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Combustion Research Aboard the ISS Utilizing the Combustion Integrated Rack and Microgravity Science Glovebox

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COMBUSTION RESEARCH ABOARD THE ISS UTILIZING THE COMBUSTION INTEGRATED RACK AND MICROGRAVITY SCIENCE GLOVEBOX

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ABSTRACT

The Physical Sciences Research Program of NASA sponsors a broad suite of peer-reviewed research investigating fundamental combustion phenomena and applied combustion research topics. This research is performed through both ground-based and on-orbit research capabilities. The International Space Station (ISS) and two facilities, the Combustion Integrated Rack and the Microgravity Science Glovebox, are key elements in the execution of microgravity combustion flight research planned for the foreseeable future.

This paper reviews the Microgravity Combustion Science research planned for the International Space Station implemented from 2003 through 2012. Examples of selected research topics, expected outcomes, and potential benefits will be provided.

This paper also summarizes a multi-user hardware development approach, recapping the progress made in preparing these research hardware systems. Within the description of this approach, an operational strategy is presented that illustrates how utilization of constrained ISS resources may be maximized dynamically to increase science through design decisions made during hardware development.

INTRODUCTION

The motivation for NASA's Microgravity (μg) Combustion Research Program grows from striving for a fundamental understanding of processes tied to daily activities on Earth. Over 85% of the U.S. energy supply relies on combustion methods. Power generation, home and office heating, personal and commercial transportation, and manufacturing all take advantage of combustion processes. Given this importance, improvements in combustion efficiency will have substantial economic and environmental impact. A complicating aspect of combustion research is the presence of transient behaviors of flames and their byproducts. Through the use of simplifying means, including those available through research in space, these complicating factors may be significantly reduced, and the research can be focused to better understand first order phenomena without the complexities of unsteadiness. (ref. 1)

MOTIVATION FOR RESEARCH

Although combustion research is conducted internationally, (ref. 2) NASA microgravity research in combustion focuses on problems that can be better understood in the absence of buoyancy-driven flows caused by gravity's effect on Earth. By using ground-based, suborbital, or orbiting platforms, a state of free-fall, described as "microgravity," (ref. 1) is available and can be used to minimize the effects of gravity on combustion processes. The NASA Office of Biological and Physical Research (OBPR) Physical Sciences Research Division has selected investigation topics and subtopics in fundamental research and focused applications. These investigations are conducted in an effort to unravel the mysteries of combustion by use of the unique environment provided via NASA's access to space.

Gravity, when used as a controlled parameter, plays a role as a revealing tool, not unlike varying temperature in a thermodynamics experiment. Yet, no matter how much is learned on the ground, there is work that can only be accomplished in the unique environment of space. In particular, a series of questions motivating the conduct of investigations on ISS have been captured: (ref. 3)

- What are the interactions between turbulence and combustion?
- What controls soot formation, agglomeration, and oxidation?
- What mechanisms control flammability limits, detonations, instabilities?
- What factors control material ignitability, smolder, flame spread?
- How do chemical kinetics and fluid dynamics couple in various scenarios?
- What controls boundary-layer interactions, acoustic-reaction feedbacks, and development of coherent structures in flames?
- How can the influences of thermophoresis, preferential diffusion, and electrical or magnetic field effects on combustion be understood and quantified?
- What are the quantitative effects of thermal radiation on various combustion processes?
- Can development of data bases for fundamental transport phenomena be populated?

RESEARCH PROGRAM STATUS

The first combustion experiment conducted in space occurred in 1974 aboard Skylab. (ref. 4) The Microgravity Combustion Science Program grew out of a need to better understand combustion processes that could occur in space. The program grew into a study of new flammability regimes of materials. The program is evolving from an investigator-idea driven mix of disparate research topics into research groupings addressing relevant areas of combustion science at large that only can be studied by the use of low-gravity facilities and access to space.

The program is being further focused as a result of necessity: solving key NASA problems in space exploration are linked to exploring regimes in material flammability phenomena and fire detection dealing with spacecraft fire safety. (ref. 5) This type of focused, applications-driven research is synergistic with the fundamental, knowledge-driven research that has been the staple of the μg Combustion Science Program for the last decade. The present suite of research, as defined by recent NASA Research Announcement (NRA) Principal Investigator (PI) selections, consists of 66 ground-based investigations and 21 flight-based investigations in combustion phenomena whose study is only achievable in a microgravity environment. Topical areas for combustion research presently cover the following breadth:

- Gaseous flames (diffusion, premixed, kinetics, suppression)
- Drops and Sprays (single drops, arrays, sooting drops, sprays, particles, dust clouds)
- Combustion Synthesis (nanoparticles, plasma synthesis, fullerenes, self-propagating high-temperature synthesis)
- Surface combustion (flame spread, flammability testing, smoldering, liquid pools, secondary fires)
- Miscellaneous areas (g-jitter, smoke detection, propellants, diagnostics, cold-boundary flames)

This work is chartered within the scope of the OBPR/Physical Sciences Research Division. Investigations are funded using a variety of grant and contract mechanisms with universities, various government agencies, and industry. Annual NASA Research Announcements solicit new research proposals that are peer-reviewed prior to selection and funding. (ref. 6)

Looking beyond the specific investigations, the biggest challenge facing this research discipline is that combustion has been so pervasive for so long in everyday life that people mistakenly believe it is well understood. But, the reality is that a substantial improvement in the quality of life in space or here on Earth requires improvement in the ability to predict and control combustion processes and products.

Ground Research

Research is solicited through the NRA process. This process results in a series of investigation selections addressing topics of interest to NASA and the combustion community. Typically, studies of four-year duration are funded, with results published in refereed journals in the discipline. Recently, focused research proposals in spacecraft fire safety have been funded. These investigations will contribute to decreasing the risk of fires and outcomes of fire events to crewmembers in orbiting and interplanetary vehicles.

Past Successes.—The ground-based component of the μg Combustion Research Program has grown from approximately 20 investigations in 1990 to over 60 PIs in 2002, developing into a robust program that has attracted the leading investigators in the field. The μg combustion ground-based investigators constitute a dominant user community for the NASA ground-based low gravity facilities (drop towers and aircraft).

The results from the ground-based program have already influenced the fire safety practices on the ISS. New combustion textbooks routinely include results from the ground-based research program. The recognized success of the ground-based program has earned the μg Combustion Science discipline the role of a separate sub-discipline at combustion conferences and has spawned ground-based facilities in Japan, Germany, and Canada.

Transitions to Future Research Directions.—Many μg combustion research areas are in the infancy of their exploration. Products have been generated whose processes are not yet understood, nor can they be analytically modeled in a predictive sense within the current knowledge base of the discipline. A number of areas show promise for terrestrial and space-based benefits and may be considered for further exploration.

- Hydrogen research (fuel cells)
- High Pressure/ high temperature research (in-situ resource utilization, regenerative life support)
- Nanostructures and combustion synthesis (using gravity as a processing variable for development of new structural building blocks and components)
- Micro-scale combustors (high energy density power sources)

Flight Research

The flight research program for combustion research not only requires that investigations be selected through the NRA process, but that each PI faces additional peer review. This additional review ensures scientific quality and that access to the low gravity conditions of space for long duration is required. Subsequent to such peer review, commitment by NASA is made to develop flight system hardware for deployment on an appropriate research platform.

Past Successes.—The microgravity flight research program for combustion began collecting flight data in 1990 with one investigation in solid surface combustion. This investigation ultimately required ten Space Shuttle flight opportunities in middeck lockers to complete its test matrix. Since that first step 13 investigations have flown on 36 flight opportunities. Of these, 34 have achieved, and in many cases surpassed, their pre-established mission science objectives. The Space Shuttle platform was augmented using sounding rockets and Russia's space station Mir to conduct these investigations. However, this success rate can be improved upon.

Intermittent access to space and a need to develop unique research systems for each experiment produced an experimental throughput that, while generating significant results, could be increased. Completion of 13 investigations from 1990 to 1998 years yielded a scientific return of 1.4 PI/year. The time required to develop unique, PI-specific research systems and the availability of low gravity carriers (Shuttle, sounding rockets, etc.) limited throughput opportunities. Scientific research could have obtained additional flight data with a commensurate increase in published results with more access to the space environment.

TRANSITION TO ISS

In the late 1990's, NASA set out to build the International Space Station to enable more frequent access to space to conduct fundamental and applied research. Concurrently with the opportunity to use this new research platform, NASA chartered development of Facility-class systems to maximize utilization of on-orbit resources. (ref. 7)

About the same time, the µg Combustion Science Program had begun development of an experimental system to conduct two independent gaseous flame investigations. The Combustion Module system was developed and flown twice in 1997 aboard the Space Shuttle as a Spacelab double rack system. CM-1, as it is known, became a pathfinder in the development and deployment of a combustion facility for ISS. Some firsts of CM-1 include:

- Developed and deployed a Facility-class system within Spacelab /STS
- System was multi-user and demonstrated ISS-like features for diagnostics and system commonality
- Accommodated on-orbit exchange of multiple independent research investigations
- Designed for crew-tended in-flight maintenance
- Use of remote (ground) command and control, real-time mission decision-making

Subsequent to the immensely successful use of CM-1 in 1997 to conduct the science of two investigators, the system was upgraded for a reflight in the Shuttle's SpaceHab carrier as CM-2. The robustness of the Combustion Module system further allowed the addition of a third investigation not previously conceived at the time of development of CM-1: a new Commercial Space Center user conducting a water mist gaseous combustion experiment. (ref. 8) Lessons learned from the development of CM-1 and from integrating a third investigation after development of the core 'facility' have been applied to the development of the Combustion Integrated Rack (CIR) of the Fluids and Combustion Facility.

ISS Research Plans

As NASA enters the era of ISS operations, the µg Combustion Science Program is well positioned to take advantage of ISS and Facility-class assets to achieve its research objectives. A total of fourteen fundamental scientific and applications-based research experiment programs in combustion research have been selected through the NRA process and plan to be conducted aboard ISS. For example, research on liquid fuels (droplet) combustion seeks to obtain fundamental parameters of flame structure and extinction. Another droplet combustion investigation extends study into applications-focused areas of soot development and propagation (having application to terrestrial pollution issues). Such synergy throughout the discipline provides a level of excitement for what the ISS research results will provide to the combustion community at large, and to the more focused NASA community seeking solutions to technology issues. Some of the specific terrestrial and NASA-specific applications being addressed in the current flight program include:

- Spacecraft Fire Safety (supporting human exploration mission goals)
    - Prevention of material ignition and fire propagation (of solid materials)
    - Fire detection and suppression

- Studies in combustion efficiency and pollutant minimization
    - Efficient burner technology design guidance (for gaseous fuels)
    - Soot development, and elimination (in liquid and gaseous fuels)

Figure 1 illustrates the plan for the upcoming decade of μg combustion research aboard the ISS. Two rack-level facilities are needed to accommodate this program plan: the Combustion Integrated Rack (CIR) and the Microgravity Science Glovebox (MSG). The CIR facility will be utilized to obtain results for droplet, solid, and gaseous fuels investigations requiring sophisticated gas-blending and diagnostics support. The MSG will conduct less complex investigations requiring a more benign environment and fewer diagnostics than provided by the CIR. It will also be host to a particularly important study in the effectiveness of smoke detectors to appropriately trigger in the event of a fire on a spacecraft, yet not provide false-positive nuisance indications.

Ultimately, the combined capability of CIR and MSG will allow the discipline to conduct 12 planned investigations in the next 5 years (at a rate of 2.4 PI/year). It is anticipated that the utilization rate of research after the initial 5 years will increase, as the ISS will have entered its operational phase after completing its assembly phase.

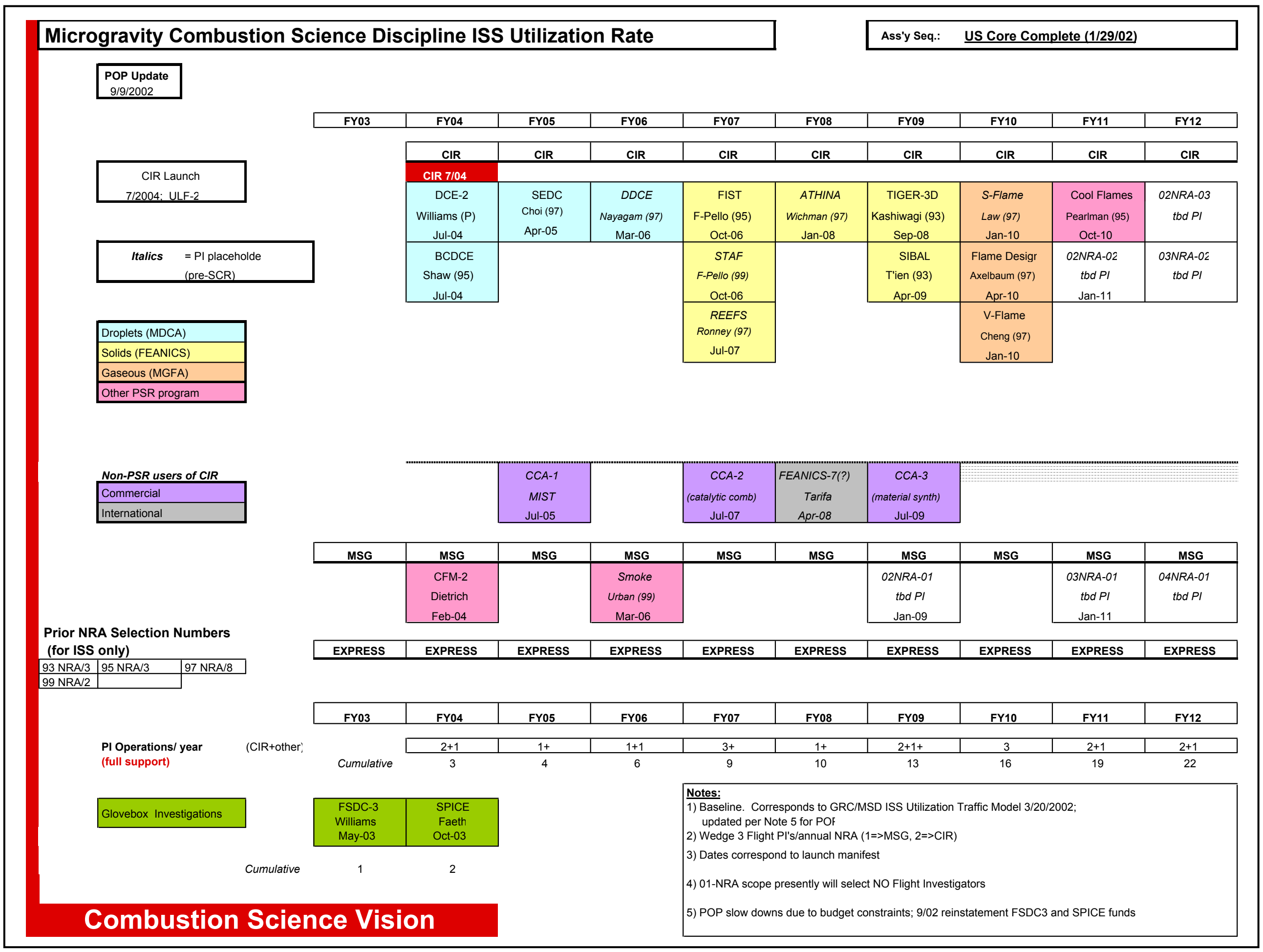

Figure 1. Combustion Research on ISS.

ACHIEVING RESULTS

Two elements are required for a successful Microgravity Combustion Research Program: a cadre of high quality researchers and frequent access to low gravity environments to conduct experimentation. The research community is present, and has demonstrated its impact to the combustion science community at large through the ground-based research program. Flight hardware systems are being developed to carry forward with the second element.

Enabling Hardware

With a transition from a typical 12 day shuttle research mission to a permanently operated research platform such as ISS, the characteristic of research opportunities changes. Both increased frequency of space research access and increased sophistication of experimental capabilities are anticipated in this new era.

International Space Station Opportunities.—In 2001, the Destiny module (U.S. Laboratory) was added as a key research capability to the permanently occupied International Space Station (ISS).

To take advantage of the unique environment provided by access to space, a complement of hardware and operational systems must be developed to perform an investigation. Since its inception, the μg Combustion Science Program has developed a variety of systems to conduct both sub-orbital and on-orbit research. A class of hardware, deemed Facility-class, is of particular interest as the transition to the ISS era is made.

Facility-Class Science.—ISS opens up a new frontier for research. A substantial increase in on-orbit operational time and other resources enable more expeditious implementation of research than previously possible. To appropriately exploit this opportunity, a Facility-class approach to deploying reusable research capabilities has been taken. Once deployed, a research rack can be outfitted with investigation-specific hardware to allow unique experimentation. Upon completion, the facility system can be reconfigured and reused with a minimal of changes, and do so while remaining on-orbit.

The μg Combustion Science Program intends to take full advantage of the deployment of two Facility-class systems to conduct combustion research over the next decade. The Microgravity Science Glovebox and the Combustion Integrated Rack will become the workhorses for combustion research aboard the ISS.

Microgravity Science Glovebox (MSG)

The MSG is a double containment sealed laboratory with gloveport access to a volume of 260 liters for conducting crew-interactive experiments. (ref. 9) It provides video, power, thermal control, vacuum vent, analog and digital data downlink, experiment commanding and telemetry, facility manipulation (lights, fans, air flow), and support for crew-operated and remote experiment and facility operations. MSG was launched to the ISS in June 2002 and is currently operational.

Four combustion science investigators are slated to operate within the MSG by 2006. Two investigate fundamental combustion science issues in liquid fuels combustion (Fiber Supported Droplet Combustion) and solid/liquid fuel transitions (Candle Flames). Two are applications-based, studying soot generation in gaseous flames and smoke detector performance in low gravity conditions (Smoke Point in Coflow Experiment and Smoke, respectively).

Combustion Integrated Rack (CIR)

The CIR is a Facility-class rack developed to conduct combustion experiments aboard the ISS. The CIR is part of the Fluids and Combustion Facility (FCF), a multi-rack system sharing many common subsystems. (ref. 7) The CIR will be launched to ISS on a Shuttle flight designated as ULF-2, with launch currently slated for July, 2004.

Deployment of CIR inaugurates a single on-orbit capability to conduct a wide-range of combustion experiments in a safely contained environment, with maximum reuse of common systems such as the combustion chamber, combustion science imaging, gas supply systems, and diagnostics. Efficiency is gained through the one-time deployment of the core infrastructure, thereby minimizing upmass, crewtime and checkout processes. The end result is a capability to conduct more research, more frequently than in the previous space shuttle era.

Figure 2 illustrates the concept employed of a multi-tiered solution to hardware deployment to the ISS. Requirements for launch upmass are significantly decreased by launching the FCF core racks once, and supplying multi-user and PI-specific hardware only as needed to support utilization and operations.

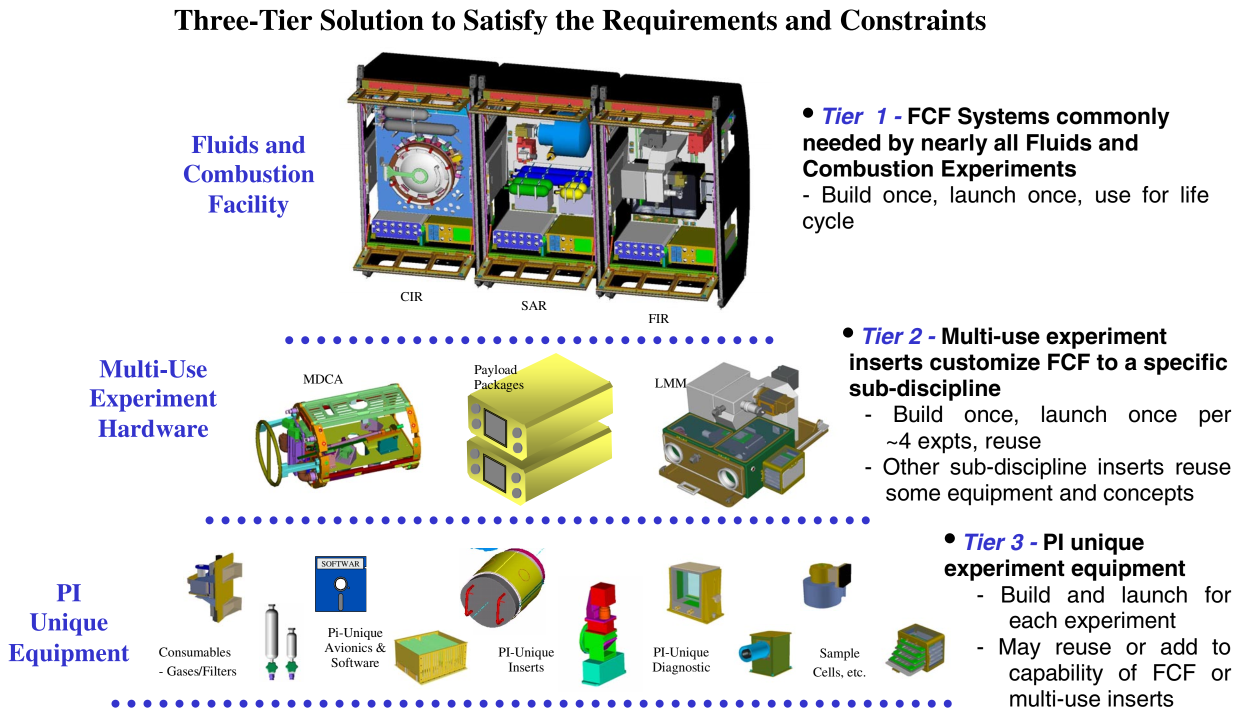

Figure 2. ISS FCF Facility System Partitioning.

The first use of CIR will occur in 2004 once on-orbit checkouts are complete. The initial set of combustion investigations to be conducted study fuel droplets. The Multi-user Droplet Combustion Apparatus (MDCA) will provide tier-two support to conduct the four investigations. Studies include structure and extinction of droplet flames, self-generated mixing flows within burning bi-component fuels, soot generation of fuel droplets, and droplet combustion in slow air-flows. (ref. 8) These four investigations address both fundamental and applications-based research areas within the μg Combustion Science discipline, and all benefit greatly from the symmetry made available as a result of access to space.

Utilization of CIR

Presently, fourteen investigations have been selected to conduct combustion science experiments in a logically grouped fashion within the CIR utilizing four multi-user systems by 2011. Additional participation by commercial and international partners will increase the CIR utilization through conduct of at least four additional investigations in that timeframe. It is anticipated that future investigators will be selected whose investigation will utilize existing multi-user system capabilities.

There are four tier-two Combustion Science Program systems being developed for the CIR: (ref. 10)

- Multi-user Droplet Combustion Apparatus (MDCA) for liquids and sprays
- Flow Enclosure for Novel Investigations in Combustion of Solids (FEANICS) for solid fuels and fire safety investigations (two systems)
- Multi-user Gaseous Fuels Apparatus (MGFA) for non-pre-mixed gases (NOX emission and combustion efficiency studies)

The multi-user insert concept approach develops as much of the tier-two common system as possible. The hardware teams and investigators identify the CIR capabilities that will meet the sub-field requirements. Then a set of common requirements and hardware are identified that meet the grouped investigators' needs, thus becoming the heart of tier-two capabilities. Then small PI-specific development efforts will be put in place for tier-three to address any requirements not met with common hardware.

An additional benefit to the use of the Facility-class and multi-user system development approach is the ability to implement desired enhancements—"desirements"—to the investigation during experiment development. Doing so allows investigators to have their science peer reviewed at a level which ensures adequately justifiable science is planned to achieve success, but still entertain possibilities to operationally obtain significantly more science in flight. Through use of ISS resources released late, such as upmass, as launch nears, the experiment project team can provide additional fuel samples and/or gas bottles for quick integration to take advantage of opportunities. Such operational flexibility becomes a cornerstone to the use of ISS and Facility-class systems to conduct research in space.

Synergy with other organizations

A significant feature of the ISS combustion research capability, as currently structured, is that the Combustion Integrated Rack is being made available to other users beyond those identified from within the Physical Sciences Research Program. In fact, partnerships are already being established to enable U.S. Commercial Space Center (ref. 8), European, and Japanese utilization of the CIR for investigations of their choosing.

μg COMBUSTION SCIENCE PLANS

The era of Microgravity Combustion Science research is in transition with plans to use the ISS as host. Two investigations remain to be completed aboard the space shuttle, on the STS-107 flight, using the CM-2 system. The remaining complement of selected flight combustion research is slated for the ISS.

Vision—10 years from now

The μg Combustion Science Program, as part of the Physical Science Research activities of NASA, is prepared to move forward in a cohesive fashion to tackle challenging problems confronting the combustion research discipline at large. This effort is directed at solving problems of significance to both NASA and to the scientific community, ultimately to benefit life here on Earth and enable exploration beyond Earth's influence.

Two specific goals of the μg Combustion Science Program address this vision. In ten years, NASA Combustion Science research results will have helped to achieve the following:

– The probability of accidental fire in spacecraft will have been significantly reduced because of an improved understanding of fire risks developed from ISS experiments.
– Knowledge gained through microgravity combustion research will have contributed to the terrestrial improvements to energy conversion efficiency and decreased environmental emissions, and to terrestrial and space transportation/ propulsion systems effectiveness.

SUMMARY

The Microgravity Combustion Science Program has planned, and is prepared to execute, a set of research investigations aboard the International Space Station. Use of multi-user and Facility-class systems provide an opportunity for a doubling of on-orbit research throughput from that achieved prior to the ISS era. Upcoming investigations will provide insights to fundamental and applied research topics of interest to NASA and to the combustion research community at large.

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