NASA MICROGRAVITY COMBUSTION SCIENCE PROGRAM

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INTRODUCTION

Combustion has been a subject of increasingly vigorous scientific research for over a century, not surprising considering that combustion accounts for approximately 85% of the world's energy production and is a key element of many critical technologies used by contemporary society. Although combustion technology is vital to our standard of living, it also poses great challenges to maintaining a habitable environment. A major goal of combustion research is production of fundamental (foundational) knowledge that can be used in developing accurate simulations of complex combustion processes, replacing current "cut-and-try" approaches and allowing developers to improve the efficiency of combustion devices, to reduce the production of harmful emissions, and to reduce the incidence of accidental uncontrolled combustion. With full understanding of the physics and chemistry involved in a given combustion process, including details of the unit processes and their interactions, physically accurate models which can then 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.

Effects of gravitational forces on earth impede combustion studies more than they impede most other areas of science. The effects of buoyancy are so ubiquitous that we often do not appreciate the enormous negative impact that they have had on the rational development of combustion science. Microgravity offers potential for major gains in combustion science understanding in that it offers unique capability to establish the flow environment rather than having it dominated by uncontrollable (under normal gravity) buoyancy effects and, through this control, to extend the range of test conditions that can be studied. It cannot be emphasized too strongly that our program is dedicated to taking advantage of microgravity to untangle complications caused by gravity, allowing major strides in our understanding of combustion processes and in subsequent development of improved combustion devices leading to improved quality of life on Earth.

Fire and/or explosion events aboard spacecraft could be devastating to international efforts to expand the human presence in space. Testing to date has shown that ignition and flame spread on fuel surfaces (e.g., paper, wire insulation) behave quite differently under partial gravity and microgravity conditions. In addition, fire signatures—i.e., heat release, smoke production, flame visibility, and radiation—are now known to be quite different in reduced gravity environments; this research has provided data to improve the effectiveness of fire prevention practices, smoke and fire detectors, and fire extinguishment systems. The more we can apply our scientific and technological understanding to potential fire behavior in microgravity and partial gravity, the more assurance can be given to those people whose lives depend on the environment aboard spacecraft or eventually on habitats on the Moon or Mars.

CURRENT PROGRAM

Currently, NASA's Microgravity Combustion Science program is supporting approximately sixty ground-based studies (including experimental studies utilizing drop-tower facilities and/or parabolic aircraft, along with analytical modeling efforts) and twenty projects which are utilizing or are expected to utilize extended duration testing in microgravity afforded by space-based experiments on sounding rockets or orbiting facilities (shuttle or space station). These studies can be divided into seven major categories: premixed gas flames; gaseous diffusion flames; combustion of individual fuel droplets, clusters of droplets, and sprays; combustion of individual solid particles and dust clouds; flame spread across liquid and solid fuel surfaces; smoldering combustion; and combustion synthesis. In addition, a number of advanced diagnostic instrumentation technologies are being developed for experimental microgravity studies, especially in the space environment, where there are severe constraints as regards volume, mass, and power. In a recent expansion of the scope of the program, we are also funding several studies whose main relevance lies in the area of access to space, rather than strictly microgravity, all related to spacecraft propulsion.

An overview of combustion experiments performed in space prior to the Microgravity Science Laboratory-1 (MSL-1) flights of April and July, 1997 was presented by this author and Dr. Howard Ross in the August, 1998 issue of the AIAA Journal (Volume 36, Number 8). Description of the experiments (Laminar Soot Processes, Structure of Flameballs at Low Lewis Numbers, and Droplet Combustion Experiment) conducted on that benchmark mission, along with preliminary results, were described in three accompanying articles by the investigators. Although the MSL-1 mission carried by far the most extensive set of space combustion experiments to date, the considerable earlier space experimentation aimed at determining the effects of microgravity on combustion processes included experiments on candle flames, combustion of fuel droplets positioned on support fibers, ignition and spread of flames across solid fuel surfaces, flame spread across liquid fuel pools, smoldering combustion, and production of soot in flames as related to fire detection. These experiments have been accompanied by numerous other microgravity experiments – providing thousands of test points – performed in the last decade in ground-based facilities such as drop towers and low-gravity aircraft in the United States, Europe, Russia, and Japan. A complete bibliography associated with these tests may be found on the Internet at http://www.lerc.nasa.gov/Other_Groups/MCFEP

To date, microgravity combustion studies have demonstrated major differences in structures of various types of flames from those seen in normal gravity. Besides the practical implications of these results to combustion efficiency (energy conservation), pollutant control (environmental considerations), and flammability (fire safety), these studies establish that better mechanistic understanding of individual processes making up the overall combustion process can be obtained by comparing of results gathered in microgravity with normal gravity tests, with potential for major improvements in design of combustion processes and hardware for use on earth as well as in space.

Future microgravity combustion experiments in space will be carried out mainly on the International Space Station (ISS) either in a dedicated Combustion Integrated Rack (CIR) with Experiment Unique Inserts or in the Microgravity Science Glovebox, a major upgrade from the Middeck Glovebox currently employed on the Shuttle. As is the case with all of the microgravity disciplines, the ISS will offer the ability to conduct a considerably larger number of microgravity combustion experiments per year, a big advantage over available opportunities on the space shuttle; regular access to a laboratory in space should bring flight-based research more closely in line with experimentation done on Earth. The CIR performance requirement is to support an average of 5 typical combustion experiments (with many data points being obtained in each) per typical year within all known on-orbit and on-earth resource limitations, including budget. In addition, if the limiting resources are increased, the CIR shall be capable of supporting up to 15 experiments per year. Over its life cycle, the CIR shall be capable of supporting 80 percent of the combustion experiments selected into the flight program. Since CIR will be on-orbit for the life of the ISS, up to about 120 combustion experiments may eventually be conducted. Central to giving the CIR the required flexibility is the use of Principal Investigator (PI) unique combustion experiment hardware/software to customize the CIR to fully meet the PI's requirements. The CIR is scheduled for launch on UF-3 in October, 2002 and will begin its scientific work immediately. Seventeen combustion experiments are tentatively planned during the first three years of CIR operation.

Flight investigators in the NASA Microgravity Combustion Program often need to conduct reduced gravity experiments in ground-based facilities during the experiment definition and technology development phases of their programs; in addition, the duration of microgravity time available in ground-based facilities is adequate for completion of many studies without recourse to a spaceflight investigation. (Given the difference in cost, it is important that investigations be carried out in ground-based facilities where feasible.) The NASA ground-based reduced gravity research facilities include two drop towers (2.2 and 5.18 seconds of high-quality microgravity time) at the Lewis Research Center (LeRC) and a KC-135 aircraft (20-25 seconds of considerably lower quality microgravity time) that is based at JSC but flies 6-10 campaigns per year from LeRC. In addition, NASA has made arrangements to use, on a cooperative basis, a Japanese dropshaft facility in Hokkaido capable of providing 10 seconds of quality microgravity time.

HEDS ENTERPRISE

In early 1994, as part of an ongoing reorganization at NASA, the agency established six major enterprises, later reduced to four. In the current organization, the Microgravity Research Division of the Office of Life and Microgravity Sciences and Applications (OLMSA) has become part of the Human Exploration and Development of Space (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 three major charges of the HEDS activities are (1) to advance and communicate scientific knowledge and understanding of the Earth, the solar system, the universe, and the environment of space for research, (2) to explore, use, and enable the development of space for human enterprise, and (3) to research, develop, verify, and transfer advanced aeronautics, space, and related technologies. 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) be established for an increasing percentage of efforts funded under this program. 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 extend the evaluation criteria to include responsiveness to specific areas of emphasis called out in these NRA's. The need for improved understanding of combustion phenomena to enable future space technologies and operations should be recognized as one of the primary opportunities of the discipline. Included are development of spacecraft combustion/propulsion systems, fire safety, use of *in-situ* resources, and power generation in extraterrestrial environments. Examples of local resource utilization-related processes include chemical reaction engineering for production of fuels and/or oxidizers, combustion of such products in a reduced-gravity environment, and fire safety during such operations. At a HEDS Technology Workshop held on August 5-7, 1997, several fire research areas of interest with respect to a manned Mars mission were defined.

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 (1999) 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 this author to ensure that they are included on this list. 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." The combustion science program seeks a coordinated research effort involving both space- and ground-based research, including both experimental and theoretical modeling efforts. Ground-based research forms the foundation of this program, providing the necessary experimental and theoretical framework for development of rigorous understanding of basic combustion phenomena. 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. NASA is currently developing several types of flight hardware; brief descriptions of the planned capabilities are given in another paper. Experimental proposals for which none of the existing flight instruments is appropriate are also encouraged; however, it must be pointed out that experiments calling for facilities considerably outside of these envelopes will involve considerably more expense to NASA, a factor which must be taken into consideration in funding decisions. 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.] Participation is open to U.S. and foreign investigators and to all categories of organizations: industry, educational institutions, other nonprofit organizations, NASA centers, and other U.S. Government agencies. Though NASA welcomes proposals from non-U.S. investigators, NASA does not fund principal investigators at non-U.S. institutions.

Examination of the other papers included in this Workshop proceedings will provide the reader with a good idea of the current scope of our research program. However, future proposals are not limited to these topic areas; extension to combustion topics not currently included in the Microgravity Combustion program is strongly encouraged to help us in broadening the program scope. At this time, the Microgravity Combustion Science Discipline Working Group (external advisory group) is working with NASA personnel to develop a list of "fundamental data sets" needed for better understanding of basic combustion processes, testing of combustion models, and design of improved practical combustion devices. Included in this effort is an attempt to prioritize the resulting list in terms of both utility and need for microgravity in filling out the data set. Categories of data sets being considered include: Physico-Chemical Constants (e.g., thermal and mass diffusivity at high temperature and pressure of various species including combustion intermediates); Fundamental Combustion Parameters which are not System/Device Dependent (e.g., laminar burning velocities, extinction strain rates, soot inception points, Markstein lengths); Classical Well-Defined Benchmark Systems for Model Validation and Calibration (e.g., flame spread rates, Burke-Schumann flame shapes); and, Emerging Topics (e.g., spacecraft fire safety, SHS, flame-synthesized materials). It is anticipated that at least a preliminary prioritized data set list will be included in the upcoming NRA.

The total amount of funding for this program is subject to the annual NASA budget cycle. The Government's obligation to make awards is contingent upon the availability of appropriated funds from which payment for award purposes can be made and the receipt of proposals which the Government determines to be acceptable for an award under the upcoming NRA. For the purposes of budget planning, we have assumed that the Microgravity Research Division (MRD) will fund 0 to 3 flight experiment definition proposals from the upcoming NRA. These efforts are typically funded at an average of $150,000 to $175,000 per year. It is also anticipated that approximately 15-20 ground-based study proposals will be funded, at an average of about $80,000 to $100,000 per year, for up to 4 years.

Active research experience is one of the most effective techniques for attracting talented undergraduates to and retaining them in careers in mathematics, science, and engineering; accordingly, MRD is endeavoring to foster the career development of undergraduate students by offering optional supplements of approximately $5,000 per student per year to approved research tasks for undergraduate student research projects. These projects should involve undergraduate students in a meaningful way in ongoing research programs or in related sub-projects specifically designed for this purpose.

The principal elements considered in the evaluation of proposals solicited by this NRA are: relevance to NASA's objectives, intrinsic merit, and cost. Of these, intrinsic merit has the greatest weight, followed by relevance to NASA's objectives, of slightly lesser weight. Both of these elements have greater weight than cost. Responding to the following questions should be kept in mind by proposers:

1. Is microgravity of fundamental importance to the proposed study, either in terms of unmasking effects hidden under normal gravity conditions or in terms of using gravity level as an added independent parameter?
2. Do the issues addressed by the research have the potential to close major gaps in the understanding of fundamentals of combustion processes?

3. Is there potential for elucidation of previously unknown phenomena?
4. Is the project likely to have significant benefits/applications to ground-based as well as space-based operations involving combustion processes?
5. Is the project technologically feasible, without requirements for substantial new technological advances?
6. What is the potential of this project in terms of stimulating future technological "spin-offs"?
7. Are there strong, well-defined linkages between the research and HEDS goals

The evaluation process for the upcoming NRA will begin with a scientific and technical external peer review of the submitted proposals. NASA will also conduct an internal engineering review of the potential hardware requirements for proposals that include flight experiments. The external peer review and internal engineering review panels will be coordinated by the NASA Enterprise Scientist for Microgravity Combustion Science. Consideration of the programmatic objectives of this NRA will be factored in by NASA to ensure enhancement of program breadth, balance, and diversity; NASA will also consider the cost of the proposal. The MRD Director will make the final selection based on science panel evaluations and programmatic recommendations. Upon completion of all deliberations, a selection statement will be released notifying each proposer of proposal selection or rejection. Offerers whose proposals are declined will have the opportunity for a verbal debriefing regarding the reasons for this decision. It is anticipated that the review process should be complete by mid-2000, with awards occurring in late 2000 (early Fiscal Year 2001).