developed into flight experiments; and, (2) providing theoretical and experimental underpinnings to support understanding of phenomena being studied in the microgravity environment. Ground-based investigations include theoretical and experimental laboratory research, drop-tower tests, and parabolic aircraft flight experiments. In the flight program experiments judged to justify use of the flight environment are developed and executed. These experiments are conducted in microgravity environments provided by suborbital sounding rockets, the Space Shuttle middeck or isolated cargo bay support structures, the Shuttle-based Spacelab or Spacehab pressurized laboratory facilities, the Russian Mir station, international Space Station facilities, and other available carriers.

Currently, the Microgravity Combustion Science program is supporting 48 ground-based studies, 7 flight definition studies, 8 flight programs, 3 Glovebox investigations, 5 Graduate Student Researcher Programs, and 2 NRC postdoctoral studies, for a total of 73 programs. In addition, two major combustion-related Advanced Technology Development programs in the area of diagnostics development are being carried out at the Lewis Research Center. In terms of the Research Thrusts described above, the number of studies involving aspects of Categories 1-12 are 7, 7, 5, 7, 11, 9, 18, 2, 8, 6, 3, and 15, respectively. [Note that this totals 97, in excess of the total number of programs being supported, since some of the programs involve aspects of more than one of the categories.]

Although the majority of the current programs are ground-based studies, centered on analytical modeling activities, testing in drop-towers and parabolic aircraft at Lewis Research Center, and testing at the Japan Microgravity Center (JAMIC) dropshaft in Hokkaido, Japan, limited flight testing has also been carried out on Sounding Rockets and on the Space Shuttle. Three Sounding Rocket tests on the Spread Across Liquids (SAL) Program of Dr. Howard Ross (Lewis Research Center) have been successfully completed to date. Each flight provided approximately six minutes of microgravity time (during which three burns were accomplished) for investigation of the flame spread characteristics across a deep pool of liquid fuel in a microgravity environment, with particle imaging velocimetry, rainbow schlieren, and flamespread data being obtained for comparison with model predictions. This program has recently been approved for five additional flights. In addition, three Sounding Rocket flights have been carried out on Prof. Robert Altenkirch's (Washington State University) Diffusive and Radiative Transport in Fires Experiment (DARTFire).

Dr. Altenkirch is also Principal Investigator on the Solid Surface Combustion Experiment (SSCE) on which eight experiments have been completed to date, with samples of PMMA being burnt in various oxygen-nitrogen atmospheres under quiescent conditions. Two additional shuttle flights have been approved for this experiment; it is expected that these will be completed during 1997. Two Getaway Special Canister (GASCAN) payload shuttle flight tests on the Microgravity Smoldering Combustion experiment (MSC) of Prof. Carlos Fernandez-Pello (University of California-Berkeley) have also been recently completed, with a request for additional flights currently under review. At this time, final preparations have been completed for three major combustion experiments on the Microgravity Space Laboratory (MSL-1) on the Space Shuttle, scheduled for April, 1997; these experiments are the Droplet Combustion Experiment (DCE) of Prof. Forman Williams (UCSD), Prof. Paul Ronney's (University of Southern California) Study of Flameballs at Low Lewis Numbers experiment (SOFBALL), and Dr. Gerard Faeth's (University of Michigan) Laminar Soot Processes in Flames experiment (LSP). In addition, Dr. Yousef Bahadori's (SAIC) Turbulent Gas Jet Diffusion Flame (TGDF) experiment is tentatively scheduled to go to flight in late 1997.

To date, four Microgravity Combustion Glovebox Experiments, one on USML-2 (Oct., 1995) and three on USMP-3 (Feb., 1996), have been carried out; these were the Fiber-Supported Droplet Combustion (FSDC) experiment, the Forced Flow Flame Spreading Test (FFFT), the Comparative Soot Diagnostics (CSD) experiment, and the Radiative Ignition and Transition to Flame Spread Investigation (RITSI). In addition, a repeat of the FSDC experiment is planned for MSL-1, with two additional glovebox experiments, Opposed-Flow Flame Spread on Cylindrical Surfaces (OFFS) and Enclosed Laminar Flames (ELF), planned for the near future. Finally, additional FFFT tests and Candle Flame Combustion tests have been carried out in the Mir Glovebox facility during 1996.

Enterprise for Human Exploration and Development of Space (HEDS)--Roadmap

In early 1994, as part of ongoing reorganizations at NASA, the agency established six major enterprises, later reduced to five. In the current organization, the Microgravity Science and Applications Division (MSAD) of the Office of Life and Microgravity Sciences and Applications (OLMSA) has become part of the Human Exploration and Development (HEDS) Enterprise. In January, 1996, a Strategic Plan for HEDS was put into place and development of "roadmaps" for the future directions of activities within HEDS was initiated; the current roadmap for the Microgravity Combustion Science program is attached as Figure 1. The three major thrusts of the HEDS activities are shown in the ellipses at the left of the figure, with applications of these to the direction(s) of the Microgravity Combustion Science program over three time periods being shown in the boxes to the right of these ellipses. It is obvious from this chart that, while basic research into fundamentals is still considered to be vitally important to the program, there is a major shift of emphasis toward "mission-oriented" research; that is, research aimed at specific problems in combustion applications on Earth as well as under reduced or microgravity conditions. Thus, it is important that firmer linkages between the research being done using microgravity and applications to practical applications on Earth (e.g., increased efficiency of conversion of chemical energy contained in fuels to useful work, reduction of combustion-generated pollutants from automobile engines and other combustors, decreased fire and explosion hazards) need to be established for an increasing percentage of efforts funded under this program. In trying to steer our program into particular areas of emphasis, however, we cannot lose sight of the fact that outside peer review weighs very heavily into selection for funding of proposals submitted in response to our NASA Research Announcements (NRA's), though final selections are made by a NASA selecting official (in this case, the Director of the Microgravity Science and Applications Division). In the past, we have asked our peer reviewers to judge proposals solely on scientific merit and microgravity relevance; for future NRA's, we will likely extend the evaluation criteria to include responsiveness to specific areas of emphasis called out in these NRA's. In addition, the question of relevance to specific program goals can be used as a "tie-breaker" in choosing between proposals with similar peer review scores.

Included among the long-term goals of the HEDS microgravity combustion program are: (1) Melding microgravity combustion space experiments together with ground-based combustion studies, using gravity as an added independent variable, to provide better understanding of the physical and chemical mechanisms involved in combustion and to provide more rigorous testing of analytical models; (2) Utilizing basic research to provide technological advances in various combustion processes/devices (e.g., internal combustion engines, turbines, combustion synthesis, incinerators); (3) Creating the understanding that will permit lessons learned in microgravity combustion experiments and modeling to be used in optimizing combustion devices here on Earth; (4) Providing quantum leaps in the areas of fire safety and minimization of combustion-generated pollution; (5) Providing the understanding which will permit efficient use of alternative fuels, which will be increasingly needed as we deplete our oil and gas reserves; and, (6) Developing a better understanding of various combustion synthesis processes, opening the door to production of novel tailored materials here on Earth as well as in space.

There are numerous potential combustion technologies for terrestrial and space exploration applications delineated in the Figure 1 roadmap. These include: (1) Active control over thermal efficiency and pollutant generation (e.g., soot, NOx) through sensor development and miniaturization accompanied by development of algorithms relating sensor readings, control settings, and system performance; (2) Use of magnetic and electric fields to improve thermal efficiency (microgravity enables improved isolation of and thus understanding of field effects on electrically-charged radicals and paramagnetic molecules such as oxygen); (3) Improved atomization methods for diesel and gas turbine engines, leading to improved fuel utilization, through improved understanding of fundamentals of liquid jet breakup and droplet interactions in sprays; (4) Flame-zone pollution control in premixed and diffusion burners, reducing the need for post-combustion cleanup devices, through fundamentally improved understanding of flame structure and of mechanisms of formation of soot and oxides of nitrogen; (5) Improved exhaust gas monitoring for cars and other combustion devices combined with development of "smart" controls to compensate for fuel variations and/or degradation of engine components to decrease pollution emissions; (6) New flame-stabilization/control technologies for burners enabling reliable, ultra-lean premixed combustion through improved understanding of flame stabilization zones in engines, burners, etc.; (7) Development of improved strategies and procedures for fire prevention, detection, and suppression in the microgravity environment associated with Space Station and in the reduced gravity Lunar and Martian environments; (8) Reduction of hazards associated with gaseous fuel combustion through better mapping and understanding of flammability limit and combustion instability phenomena; (9) Development of improved protection against large-scale fires (house fires, forest fires) via better fundamental understanding of material ignition and flamespread phenomena; (10) Reduction of mine and grain silo explosion hazards through development of understanding of fundamentals associated with these phenomena; (11) Improved reliability in hazardous liquid waste incineration, resulting from studies of droplet and spray burning and of pollution generation; (12) Industrial-scale, combustion-generated fullerene production through determination of approaches for improving the yields of fullerenic material in flame systems; (13) Production of composite materials with improved strength, reliability, and ductility through better understanding of how to improve micro-structural uniformity and control porosity via gravitational control; and, (14) Development of methods for producing and utilizing alternate fuel/oxidizer combinations associated with Lunar, Martian, or other extraterrestrial habitats.

Upcoming Microgravity Combustion NASA Research Announcement

In the Microgravity Combustion Program at NASA, investigators are selected in response to a NASA Research Announcement (NRA) issued once every two years and are placed either in the Ground-based Category or in the Flight Definition Category. At this time, it is anticipated that an NRA will be released early in the Fall of this year (1997) with proposals being due approximately three months after the NRA release date; it is suggested that, even though distribution of postcards describing how to obtain the NRA will be made to an existing extensive distribution list, potential proposers contact the author to ensure that they are included on this list. Proposals received in response to this NRA will first be examined for responsiveness and divided into categories, with external peer review panels being established for each category. Next, written reviews and ratings (three per proposal) will be obtained from the reviewers, each of whom will review approximately 10 proposals, with each proposal being rated on scientific merit, microgravity relevance, and linkage to goals outlined in the HEDS Roadmap. All the reviewers on a given panel will then be assembled for discussion of the proposals within that group with the ultimate output of a consensus evaluation of each proposal and assignments into "Highly Qualified", "Qualified", or "Not Qualified" categories. For strong candidate proposals which are likely to require flight, feasibility and resource compatibility reviews will be carried out by NASA/Lewis personnel. Finally, the "Highly Qualified" and "Qualified" proposals will be assessed in terms of program balance and linkage to HEDS goals by the Enterprise Scientist for Microgravity Combustion and a list of suggested awardees for Ground-Based and Flight Definition Programs will be developed. A list of proposals recommended for funding will be generated in a meeting of the Microgravity Science Branch, with final approval by the Lead Scientist and Division Director. It is anticipated that the review process should be complete by mid-1998, with awards occurring in late 1998 (early Fiscal Year 1999).

For proposals receiving awards in the Flight Definition category, the programs may proceed, following passing of a peer-reviewed Science Concept Review (SCR) and Requirements Definition Review (RDR) and acceptance of a Science Requirements Document (SRD) generated by the Principal Investigator, into the Flight Program. In addition, there is opportunity for Ground-Based investigators to participate as "guest" investigators in Glovebox Experiments on a Space Platform based on internal NASA review of proposals submitted in response to Glovebox

Opportunity Announcements. [More details on these processes are available from the author.] In the overall (flight plus ground-based projects) Microgravity Combustion program, both experimental and theoretical modeling efforts are supported. Experimental test beds for microgravity experiments include drop-towers at NASA/Lewis, capable of providing 2.2 to 5 seconds of microgravity time, aircraft flying parabolic trajectories, providing up to twenty seconds of reduced gravity (0.001 to 0.01 g), sounding rockets which supply very low gravity for up to 6-7 minutes, and Shuttle or Space Station facilities of various types, allowing basically unlimited microgravity operating times. In addition, we are participating in cooperative studies with Japanese investigators allowing us access to a 10-second drop tower at Hokkaido, Japan.

As indicated earlier, while conduct of fundamental science investigations remains a cornerstone of the Microgravity Combustion Science program, more emphasis will be placed in the future on relevance to the goals outlined in the HEDS Roadmap, with linkage of the proposed research to attainment of these goals receiving increased emphasis. However, future proposals are <u>not</u> limited to the topic areas discussed in this paper; <u>extension to combustion topics not currently included in the Microgravity Combustion program is strongly encouraged</u> to permit us to broaden the program scope. Evaluation criteria which should be kept in mind by proposers include:

1. Is microgravity of fundamental importance to the proposed study?

2. Do the issues addressed by the research have the potential to close major gaps in the understanding of fundamentals of combustion processes?

4. Is there potential for elucidation of previously unknown phenomena or interactions between phenomena?

5. Is the project likely to have significant benefits/applications to ground-based as well as space-based operations involving combustion processes?

6. Are the results likely to be broadly useful, leading to further theoretical or experimental studies?

7. Can another project in the specific subarea be justified in terms of limited resource allocation?

8. Is the project technologically feasible, without requirements for substantial new technological advances?

9. How will this project stimulate research and education in the combustion area?

10. How does the projected cost/benefit ratio compare with other projects competing for the same resources?

11. What is the potential of this project in terms of stimulating future technological "spinoffs"?

12. Are there strong well-defined linkages between the research and HEDS goals?

It appears that the most fruitful approach to achieving meaningful technology gains in processes involving combustion is to concentrate on developing better understanding of the fundamentals of the individual processes involved. With such understanding, including definition of details of the unit processes and their interactions, physically accurate models which can be used for parametric exploration of new combustion domains via computer simulation can be developed, with possible resultant definition of radically different approaches to accomplishment of various combustion goals. As discussed earlier, normal-gravity conditions have prevented study of many elementary processes which are over-shadowed by processes such as buoyancy, making it difficult to develop mechanistic understanding of unit phenomena making up overall combustion processes. It cannot be emphasized too strongly that our program is dedicated to taking advantage of microgravity to untangle these complications, allowing major strides in our understanding of combustion processes and in subsequent development of improved combustion devices leading to improved quality of life here on Earth.

Figure 1. Combustion Science Research

Strategies to Accomplish Program Objectives

	1996 - 2002 **Revolutionize NASA** *Deliver world-class programs and cutting-edge technology through a revolutionized NASA*	2003 - 2009 **Expand our Horizons** *Expand our horizons in space and aeronautics to assure continued U.S. leadership*	2010 - 2020 & Beyond **Open the Frontier** *Open the space frontier to international human expansion and commercial development*
To advance and communicate scientific knowledge and understanding of the Earth, the environment of space, the solar system, and the universe	• Work information exchange and cooperative projects with other US agencies funding combustion research (NSF, NIST, AFOSR, ONR, ARO, DOE, EPA, FAA, DOT) • Produce significant findings from microgravity expts which will attract a vested research community of at least 100 PIs • Hold workshops to distribute information and focus activities • Delineate mechanisms associated with flammability limits and combustion instabilities • Use ground-based research and limited space experiment results to define a decade of ISS research	• Conduct ISS studies of microgravity combustion processes, focusing on problems of highest current terrestrial interest • Use results to replace and fill gaps in combustion textbooks • Develop benchmark data bases on combustion processes against which extensions to and altogether new theories can be developed, enabling a new and broad understanding of combustion science • Improve understanding of large scale fires with eye to development of means of prevention and suppression • Continue shift of emphasis to "hypothesis-driven" combustion research rather than exploratory research	• Complete data collection, reduction, and analysis of data sets to serve as standard references • Use data sets for development of unified treatments for analysis of combustion processes at all g-levels • Sustain continued development of fundamental understanding and control of combustion processes • Develop fundamental understanding of combustion-turbulence interactions • Reduce/eliminate reliance on trial-and-error design procedures for combustion devices
To explore, use, and enable the development of space for human enterprise	• Scope potential critical knowledge needs • Assume responsibilities for space fire safety • Develop understanding of and characterization methods for detection of fires in microgravity environment and develop tests for characterization of material flammability under ug • Define effects of reduced pressure and higher oxygen mole fraction on ignition and flamespread over materials for station and other reduced g environments • Develop agreements with foreign agencies regarding specific areas of cooperation and division of responsibilities	• Expand program to examine ISRU for propulsion, power generation, and combustion synthesis • Delineate mechanisms controlling material ignitability, smolder, flamespread, and extinction in normal and ug environments, with emphasis on fire safety in reduced or ug environments • Develop tools permitting accurate prediction of effects of low gravity on combustion processes in space or other extraterrestrial bodies leading to improved design tools • Perform in-space demos and validations of combustion-related technologies as preparation for Lunar and Martian habitats	• Develop extraterrestrial laboratories for combustion research and engineering development • Develop energy conversion processes optimized for use in space applications involving reduced gravity • Explore combustion processes involving alternative fuels and oxidizers which may have to replace "normal" Earth-based fuels and oxidizers • Develop, demonstrate, and enable ISRU techniques using combustion technologies for power, propulsion, and ECLSS support of Lunar and Martian habitats
To research, develop, verify, and transfer advanced aeronautics, space, and related technologies	• Steer combustion research efforts into more specific, prioritized subtopic areas (mission-oriented research) • Expand menu of diagnostic tools with emphasis on direct rather than inferential measurements • Increase capabilities of ground-based facilities • Expand research on combustion synthesis processes • Use ground-based and suborbital flight experimental studies to better scope combustion experiments requiring longer ug durations in preparation for ISS • Study soot formation, agglomeration, oxidation to define control strategies for Earthbound combustion devices	• Increase emphasis on detailed quantitative measurements with emphasis on delineation of mechanisms • Emphasize potential for high economic feedback • Increase emphasis on combustion synthesis processes for production of novel high-value materials; develop industrial-scale combustion synthesis processes • Contribute to development of low NOx emission combustors for supersonic combustion devices • Develop miniaturized instrumentation for sensing and controlling combustor performance; utilize this technology in improving terrestrial combustion processes	• Apply knowledge gained to development of ways for increasing fuel utilization efficiency and reducing pollutant emissions for many processes • Develop diagnostics/process control combinations to permit continual optimization of combustion devices • Develop strategies for improving combustion devices via smart sensors, magnetic and electric field utilization, improved mixing technologies, improved atomization, and flame-zone pollution control • Develop radically new approaches to conversion of chemical energy to useful work

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