

FLEX: A DECISIVE STEP FORWARD IN NASA'S COMBUSTION RESEARCH PROGRAM

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Stemming from the need to prevent, detect and suppress on-board spacecraft fires, the NASA microgravity combustion research program has grown to include fundamental research. From early experiment, we have known that flames behave differently in microgravity, and this environment would provide an ideal laboratory for refining many of the long held principals of combustion science. A microgravity environment can provide direct observation of phenomena that cannot be observed on Earth. Through the years, from precursor work performed in drop towers leading to experiments on the International Space Station (ISS), discoveries have been made about the nature of combustion in low gravity environments. These discoveries have uncovered new phenomena and shed a light on many of the fundamental phenomena that drive combustion processes. This paper discusses the NASA microgravity combustion research program taking place in the ISS Combustion Integrated Rack, its various current and planned experiments, and the early results from the Flame Extinguishment (FLEX) Experiment.

INTRODUCTION

NASA's microgravity combustion research program includes gaseous, liquid, and solid combustion. Most will be performed in the microgravity environment of the ISS. These experiments are generally accommodated in the Microgravity Science Glovebox (MSG), the Combustion Integrated Rack (CIR), and in other combustion facilities provided by and in collaboration with partner space agencies.

The first investigation in a series of ISS experiments to be operated in the CIR,¹ under the collective title of the Flame Extinguishment (FLEX) Experiments, has just completed nominal operations. The FLEX experiments are a group of investigations sharing the common and much studied droplet flame configuration. Each set of FLEX experiments has a specific theme, which encompasses a wide range of scientific objectives. The first of these, FLEX-1 (also referred to as MDCA/FLEX or just FLEX in the literature²), has completed the majority of its science matrix

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and is currently waiting for the final shipment of fuel reservoirs to complete its full mission. To date, the FLEX-1 experiment has provided an abundance of data that is undergoing analysis, the results of which are just starting to appear in conferences and publications. FLEX has two objectives for its primary scientific theme:

1. to provide a scientific basis for the appropriate selection of inert gaseous fire suppressants and
2. to better understand the fire safety implications of high O₂ reduced pressure environments commonly used for pre/post-breathing associated with Extra Vehicular Activities.

Analysis of the FLEX data will allow the development of rational design rules for fire suppression in exploration vehicles and habitats. The experiment enables the development and validation of detailed and reduced-order transport and chemistry models that are the foundation for real engine simulations. This will lead to the ability to design future terrestrial combustors to minimize pollutant emissions, utilize alternative fuel sources, and maximize fuel efficiency (i.e., to reduce the carbon footprint associated with hydrocarbon combustion).

The results of the FLEX experiments will also help evaluate the efficacy with which inert gases extinguish flames in low-gravity for spacecraft safety applications. These results will allow for further development of fire safety standards and detection/alarm systems for extraterrestrial spacecraft and habitats. FLEX will further lead to improvements in energy efficiency (reduced carbon footprint) and reduced pollutant formation for terrestrial application. Data collected will lead to better engine design, including those for alternative fuel sources (e.g., biofuels).

The NASA microgravity combustion research program, a part of the overarching Physical Science Program, is currently operating the follow-on FLEX-2 Experiment in the CIR. FLEX-2 continues to study pure fuels to examine the steady and unsteady liquid and gas-phase phenomena, flame extinction, soot formation mechanisms and radiative heat transfer. FLEX-2 begins the study of practical fuels by burning bi-component and surrogate fuels. Beyond FLEX-2, the program will complete two international experiments, the FLEX-2J investigation, in collaboration between NASA and the Japanese Space Agency, JAXA, and the Italian Combustion Experiment for Green Air (ICE-GA), in collaboration with the Italian Space Agency, ASI. Following the liquid fuel FLEX series, NASA plans to study gaseous flames and solid materials combustion. The current program is planning its operations through the end of 2019, with proposed investigations that can extend to 2021. A description of the program details follow.

This paper is intended to document the NASA ISS combustion program taking place via the Combustion Integrated Rack in the Fluids and Combustion Facility. It represents the state of the program at the time of the writing of this paper and its possible future path. This paper does not include detailed science results or models. The project scientists and principal investigators will publish that information in peer-reviewed journal articles and at science conferences. However, this paper serves as a reference for those science papers and for information of the program to the general community.

NASA PHYSICAL SCIENCES PROGRAM

The NASA Physical Sciences Program, based at NASA Headquarters in Washington D. C., is under the auspices of the Space Life and Physical Sciences Research and Applications (SLPSRA) Division. This division within the Human Exploration and Operations Mission Directorate oversees multiple activities in the agency: research and applications activities, physical sciences, space life sciences, human research, and crew health and safety. The goals of the research and application activities of the division are to lower risks to crew and to develop technologies that will allow humans to travel safely and productively beyond Earth. As most of the work of the

SLPSRA Division is realized on the orbiting laboratory of the International Space Station (ISS), the objectives of the work involve determining the effects of the absence of terrestrial gravity on systems of interest. These objectives include reducing risks of long duration space exploration and the specific purposes of basic and applied science research in life and physical sciences.

NASA's Physical Science Research Program, together with its predecessors, has significantly improved space systems and produced new innovations that have terrestrial and space applications. NASA's experiments in various disciplines of physical science reveal how physical systems respond to the near absence of gravity. They reveal how other forces, that on Earth are small compared to gravity, can dominate system behavior in space. For example, in the area of combustion research, terrestrial measurements of flammability limits are hampered by gravity-induced convection and instabilities. The near absence of gravity on the ISS simplifies the measurements and the modeling of systems from the experimental data.

This program encompasses basic and applied research in multiple areas: fluid physics, combustion science, materials science, complex fluids, and fundamental physics. NASA's Physical Sciences Research Program is conducted at the Glenn Research Center (GRC), the Jet Propulsion Laboratory (JPL) and the Marshall Space Flight Center (MSFC).

COMBUSTION PROGRAM

Goals

The entirety of the ISS combustion science effort within the physical sciences program is done at the NASA John H. Glenn Research Center at Lewis Field, Cleveland, Ohio. The GRC ISS and Human Health Office develops experiments that utilize the ISS as a test bed for technology development in support of human exploration in the areas of life support and human health countermeasures, power, propulsion, thermal management, etc., and conducts fundamental microgravity research in the physical sciences. In support of these goals, this office manages projects in combustion science, fluid physics, and materials science, including those investigations related to spacecraft fire safety; solid, liquid and gaseous combustion; supercritical reacting fluids; and soot formation. The GRC Combustion and Reacting Systems Branch Project Scientists, who work closely with Project Managers and Principal Investigators, determine science requirements and lead the science validation and on-orbit operations efforts. Contracted engineering teams or in-house civil servant engineering teams perform the development of the flight and ground hardware and software.

The GRC combustion experiments are conducted in either the Microgravity Science Glovebox (MSG)* or the Combustion Integrated Rack. The MSG is one of the major dedicated science facilities inside the Destiny module. It has a large front window and built-in gloves to provide a sealed environment for conducting science and technology experiments and for handling hazardous materials. The MSG is managed out of MSFC.

GRC ISS experiments that have or will be operated on ISS within the MSG are the Smoke Aerosol Measurement Experiment (SAME), the follow-on SAME-R investigation, the Smoke Point in Coflow Experiment (SPICE), the Structure and Liftoff In Combustion Experiment (SLICE), and the Burning and Suppression of Solids (BASS). For more details of these experiments, visit the GRC ISS website.†

* <http://msglovebox.msfc.nasa.gov/capabilities.html>

† <http://issresearchproject.grc.nasa.gov/MSG/>.

The Combustion Integrated Rack (CIR) is one of two racks that make up the Fluids and Combustion Facility (FCF). The FCF, designed and built at the NASA Glenn Research Center, was developed to accommodate combustion and fluid physics experiments in microgravity and to provide services and capabilities comparable to those found in traditional Earth-based laboratories. The CIR is used to perform combustion experiments in microgravity, and is designed to be easily reconfigured on-orbit to accommodate a wide variety of combustion experiments.

Table 1. CIR Combustion Experiments Alignment to Decadal Survey 2011

Recommendation Identifier	Recommendation	Enabled by (EB) and/or Enabling (E) Space Exploration
AP6	Fire safety research to improve methods for screening materials for flammability and fire suppression in space environments.	E
AP7	Combustion processes research, including reduced-gravity experiments with longer durations, larger scales, new fuels, and practical aerospace materials relevant to future missions	EB/E
AP8	Research on numerical simulation of combustion to develop and validate detailed single phase and multiphase combustion models for interpreting and facilitating combustion experiments and tests	EB/E

Current and planned CIR experiments are the Flame Extinguishment (FLEX) experiment, the follow-on FLEX-2 experiment, the Japanese Space Agency’s modification to the FLEX-2 experiment, called FLEX-2J, the Italian Combustion Experiment for Green Air (ICE-GA), the Advanced Combustion via Microgravity Experiments (ACME), and Flammability Assessment of Materials for Exploration (FLAME). These experiments align with and satisfy the research recommended by the National Research Council of the National Academies in their report “Recapturing a Future for Space Exploration,” otherwise known as the Decadal Survey (2011). Table 1 shows the NRC recommended research in the area of Applied Physical Sciences³ in Space that are enabled by exploration and/or enable exploration by their accomplishment.

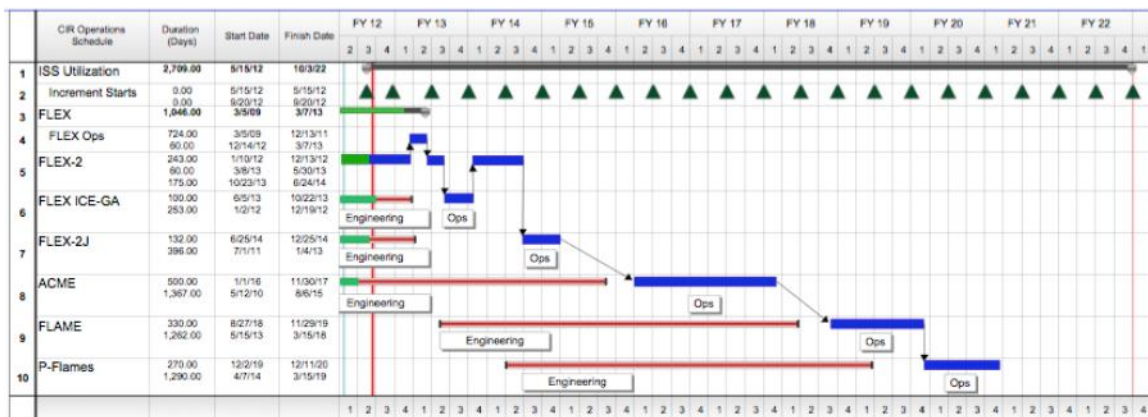


Figure 1. The CIR Utilization Schedule

The ISS combustion program will fully utilize the CIR through 2020 with two exceptions. Currently a gap in the CIR utilization exists in 2015. Efforts are currently being worked to fill the gap in 2015 with additional droplet combustion experiments in the MDCA. Another gap exists for about 8 months in 2018, however this gap could be filled with additional ACME testing. Figure 1 shows the current engineering and operations schedule for the CIR through 2020.

The FLEX investigation has obtained data that will become the benchmark for textbooks and the standard for droplet combustion research for the foreseeable future. FLEX to date has obtained 276 single fuel droplet combustion tests in 225 unique test conditions involving different fuels, oxygen/diluent concentrations, and ambient pressures. FLEX is currently in hiatus while waiting for the last four fuel reservoirs of n-heptane and methanol to be launched to ISS. In the meantime, FLEX-2 has started its tests from its science matrix. While waiting for the final FLEX tests to resume, the FLEX Science Team continues to analyze the data obtained from past experiments. A synopsis of the FLEX results and a discussion of some phenomena not predicted by existing models are presented.

Hardware Systems

The CIR is designed to support microgravity combustion science experiments on-board ISS. The CIR incorporates an optics bench, fuel and oxidizer management assembly (including gas supply systems), exhaust vent system, facility-provided combustion science diagnostics, power supplies, air and water thermal control subsystems, command and data handling avionics, a Space Acceleration Measurement System and various FCF common hardware and software items. CIR specifically provides a 100-liter combustion chamber with eight optical windows with easily reconfigurable diagnostics, digital cameras and lighting with large data storage capability, gas distribution/cleanup, passive vibration isolation, and vacuum resources. These support a wide range of gravity-dependent gaseous, liquid and solid combustion experiments. A gas chromatograph was planned to be included, but has not been completed. This diagnostic instrument is to launch in 2013.

Investigation-specific equipment can be installed on-orbit in the CIR to customize it to perform many different combustion science experiments (See Figures 2, 3, and 4). This equipment will include an experiment insert that is installed in the combustion chamber for each investigation. It contains experiment-unique combustion science diagnostics,

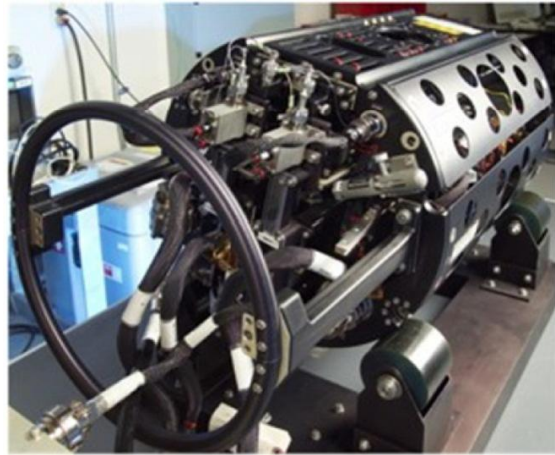


Figure 2. The Multi-user Droplet Combustion Apparatus (MDCA) prior to launch.



Figure 3. NASA astronaut Nicole Stott, Expedition 20 flight engineer, works with the Combustion Integrated Rack (CIR) in the Destiny laboratory of the International Space Station. (ISS020-E-042203, 26 Sept 2009)

avionics, and software for a modular experiment computer that controls experiment equipment in the rack. The combustion chamber insert may include equipment such as a sample holder or burner, solid or liquid fuels, ignition source, flow duct, small diagnostics such as radiometers and experiment-specific instrumentation such as thermocouples. The project supplies consumable items such as solid and liquid fuels, exhaust vent filters, and oxidizer and diluent gases.

For the FLEX series of experiments, the cylindrical-combustion chamber insert is called the Multi-user Droplet Combustion Apparatus. The MDCA is a multi-user facility designed to accommodate different droplet combustion science experiments. It consists of a Chamber Insert Assembly (CIA), an Avionics Package, and a multiple array of diagnostics. Its modular approach permits on-orbit changes for accommodating different fuels, fuel flow rates, soot sampling mechanisms, and varying droplet support and translation mechanisms to accommodate multiple investigations. Unique diagnostic measurement capabilities for each investigation are provided. Combustible fuel droplets of varying sizes, freely deployed or supported by a tether, are planned for study using the MDCA. Such research supports how liquid fuel droplets ignite, spread, and extinguish under quiescent microgravity conditions.



Figure 4: Expedition 18 commander Michael Fincke in the Destiny module of the ISS next to CIR (NASA Image: ISS018E18365)

TSC and Operations

NASA Glenn Research Center's Telescience Support Center (TSC)* allows researchers on Earth to operate experiments onboard the International Space Station (ISS). The TSC enables payload developers and scientists to monitor and control their experiments. The quality of scientific and engineering data is enhanced while the long-term operational costs of experiments are reduced because principal investigators and engineering teams can operate their payloads from their home institutions. Moreover, the TSC is a secure, multipurpose facility designed to provide dedicated support for simultaneous training, simulations, and real-time operations of space experiments. The current configuration consists of the Payload Operations Center, the Communication and Network Support Room, the TSC Operations and Support Room, and a visitors viewing area that provides access on a noninterference basis. Secure, dedicated audio, video, and data interfaces are provided to payload teams, including a digital stream of two channels of video from the ISS and the ability to communicate directly with the ISS crew. Hardware and software provide the ability to send commands to payload hardware and to receive feedback via telemetry data and video links.

Pre-mission planning and post-mission debriefing support is provided for all payloads. The TSC staff begins planning for support of a payload up to 18 months prior to the start of operations, depending on the complexity of the payload's operational requirements. Payload developers (i.e., the project engineering team) plan the operations, such as mission timeline

* <http://issresearchproject.grc.nasa.gov/TSC/>

development, resource planning, simulations, and training from the TSC. The TSC staff trains all the payload operations teams prior to mission operations. Training is tailored to each payload and covers all aspects of operations.

In addition to 5000 ft² (465 m²) for conducting payload operations, the TSC is a communications and data center. The TSC provides secure digital audio links with the ISS Huntsville Operations Support Center. Audio systems at the TSC provide 45 separate digital channels for payload developers to communicate with the various groups working to support ISS operations. All data, voice, and video resources are available for each payload at its respective console workstation. Workstations and unique audio channels are configured for each payload team according to the team's needs so that the team can receive specific data from their flight hardware on orbit.

The TSC provides at least two workstations for each payload and can manage dozens of terabytes of downlinked data from payloads. Real-time video is networked to the TSC, allowing payload developers to view ISS video. The video displays crew members interacting with experiments on orbit and can include images of experiment execution. The TSC can receive two of the four ISS video channels simultaneously, and can route video directly to the payload developer's console position, on the basis of the developer's requirements. All systems are monitored by the sustaining engineering staff daily and by automated systems around the clock. Short- and long-term storage of scientific and engineering data and access to a public Web site containing processed data is provided. Technical support can be provided to operation sites outside Glenn when requested.

CIR EXPERIMENTS

The MDCA/FLEX Experiment

The first of the FLEX series of experiments is known as MDCA/FLEX, FLEX-1, or simply FLEX. The MDCA insert to the CIR and the FLEX experiment were developed simultaneously and are intertwined in engineering and nomenclature. The purpose of FLEX is to use the MDCA modular apparatus to study methods to suppress and extinguish fires on-board space vehicles and habitats. As a side benefit, data collected of the combustion of single fuel droplets in microgravity are yielding valuable insights to our fundamental understanding of combustion.⁴

The results of the FLEX investigation will allow the development of rational design rules for fire suppression in exploration vehicles and habitats, based on the unique hazards of space. By assessing and quantifying the effectiveness of inert gas suppressants in microgravity, the PI science team obtains the most conservative estimate of the limiting oxygen index for steady combustion, the least amount of oxygen that will sustain combustion. The investigation will study the behavior of near-limit diffusion flames, examining in detail liquid- and gas-phase transport and chemical kinetics.

Background and Precursor Experiments. From its inception, NASA GRC has studied combustion to enable and advance aeropropulsion technology. Since the Apollo 1 tragedy, NASA GRC has been involved in flame research in crew habitats and in microgravity environments. Previous fuel droplet combustion experiments in microgravity significantly increased our understanding of the fundamental nature of combustion. Removing the effects of gravity-generated buoyancy in flames reduced the number of factors and has illuminated more subtle effects of combustion and flame transport. More recent investigations have used the unique platforms of the Space Shuttle and International Space Station as long duration microgravity laboratories. In the past decade, several seminal investigations have provided significant and groundbreaking findings, and have paved the way for the FLEX series of investigations.

The STS-83 mission had planned to carry the Droplet Combustion Experiment (DCE) and the Combustion Module-1 (CM-1) Facility. Unfortunately, this mission was cut short due to a problem with a fuel cell and returned to earth after only a few days in orbit. Approximately 3 months later, a reflight of the experiments was realized on the STS-94 mission. The Droplet Combustion Experiment (DCE) was designed to investigate the fundamental combustion aspects of single, isolated droplets under different pressures and ambient oxygen concentrations for a range of droplet sizes varying between 2 millimeters (0.079 in) and 5 millimeters (0.20 in). The DCE apparatus was integrated into a single width Microgravity Science Laboratory (MSL) Spacelab rack in the cargo bay.^{5,6}

The DCE experiments, which were carried out during the MSL mission in Spacelab, burned n-heptane droplets in helium-oxygen test gases and identified three regimes of droplet combustion. Droplets burned for as long as 20 seconds, not possible in Earth-bound facilities. The first regime was the quasi-steady regime, a fairly well documented regime in which the droplets and flames decrease linearly with time until extinction. The extinction size can be related to the chemical kinetics of combustion. A much less well-documented regime (flame radiation) occurred when sufficiently large droplets and low oxygen levels were used. Extinction occurred soon after ignition because of the large radiation heat losses from the flames. Finally, another less well-documented regime (droplet disappearance) occurred when oxygen levels were sufficiently high. A flame would persist for a short time after the droplet had completely vaporized and would extinguish at a nonzero flame radius. This regime leaves behind a small vapor cloud that might be responsible for combustion inefficiencies in practical combustion systems. Professor Forman A. Williams of the University of California, San Diego, and Professor Frederick L. Dryer of Princeton University served as the principal investigator and co-investigator, respectively, for the DCE experiments.

The Combustion Module-1 (CM-1) facility housed experiments on Laminar Soot Processes Experiment and the Structure of Flame Balls at Low Lewis-number Experiment (SOFBALL). Study of the data from the Laminar Soot Processes (LSP) experiment quickly resulted in discovery of a new mechanism of flame extinction caused by radiation of soot, a solid byproduct of the combustion of hydrocarbon fuels.⁷ Scientists found that the flames emit soot sooner than expected. These findings have direct impact on spacecraft fire safety, as well as the theories predicting the formation of soot. This is a major factor as a pollutant and in the spread of unwanted fires. The experiment was performed using a laminar jet diffusion flame, which is created by simply flowing fuel (like ethylene or propane) through a nozzle and igniting it, much like a butane cigarette lighter. The LSP principal investigator was Professor Gerard Faeth, University of Michigan, Ann Arbor. LSP results led to a reflight for extended investigations on the STS-107 research mission in January 2003.

The Structure Of Flame Balls At Low Lewis-number (SOFBALL) experiment⁸ was to study weakly burning flames in hydrogen-oxygen-inert and methane-oxygen-inert mixtures in a configuration called "flame balls." These structures were originally predicted in 1944 but were not seen experimentally until 1984 when they were observed in short-duration drop tower experiments. Because flame balls are steady, convection-free, spherically symmetric, and occur in fuels with simple chemistry, they represent the simplest possible interaction of chemistry and transport in flames. The later FLEX investigation used simple fuels, methanol and n-heptane, to simplify the flame chemistry and transport.

A total of 39 SOFBALL tests were performed in 15 different mixtures, resulting in a total of 55 flame balls. The total burn time for all flames was 6 1/4 hours. Because flame balls are extremely sensitive to gravitational acceleration, all tests were conducted during orbiter free drift

periods, i.e., time blocks where the small attitude control thrusters are not used. Microgravity levels (low frequency to quasi-DC) were measured using the Orbital Acceleration Research Experiment (OARE).

The SOFBALL experiment resulted in several accomplishments. One result was the creation of the weakest flames ever burned, either in space or on the ground. The weakest flame balls produced about 0.5 watts of thermal power. By comparison a birthday candle produces about 50 watts of thermal power. Another result was the creation of the leanest flames ever burned, either in space or on the ground. The leanest hydrogen-air test points burned contained about 8 percent of the chemically balanced mixture. By comparison, the lean limit for gasoline-air mixtures in an internal combustion engine is about 70 percent of the chemically balanced mixture. An additional milestone was the creation of the longest-lived flame ever burned in space (81 minutes). Several totally new results were found, one of which was the creation of oscillating flame balls that were predicted theoretically by Prof. John Buckmaster at the University of Illinois and Dr. Guy Joulin of CNRS in Poitiers, France, but were never observed experimentally until this experiment.

FLEX-Specific Goals and Objectives. The work cited above and other investigations have shown that microgravity combustion, whether a smoldering or flaming fire, has a unique nature and thus operates differently than terrestrial combustion. Fire safety for orbiting and deep space manned mission will be of prime importance as external assistance will not be possible. The first line of defense in a fire safety policy is fire prevention through material selection and control. Experience has shown; however, that control is not sufficient to prevent fires on spacecraft. Flammable materials exist, by necessity or convenience, and will likely be present in future spacecraft and habitats. Therefore, fire detection and suppression systems are required in the event a fire does occur.

The FLEX experiment was designed to assess and quantify the effectiveness of inert-gas suppressants in microgravity and obtain the most conservative estimate of the limiting oxygen index for steady combustion. FLEX studied the behavior of near-limit diffusion flames examining in detail liquid- and gas-phase transport and chemical kinetics, and developed and validated detailed and reduced-order transport and chemistry models that are the foundation for real engine simulations.

Application to Fire Safety. Because flammable materials will exist in future spacecraft and habitats, fire detection and suppression systems will be key in preventing loss of crew and habitat. However, fires in reduced gravity function differently than on Earth. The absence of large gravity forces means the reduction of related material transport processes such as buoyancy, convection, and thermal gradient transport. Forces that are smaller than gravity, that were minimal or negligible, now have larger influence on systems of interest.

For example, by-products of combustion in microgravity, e.g., soot aggregates, tend to be much larger in size than on Earth. Thus, smoke detectors designed for terrestrial use are generally useless in space habitats. The lack of convection to move combustion by-products from the fire to a detector means that a fire might go undetected for a significant amount of time. Lack of early detection may lead to the fire growing larger and more dangerous before it can be discovered. Flame characteristics including, but not limited to, heat release rates, luminosity, flammability limits, particulate formation rates, etc., are all different in reduced gravity. Therefore, understanding combustion processes and by-products are extremely important to protect crew and facilities in space.

Utilization to date. The FLEX experiment was flown to the ISS in November of 2008 along with the CIR and MDCA hardware. FLEX test points were started May 2009, the first test points

essentially being engineering tests of the FLEX system, although the data was sufficient to be considered good science test points. FLEX tests in the early months were widely spaced as the ground crew was characterizing the FLEX system, they were learning how best to operate the tests from the GRC TSC, and the FLEX tests were subject to ISS operations schedules. Once the experiment was included in the On-orbit Operations Summary (OOS), beginning with Increments 23-24, more powered-rack time was made available for operating the experiment. Various issues occurred that has caused the operations to be halted during the operations of FLEX; however, these issues were resolved over time and the main FLEX sequence of tests were concluded in December 2011.

A few lingering elements of the science matrix were not completed by December 2011 when the last of the on-orbit fuels were depleted. Four supplementary reservoirs, two n-heptane and two methanol, will be flown on HTV-3 to support final FLEX tests in November 2012 through January 2013. In addition, a CIR manifold gas bottle will be flown containing 40 percent oxygen and 60 percent xenon to use with some of the n-heptane and methanol tests. The xenon will augment the helium tests by including another inert suppression gas.

Nominal Operations. The FLEX experiments were conducted in the MDCA. The MDCA is a cylindrical-combustion chamber within the CIR, and has a free-volume of approximately 95 liters. The fuel droplets are freely deployed via a fuel deployment needle and syringe system calibrated to provide droplets of a chosen size. For some FLEX tests, a fine silicon carbide filament is used to fix the position of the fuel droplets. Two symmetrically positioned hot-wire igniters are brought into proximity to the free-floating or fixed droplet to ignite the fuel. The diagnostic suite included a black-and-white, backlit droplet image-capture camera; a UV-sensitive flame-imaging camera; and a CCD color camera with a wider view angle. All of the camera images, captured at 30 frames per second, were digitally stored on-board the CIR and downlinked at a later time for analysis. The color camera has real-time downlink capability and was used to conduct experiment operations from the ground at the TSC at NASA GRC.

Prior to an experiment run, the combustion chamber is filled with the desired ambient gas mixture, consisting of oxygen, nitrogen, and sometimes carbon dioxide, at a selected pressure. Future FLEX experiments in late 2012 will use xenon as a diluent. Typically, several droplets are burned before the chamber atmosphere is vented into space and refilled.

Test Matrix. The test matrix consists of various combinations of the prime parameters studied. These parameters are fuel type (n-heptane or methanol), atmospheric pressures (from approximately 0.7 atm to just over 3 atm), planned fuel droplet initial diameter (~2 mm, 3 mm, or 4 mm), and amount (mole fraction) of chamber gasses (mixtures of oxygen with helium, nitrogen, carbon dioxide, and/or xenon). The first nine “engineering” tests used cabin air rather than specified diluent gasses.

The FLEX experiments operate by ground command of the MDCA inside the Combustion Integrated Rack (CIR). The CIR allows for the accurate control of the ambient environment and provides the diagnostics, while the MDCA consists of the equipment necessary to dispense, deploy and ignite the free-floating liquid fuel droplet. For each test, the measured parameters are the droplet-burning rate used for model validation and the radiative and diffusive extinction limits⁹ used for extinguisher design. The tests involve studying the combustion characteristics (droplet burning rate, extinction droplet diameter, and flammability limits) of a single droplet in varied oxygen mole fraction ambient gas atmospheres with inert gas suppressants added.

To date, FLEX has obtained 276 single fuel droplet combustion tests in 225 unique test conditions involving different fuels, oxygen/diluent concentrations, and ambient pressures.

Analysis of the tests continues, but some global results are starting to be realized. The Principal Investigator for FLEX is Prof. Forman Williams of the University of California, San Diego. Co-Investigators are Prof. Frederick Dryer, Princeton; Prof. Mun Choi, University of Connecticut; Prof. Benjamin Shaw, USC-Davis; Prof. Thomas Avedisian, Cornell (FLEX-2); Dr. Vedha Nayagam, NCSER, and Michael Hicks, NASA GRC. The GRC Project Scientist is Dr. Daniel Dietrich.

Problems with Utilization. A significant amount of time that could have been used to operate the experiment was lost due to various reasons. The causes for these down times can be assessed as project related or externally related.

Project related down times were due initially to operational characterization of the MDCA and FLEX systems. FLEX is the first experiment to be run in the CIR and bore the brunt of initial startup difficulties. Other project related down times were due to loss and repair of various hardware and software items, such as Image Processing and Storage Unit (IPSU) software boot up parameters, igniters, silicon fibers, Diagnostic Control Modules (DCMs), fuel deployment needles, MDCA windows, and fiber optic cables. In addition, there were issues due to failed o-rings, fuel line priming, and foreign object debris (FOD) accumulation on the fuel deployment needle tips. The availability of on-orbit spares ameliorated the down time for some of the project related interruptions in operations.

Operations slowed, but were not fully discontinued, when it became evident that the radiometers were not capturing the illumination range of the burning fuel droplets. The radiometers were properly designed for the requirements, but the requirements were inadequate for the amount of light being given off by the flames in microgravity. Redesigned radiometers were flown and are now operating within the droplet illumination range. Some tests prior to the improved radiometers did not collect radiometric data.

Problems that were external to the project caused interruptions in the science acquisition. Such external stoppages were due to waiting for powered-on rack time; waiting for crew availability for fuel line inspections, silicon carbide (SiC) fiber installations, Active Rack Isolation System (ARIS) snubber* replacement, fuel reservoir replacement, and bayonet refitting; and waiting for STS docked operations completion.

Waiting for crew availability was an issue in so far as anytime a crew member was required to perform even the simplest maintenance, an Operations Change Request (OCR) would need to be submitted. Often, plans for crew activities were planned out three weeks in advance, so a request for crew time might take 3-4 weeks to be approved and implemented. Some regular maintenance, such as fuel reservoir or gas bottle replacements could be predicted, and the OCR was submitted at least three weeks in advance of the needed activity. Other activities, such as the reinsertion of a bayonet fitting along with some electrical reconnections took considerably more time, 73 days to be exact. This request did occur during the flurry of activity of the last of the shuttle flights, so ISS planners were more concerned with getting the last of the large cargo items on ISS. It was more a matter of unfortunate timing than a lack of concern for the science.

In all, operations were suspended due to external ISS related issues approximately 250 days. Down time due to project related issues were approximately 280 days. FLEX would not have operated all of those days because the OOS only scheduled the FLEX for about three powered-on days per week, on average. The FLEX experiment enjoyed over 390 days of uninterrupted operations, with powered-on operations about half of those days.

* A snubber is a mechanical restraint device designed to protect components from excess shock.

Table 2. Lessons Learned

Issue	Lessons Learned
1. The MDCA radiometer, while operating to design specification, did not provide useful data	<ul style="list-style-type: none"> • Careful review of derived requirements is needed to establish an instrument’s performance characteristics • Instrument performance validation needs to be conducted with flight-like test conditions
2. Debris formed on the fuel deployment needles; discovered to be from conformal coating materials not identified in the Materials Identification and Usage List	<ul style="list-style-type: none"> • Materials assessments must be conducted with a full understanding of all materials used in an assembly; assembly drawing bill of materials needs to include materials including coatings that are typically called out in drawing notes
3. Silicon carbide fibers on the Fiber Arm Assembly were broken in transportation packaging due to stacking.	<ul style="list-style-type: none"> • Create packaging that precludes encroachment upon or impingement of the fibers.
4. Design of solenoid valve bore caused o-ring to chaff resulting in sheared seal	<ul style="list-style-type: none"> • Future solenoid valve bores will be chamfered to prevent bayonet insert o-ring chaffing
5. An automatic software boot-up parameter file loader was created to eliminated the need to require crew time for a manual boot after file corruption, but the code was not loaded on ISS for implementation	<ul style="list-style-type: none"> • Time should be made to implement corrective actions so that issues do not repeat themselves
6. Several Diagnostic Control Modules (DCMs) have gone bad during the two years of operations, the cause of which is not fully known	<ul style="list-style-type: none"> • Designing critical components to be replaceable and having sufficient numbers of on-orbit spares for those critical items is a prudent plan

Corrective Actions and Lessons Learned. As with many projects, problems during operations arise and require some corrective action. By documenting the root cause, if discernable, and the corrective action taken, others may learn by the errors and oversights and perhaps avoid similar issues and problems. Table 2 outlines some of the major issues that slowed down the successful operations of the FLEX investigation and the lessons that were learned by the experience.

Results. FLEX is providing information on simple, single-component, spherically shaped fuel droplet combustion. The spherical shape reduces the combustion to a single radial dimension. To date, the FLEX experiment has achieved 276 single fuel droplet combustion tests in 225 unique test conditions involving different fuels, ambient pressures, and oxygen/diluent concentrations. Analysis of the FLEX data has provided droplet burning rates, flame stand-off ratios, and extinction diameters for varying concentrations of oxygen and diluents. These measurements have agreed reasonably well with simplified theoretical models as well as detailed numerical simulations for methanol fuel. For oxygen concentrations approximately below 14 percent, radiative extinction was found to occur rather than extinction caused by water absorption. At low oxygen concentrations, the burning rate constant deviated substantially from quasi-steady predictions showing that for concentrations below 14 percent only transient combustion leading to radiative flame extinction occurs.

The FLEX data has determined the Limiting Oxygen Index (LOI) for methanol and n-heptane fuels and conditions that will sustain combustion of the fuel droplet. Both radiative and diffusive extinction boundaries were determined experimentally and compared against numerical

simulations. The results show that microgravity conditions can sustain flaming combustion at a lower oxygen concentration than what is possible under normal gravity. Generalization of these results for other configurations and their implications for microgravity fire suppression is currently underway.

From the data,¹⁰ one can state that for quiescent flames (no air flow) that radiation is the predominant factor that determines how a flame will extinguish, not convection as on earth. The previous model that assumes that without convection a flame cannot be self-sustaining is incorrect. Flames in microgravity environments burn at lower temperature and their burning rates are lower (i.e., the amount of heat released through burning is less). Thus, in general, their flames are weaker. They burn at lower oxygen levels, as much as 2-3 percent less oxygen, and are harder to detect, harder to extinguish, and are more persistent. Terrestrially-based fire suppression protocols are insufficient on their own for application in space; and protocols for spacecraft and space habitat fire safety will need to be much more rigorous.

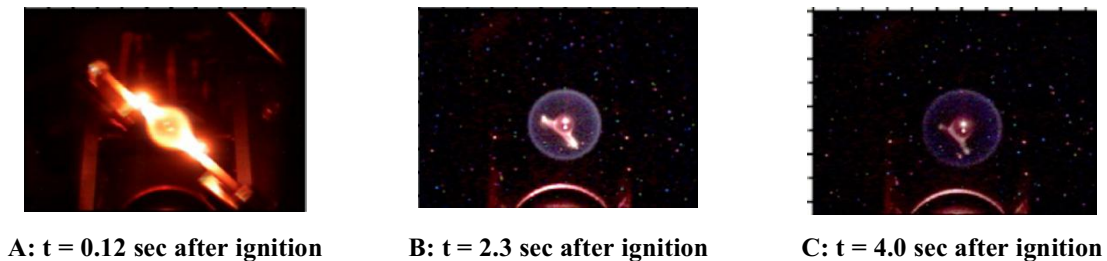


Figure 5. Liquid n-heptane fuel droplet ignition and combustion sequence.

FLEX provided some surprises. During the FLEX n-heptane combustion tests, an anomalous burning behavior was observed. It was noted that for larger n-heptane droplets, the normal sequence of ignition, transient burn, and radiative flame extinction occurred. However, after the visible flame extinguished, a vigorous vaporization of the droplet continued. This phenomenon cannot be adequately explained by conventional theories of droplet combustion. After careful and detailed consideration, the science team has concluded that the event is a unique observation of second-stage vaporization sustained by a low-temperature, soot-free, chemical reaction, referred to as a “cool flame.”¹¹ This phenomenon was not expected in the design of the experiment, nor would cool flames be expected in this configuration or in quasi-steady, non-premixed flames. This shows the importance of low temperature chemistry, different from the “hot” combustion extensively studied thus far by many researchers. This has very significant theoretical and practical implications. For instance, engine knock, predominantly in diesel engines, is a cool flame pre-ignition of the fuel that reduces the compression ratio and lowers the thermal efficiency of the engine. Better understanding of cool combustion could improve engine cycle efficiency, improving mileage and decreasing costs (See Figure 5).

If this second stage combustion is indeed “cool combustion,” this could indicate an increased risk of fires in microgravity space habitats as the cool combustion persists after hot-flame extinction. Safety procedures based only on considerations of hot flames may be inadequate for assuring safety under all conditions. Under certain conditions, it may be possible that a cool flame could reignite in the hot mode, essentially restarting the fire that the crew had thought to be extinguished. Most of the practical hydrocarbon fuels currently in use, such as gasoline, diesel, and aviation fuels, all have a straight-chained alkane as one of their components. Any improvement in better understanding of their chemistry will lead to improvements in their burning efficiency as well as in reduction in the pollutants they produce. It is hoped that the present observation of quasi-steady diffusion-flame combustion supported by “cool flame”

chemistry will improve the current chemical kinetic models that are used worldwide in designing combustors. For further information on FLEX, please visit the GRC Physical Science Research Program website.*

The FLEX-2 Experiment

The second in the FLEX series of experiments is FLEX-2. FLEX-2 uses fuels and environmental conditions that mimic real combustor conditions. The investigation will extend and advance the research into droplet combustion, studying the influence of sub-buoyant convective flows on combustion rates, determining the influence of a second burning droplet on a linear array, and beginning the study of practical fuels by burning bi-component and surrogate fuels. As the research extends into increasingly complex fuels, FLEX-2 data can help verify models of real fuels used in transportation and industry. Results of the FLEX-2 experimental data will help to develop verified detailed and reduced-order models of droplet combustion, particularly with flow-field and droplet-droplet interactions.

FLEX-2 uses the MDCA insert in the CIR, using the same diagnostic packages with the addition of a second High Bit Depth/Multispectral Imaging Package (HiBMS) camera. Crossed silicon carbide (SiC) fiber arrays will be flown to allow for pinning droplets at multiple locations for studying the interaction of combusting droplets. Approximately 400 test point conditions will be attempted using various fuels, droplet sizes, ambient pressures, oxygen percentages, types of gas diluents, droplet spacing, and in some cases translation velocities. The diluent gasses are nitrogen and helium. The FLEX-2 fuels are pure n-decane, ethanol, propylbenzene, and toluene, and mixtures of heptane-hexadecane, propanol-glycerol, decane-propylbenzene, and n-heptane-toluene.

FLEX-2 operations started in January 2012 and are expected to be complete by July 2014. FLEX-2 operations will be interrupted on two occasions. The first occasion is to allow for the completion of the MDCA/FLEX investigation in November 2012. The second occasion is in June 2013 to allow the Italian Combustion Experiment for Green Air (ICE-GA) to operate during Increments 35-36 when an astronaut from the Italian Space Agency (ASI) will be on-board ISS and can monitor the Italian experiment. For further information on FLEX-2, please visit the GRC Physical Science Research Program website.†

The Italian Combustion Experiment for Green Air (ICE-GA) Experiment

An international agreement is in formulation to fly surrogate fuels as defined by the Italian Space Agency (ASI) within the CIR in the FLEX-2 configuration. The bilateral agreement would allow U.S. and Italian scientists from the Italian National Research Council–Istituto Motori to collaborate on research into biologically derived fuels (bio-fuels) in an investigation into new, green energy sources. The U.S. would provide two fuel reservoirs, check-gas bottles, and other, various FLEX-2 supporting hardware. Researchers from the National Research Council–Istituto Motori have identified the fuels to be used as 50–50 mixtures of n-heptane/ethanol and 50–50 n-hexanol/n-decane.

The intent of ICE-GA is to investigate the ignition and combustion of a single droplet of a surrogate bio-fuel in a quiescent microgravity environment. The research will dispense, deploy and ignite single droplets and study the droplet and flame regression histories, in a well-controlled (and variable) ambient environment. The results of the research will provide

* <http://issresearchproject.grc.nasa.gov/Investigations/FLEX/>.

† <http://issresearchproject.grc.nasa.gov/Investigations/FLEX-2/>.

benchmark data that will assist in the development and validation of models of bio-fuel combustion. Phenomena such as finite-rate gas-phase chemistry, multicomponent-species gas- and liquid-phase transport processes, production of soot and other pollutants, phase-change processes, liquid-phase species separation and fluid motion, and radiation and conductive energy transfer, are all present in microgravity droplet combustion. These examples determine, to varying degrees, the performance of a practical combustor. The metrics, for comparison, include burning rate, burning time, soot aggregate size, extinction diameter, flame diameter, and flame luminosity.

ICE-GA is planned to operate during ISS Increments 35-36, June–November 2013. The FLEX-2 experiment will stand down during this period. This is approximately at the halfway point for FLEX-2. This hiatus will not only permit the operation of ICE-GA, but will give the FLEX-2 science team time to assess the results to date and to make some alterations in experiment conditions to provide improved results for subsequent tests.

The FLEX-2 JAXA (FLEX-2J) Experiment

The FLEX-2J experiment is a joint effort between NASA and the Japanese Space Agency, JAXA, as well as Nihon University and Yamaguchi University. Derived from the JAXA Group Combustion Experiment (GCE) science objectives, the FLEX-2J will complement the goals of GCE using the NASA FLEX-2 hardware and combustion facilities on ISS.

FLEX-2J will observe and measure fuel droplet motions during flame spreading along a one-dimensional droplet array. Three droplets will be deployed to fixed positions upon ceramic beads on a SiC fiber. Then an additional three to ten movable droplets are positioned to the fiber at known locations. The first fixed droplet is ignited and the flame is propagated down the array from droplet to droplet. The subsequent burning and motions of the unpinned droplets are recorded; particularly the velocities of the free droplets before and after flame spread are measured. In addition, the experiment will obtain the history of flame leading edge position, flame spread limit span, and the growth process of the group flame along the fuel droplet array. Specifically, the experiment will measure burning rate, burning time, flame spread and droplet motion as a function of inter-droplet spacing, ambient pressure and gas composition.

The FLEX-2J experiment will employ FLEX-2 hardware in the CIR. Hardware specific to FLEX-2J that will need to be procured or manufactured and sent to ISS are a SiC fiber kit containing six beaded fibers (supplied by JAXA), two pairs of igniter tips, two n-heptane fuel reservoirs, two CIR manifold bottles for diluent gasses, one pair of fuel deployment needles, and two adsorber cartridges.

FLEX-2J will operate in the last half of 2014, July through December. FLEX-2J is currently the last investigation planned to use the MDCA chamber insert and the final liquid fuel combustion experiment planned for the CIR. For further information on FLEX-2J, please visit the GRC Physical Science Research Program website *

Advanced Combustion via Microgravity Experiments (ACME)

ACME is the first gaseous combustion project planned to operate in the CIR. The ACME project is a suite of five independent experiments intended to extend our knowledge of combustion through fundamental research. Four of the five investigations address energy production and environmental concerns, the fifth experiment addresses spacecraft safety. The overall goals are to improve our understanding of materials flammability, combustion at lean fuel

* <http://issresearchproject.grc.nasa.gov/Investigations/FLEX-2J/>

conditions where both optimum performance and low emissions can be achieved, flame stability and extinction limits, soot control and reduction, oxygen-enriched combustion which could enable practical carbon sequestration and the use of electric fields for combustion control.¹²

With the exception of the Burning Rate Emulator (BRE) experiment discussed immediately below, the general goal of the current ACME experiments is to gain fundamental understanding that can enable improved efficiency and reduced emissions in practical combustion processes on Earth. For example, the data obtained from the ACME experiments could be used to develop and verify models for chemical kinetics and transport processes in computational simulations. In addition to enhanced performance, improved modeling capability can lead to reductions in the time and cost for combustor design. In summary, microgravity investigations of non-premixed flames could lead to eco-friendly combustion systems providing our nation with green power for the future. For further information on ACME, please visit the GRC Physical Science Research Program website.*

Burning Rate Emulator (BRE). Unlike the other experiments in the suite of ACME investigations, the Burning Rate Emulator (BRE) experiment is focused on fire prevention, especially in spacecraft. Specifically, BRE's objective is to improve our fundamental understanding of materials flammability, such as ignition and extinction behavior, and assess the relevance of existing flammability test methods for low and partial-gravity environments. A flat porous burner fed with gaseous fuel will simulate the burning of solid and liquid fuels. The fuel flow rate will be controlled based on the measured heat flux (at the burner) and surface temperature, mimicking the dependence of condensed-phase fuel vaporization on thermal feedback. A small number of gaseous fuels will be used to simulate the burning of fuels such as paper, plastic, and alcohol by matching properties such as the surface temperature and smoke production. (See Figure 6.)

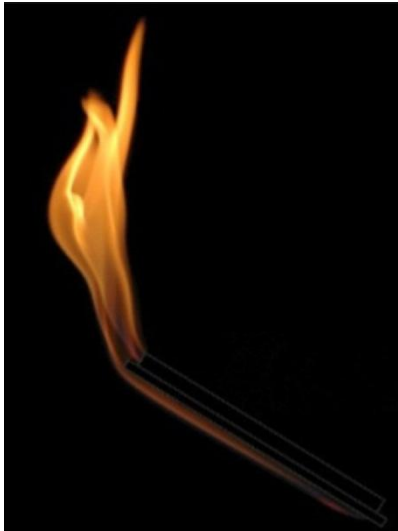


Figure 6. Image of a normal-gravity flame extending from a flat burner facing downward at an angle. In this conceptual test, a liquid fuel is being burned with a porous wicking burner.



Figure 7. Image of a lifted flame of 50% propylene in a co-flow of air (at ambient pressure) from an exploratory test conducted on the International Space Station in 2009 as part of the Smoke Point In Co-flow Experiment (SPICE).

* <http://issresearchproject.grc.nasa.gov/Investigations/ACME/>

Co-flow Laminar Diffusion Flame (CLD Flame). Research has revealed that our current predictive ability is significantly lacking for flames at the extremes of fuel dilution, namely for sooty pure-fuel flames and dilute flames that are near extinction. The general goal of the Co-flow Laminar Diffusion Flame (CLD Flame) experiment is to extend the range of flame conditions that can be accurately predicted by developing and experimentally verifying chemical kinetic and soot formation submodels. The dependence of normal co-flow flames on injection velocity and fuel dilution will be carefully examined for flames at both very dilute and highly sooting conditions. Measurements will be made of the structure of diluted methane and ethylene flames in an air co-flow. Lifted flames will be used as the basis for the research to avoid flame dependence on heat loss to the burner. The results of this experiment will be directly applicable to practical combustion issues such as turbulent combustion, ignition, flame stability, and more. (See Figure 7.)



Figure 8. Image of a gas-jet diffusion flame (in air at ambient pressure) from a test conducted in NASA's 2.2 Second Drop Tower. The flame is being forced downward by the electric field between the burner and an electrode mesh, which is at +2 kilovolts and is down-stream of the burner.

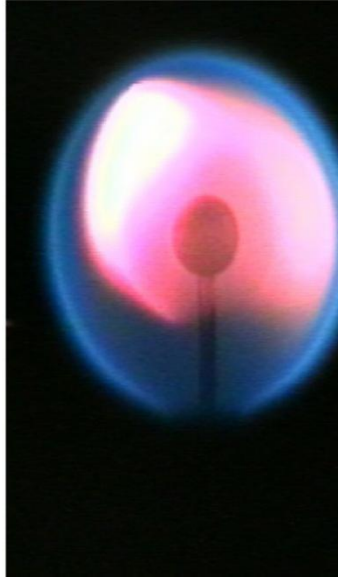


Figure 9. Image of a spherical diffusion flame on a porous burner (which is also visible) at the end of a test conducted in NASA's 2.2 Second Drop Tower. From the burner, there was 1.51 mg/s of 100% ethylene flowing into air at atmospheric pressure.

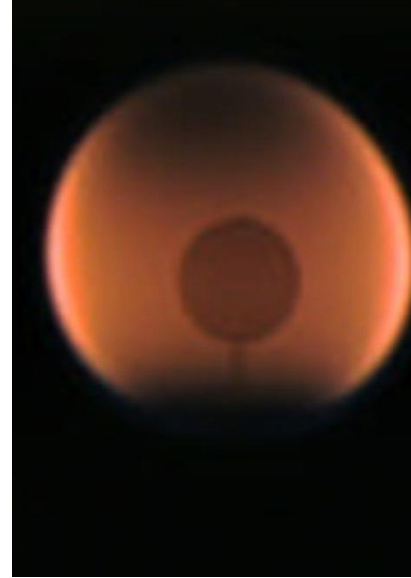


Figure 10. Image of a partially-premixed spherical flame on a porous burner (which is also visible). The microgravity test was conducted in a NASA drop facility. The gas issuing from the burner was 25% propane, 2% oxygen, 49% argon, and 24% nitrogen

Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames). Electric fields can strongly influence flames because of their effect on the ions present as a result of the combustion reactions. Direct transport of ions and the induced ion wind can modify the flame shape, alter the soot or flammability limits, direct heat transfer, and reduce pollutant emission. The purpose of the Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames) experiment is to gain an improved understanding of flame ion production and investigate how the ions can be used to control non-premixed flames. This investigation should significantly contribute to our critical understanding of combustion processes in the presence of electric fields. The experiment will be

conducted with a normal co-flow flame (as in the CLD Flame experiment) or perhaps with a simple gas-jet flame, where there is no surrounding co-flow. An electric field will be generated by creating a high voltage (up to 10 kV) differential between the burner and a flat circular mesh suspended above (i.e., downstream of) the burner. Measurements, as a function of field strength and fuel dilution, will be made of the ion current through the flame and the flame's response time to electric forcing. (See Figure 8.)

Flame Design. The primary goal of the Flame Design experiment is to improve our understanding of soot inception and control in order to enable the optimization of oxygen enriched combustion and the “design” of non-premixed flames that are both robust and soot free. Flame Design could lead to greatly improved burner designs that are efficient and less polluting than current designs. Flame Design will investigate the soot inception and extinction limits of spherical microgravity flames, created in the same manner as for the s-Flame experiment. Tests will be conducted with various concentrations of both the injected fuel (i.e., ethylene or methane) and an oxygen-enriched atmosphere in order to determine the role of the flame structure on soot inception. The effect of the flow direction on soot formation will be assessed with an inverse spherical flame. The flame center is oxygen, and the fuel is on the outside of the flame shell. In the case of the inverse flames, the oxygen/inert mixture is injected from a central tube, while the fuel is ejected from a surrounding annulus. The Flame Design experiment will explore whether the stoichiometric mixture fraction can characterize soot and flammability limits for non-premixed flames like the equivalence ratio serves as an indicator of those limits for premixed flames. (See Figure 9.)

Structure and Response of Spherical Diffusion Flames (s-Flame). The purpose of the Spherical Flame (s-Flame) experiment is to advance our ability to predict the structure and dynamics, including extinction, of both soot-free and sooty flames. The spherical flame, which is only possible in microgravity, will be created through use of a porous spherical burner from which a fuel/inert gas mixture will issue into the CIR chamber. Flames will be ignited at non-steady conditions and allowed to transition naturally toward extinction. Tests will be conducted with various inert diluents, in both the fuel and chamber atmosphere. The fuel gases include hydrogen and methane for soot-free flames, and ethylene for sooty flames. One experiment objective is to identify the extinction limits for both radiative and convective extinction. Another objective is to determine the existence, onset, and nature of pulsating instabilities that have been theoretically predicted to occur in such flames. (See Figure 10.)

Flammability Assessment of Materials for Exploration (FLAME)

FLAME is the first solid-materials combustion experiment planned to operate in the CIR. This suite of investigations is still in the preliminary (Pre-Phase A), planning stage. The types of investigations that can be accommodated range from material ignitability, fire growth and spread, and fire suppression. The experiments under the FLAME umbrella will study the ignitability and flammability of spacecraft materials in practical geometries and within realistic atmospheric conditions. Experiments could include ignition studies of materials representing cabin materials and EVA suit designs. Furthermore, the investigations could study the suppression of burning materials by diluents, airflow reductions, and habitat air venting.

Low-gravity testing has shown that current NASA material qualification methods may not be as conservative as they are believed to be. While NASA has a long history of materials controls, they are based on a 1-g understanding of flammable materials and the data from Earth-based tests. FLAME will improve our understanding of early fire growth behavior and help validate material

flammability numerical models for reduced gravity environments. For further information on FLAME, please visit the GRC Physical Science Research Program website.*

Other Investigations

Other possible investigations beyond FLAME are being considered. One such investigation, Premixed Flames (P-Flames), would focus research on the fundamental unit of combustion in practical engines, the premixed gas flame. Automobiles and turbines generally spray fuel into a combustion chamber that contains an oxidizer (often oxygen from air) and inert gasses. Combustion can occur via a spark or by the high pressures and temperatures in the chamber.

Lean fuels, that is, minimum amounts of fuel needed to produce combustion, are being studied to improve fuel efficiency and reduce the amounts of pollutants created, such as oxides of nitrogen and sulfur and carbon particulates (soot). Tens of thousands of tons of nitrogen oxides are released into the air in just the United States. These harmful pollutants cause, among other things, smog and acid rain, and are a major contributor to asthma. Soot particle pollution is responsible for 60,000 deaths per year in the U.S. Furthermore, concerns about damaging the Earth's ozone layer as a result of flying high-altitude, high-speed aircrafts have prompted the studies of lean premixed combustion in aircraft engines.

P-Flames would study the basic unit of combustion, the premixed gas combustion flame. In particular, the investigation would obtain accurate measurements of flame velocities and flames in a microgravity environment. It would determine the limits of flame combustion for fuel-lean mixtures. The results of this study would help to improve the fuel consumption by combustion engines, with significant benefits to automotive and aerospace industries. The use of leaner premixed flames in automobile and other engines would have a substantially positive environmental impact by reducing atmospheric emission of pollutants. Moreover, P-Flames will provide improvements in fire safety, both in space and by avoiding accidental explosions in such places as grain silos, flourmills, and coalmines.

SUMMARY

NASA's Physical Science Research Program, along with its predecessors, has conducted significant fundamental and applied research, both which have led to improved space systems and produced new products offering benefits on Earth. NASA's experiments in various disciplines of physical science reveal how physical systems respond to the near absence of gravity. They reveal how other forces that on Earth are small compared to gravity, can govern system behavior in space.

The ISS combustion research program, encompassing experiments in the MSG and CIR, is robust with multiple investigations ongoing and planned through the end of the decade. These investigations are aligned with and support the National Research Council's recommended research themes and priorities. Results from FLEX and FLEX-2 are being analyzed, and additional tests are yet to be accomplished. FLEX data will help to update current, quasi-steady combustion models, and have already shown that more rigorous safety protocols are needed as fires in microgravity are more persistent and dangerous than once thought. FLEX data will help to improve suppression methodologies that will fight fires in space, and perhaps here on Earth, without risking crew health.

* <http://issresearchproject.grc.nasa.gov/Investigations/FLAME/>

FLEX-2, FLEX-2J, and ICE-GA will continue the FLEX series and will obtain fundamental combustion knowledge that could lead to new designs for cleaner fuels that have a smaller carbon footprint and emit fewer pollutants, among other applications.

ACME will begin the fundamental study of gaseous combustion in the CIR, followed by solid and pre-mixed gaseous combustion studies.

While research continues on alternative energy sources, 85 percent of all energy in the U.S. (and similarly in other nations) is derived from some form of combustion and will be for the foreseeable future. The NASA ISS combustion program will help to find ways to augment and perhaps reduce the usage of petroleum-based fuels, create more efficient combustion models and engines, and reduce pollution and greenhouse gases, as well as make space a safe place to live and work.

NOMENCLATURE

ACME	Advanced Combustion via Microgravity Experiments
AVP	Avionics Package
BRE	Burning Rate Emulator
CIA	Chamber Insert Assembly
CIR	Combustion Integrated Rack
CLD Flame	Coflow Laminar Diffusion Flame
E-FIELD Flames	Electric-Field Effects on Laminar Diffusion Flames
FCF	Fluids and Combustion Facility
FLEX	Flame Extinguishment Experiment
GRC	Glenn Research Center
ISS	International Space Station
MDCA	Multi-User Droplet Combustion Facility
OOS	On-orbit Operations Summary
s-Flame	Structure and Response of Spherical Diffusion Flames
STS	Space Transportation System vehicle (i.e., the Space Shuttle)

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FLEX

A Decisive Step Forward in NASA's Combustion Research Program

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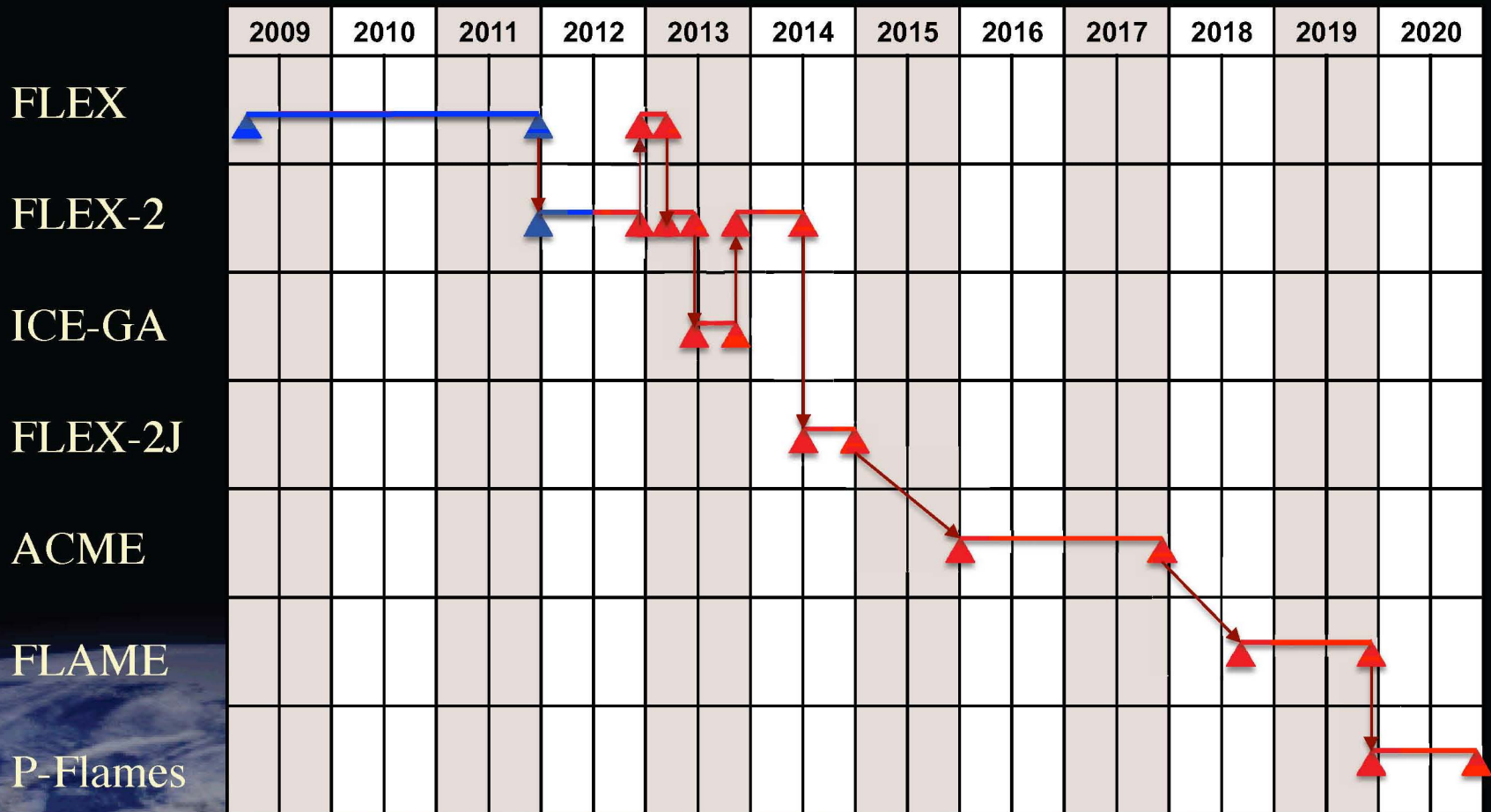


- NASA has performed space combustion research since the 1960's
 - Focus initially on spacecraft fire safety; later integrated fundamental combustion research
- Research in space is ideal for uncovering new phenomena and illuminating the principal phenomena that drive combustion processes
 - Eliminates buoyancy driven convection simplifying analysis and modeling
 - Early program used drop facilities, aircraft, and sub-orbital flights
 - Later program employed Skylab, Mir, and the Space Shuttle
 - ISS research has employed the Microgravity Science Glovebox (MSG) and the Combustion Integrated Rack (CIR)
- CIR launched to ISS in November 2008; started operations March 2009
 - CIR supports experiment inserts that carry specific investigations and suites of experiments
 - First CIR insert is MDCA; first experiment is FLEX
 - Future inserts will support gaseous, pre-mixed gaseous, and solid material combustion investigations



- CIR is a facility designed to support combustion research experiments on the ISS
- MDCA is a modular apparatus designed for fire suppression tests, liquid droplet flame extinguishment investigations, and fundamental combustion research experiments
 - MDCA supporting FLEX, FLEX-2, FLEX-2J, and ICE-GA, and possibly additional future liquid droplet combustion experiments







Science Objectives

- Map flammability boundaries for liquid fuel combustion in reduced gravity
- Quantify suppressant efficacy of gaseous suppressants over range of candidate habitable atmospheres (i.e., varying total pressures and O_2 concentrations)
- Develop predictive theoretical/numerical codes and refined chemical kinetic models to determine flammability boundaries in relevant space exploration environments
- Develop improved reduced order theoretical/numerical process specific sub-models that can be used to simulate realistic and/or large scale fires



Color image of a burning droplet



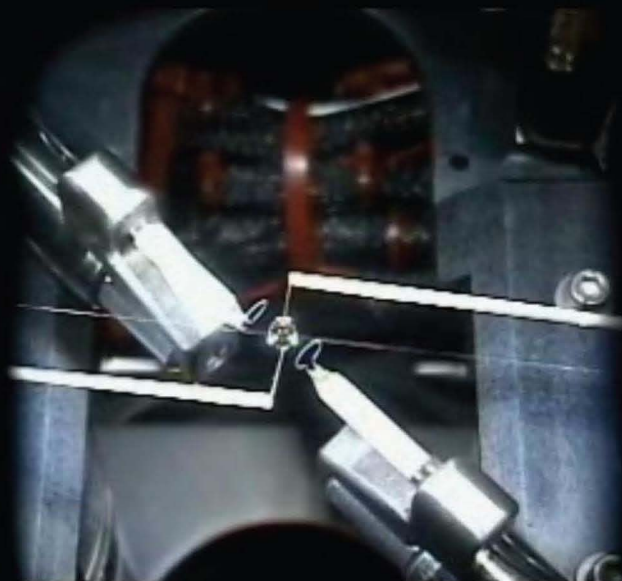
➤ Science objectives are

accomplished by carrying out a series of isolated, single droplet combustion experiments in microgravity over a wide range of parameter space (O_2 , suppressant, pressure, flow field, and droplet size)

➤ Diagnostics include droplet image, flame image, radiation measurements, soot volume fraction, and soot temperature

➤ Series of ground-based supporting experiments using smaller droplet sizes (2.2 and 5 second drop-towers)

➤ Theoretical and numerical models to analyze and interpret the data





Test Fuels

- A sooting alkane fuel (n-heptane, C_7H_{16}) and a non-sooting alcohol fuel (methanol, CH_3OH) are used in these experiments
- Both these fuels have been used extensively in the past (DCE-1, Fiber-Supported Droplet Combustion (FSDC), and Ground-based studies)
- Chemical kinetics are reasonably well understood
- Fuel stoichiometry and consequently, flame dynamics, are different and may impact extinction processes

Ambient Test Conditions

- Ambient environment is made up of O_2 , N_2 , and a suppressant gas (CO_2 , N_2 , or He)
- O_2 mole fraction ranges from 0.12 to 0.34
- Suppressant mole fraction ranges from 0 to 0.7
- For non-flow tests, gases are well-mixed and quiescent
- Ambient gas temperature is in the range $18^\circ C$ to $27^\circ C$
- Relative humidity is less than 10% for n-heptane tests and is less than 2% for methanol tests

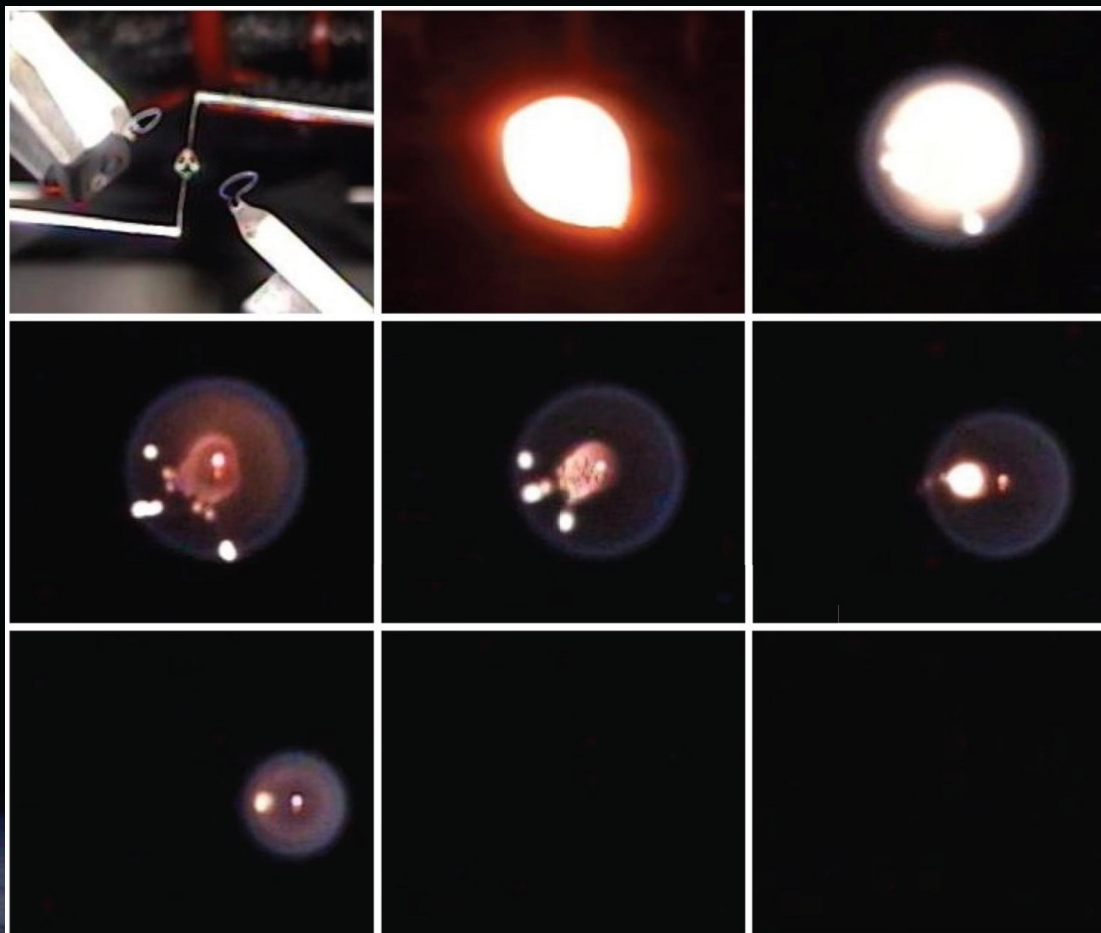


Images show n-heptane flame burning in air at 1 atm. Initial droplet diameter is 2.5 mm.

The first frame shows the droplet suspended on the needles just before deployment.

There is a substantial amount of soot produced initially which fades to a mostly blue flame.

The nearly stationary flame shrinks as it burns, producing a few small soot particles which stream away from the droplet. Eventually the flame goes out.

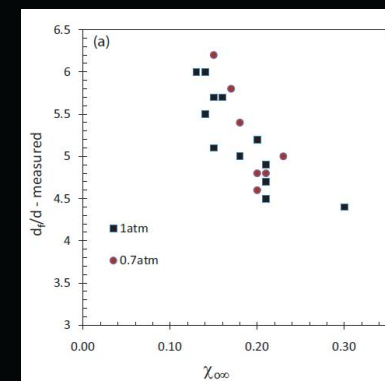


Frames are 1 sec. apart (progression from left to right and top to bottom).

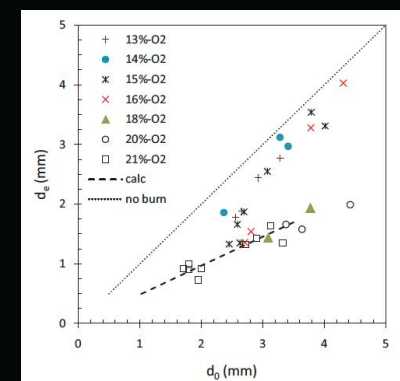
Each frame spans 36mm x 30 mm.



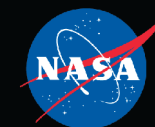
- Obtained 276 single fuel droplet combustion tests in 225 unique test conditions
- Determined Limiting Oxygen Index (LOI) for methanol and n-heptane that will sustain combustion of the fuel droplet
 - Results show that microgravity conditions can sustain flaming combustion at lower oxygen concentrations than in normal gravity
- FLEX measured droplet burning rates, flame stand-off ratios, and extinction diameters for varying concentrations of oxygen and diluents
 - Burning rates, flame standoff ratios, and extinction diameters agreed reasonably well with simplified theoretical models
 - For oxygen concentration approximately below 14%, radiative extinction was found to occur rather than extinction caused by water absorption
 - In microgravity, radiation determines flammability limits rather than convection
 - Burning rates lower, temperature lower, but burns at lower O_2 levels – flames weaker but more persistent
 - At very low oxygen concentrations in a high CO_2 ambient atmosphere the burning rate constant deviated substantially from the quasi-steady predictions
 - FLEX data will be instrumental in improving the current simplified models of burning rates



Flame stand-off ratio vs. ambient oxygen mole fraction



Extinction diameter as function of initial diameter at 1 atm pressure



- Observation of continued and vigorous vaporization of droplet after visible flame extinction
 - Unique observation of second-stage vaporization sustained by a low-temperature, soot-free, chemical reaction
 - Phenomenon not explained by conventional theories of droplet combustion
 - Speculating that event is low temperature chemical reaction – Cool Flame
 - Not expected in this configuration or in quasi-steady, non-premixed flames
- This represents a finding of a new chemistry different from the “hot” combustion studied heretofore
- This could indicate an increased risk of fires in microgravity space habitats as the cool combustion persists after hot-flame extinction
 - Safety procedures based only on considerations of hot flames may be inadequate for assuring safety under all conditions
 - More rigorous suppression may be needed
 - Under certain conditions, it may be possible that a cool flame could reignite in the hot mode, essentially restarting the fire that was thought to be extinguished



- FLEX experiments will allow the development and validation of detailed chemical kinetic mechanisms of n-heptane and methanol
 - Could lead to greater fuel efficiency and reduced pollution
 - Requires detailed knowledge (predictive) of combustion characteristics
 - Heptane relevant to combustion of gasoline
 - Methanol relevant as alternative fuel and sub-mechanism of ethanol combustion
 - Droplet combustion data validating chemical kinetic mechanisms used by gas turbine manufacturers
- Cool Flames data could lead to improved engine cycle thermal efficiencies
 - Eliminate double ignition from cool flame temperature chemistry transitioning to hot combustion – i.e., prevent Engine Knock
 - Could allow engines to run at higher compression ratios



- Initiated January 2012; anticipated to run until July 2014
- Further examine droplet combustion phenomena such as droplet-droplet interactions, fuel mixtures, and surrogate fuels
 - Study the influence of sub-buoyant convective flows on combustion rates
 - Determine the influence of a second burning droplet on a linear array
 - Begin the study of practical fuels by burning bi-component and surrogate fuels
 - *As the research extends into increasingly complex fuels, verify models of real fuels used in transportation and industry*
 - *Results of the FLEX-2 experimental data will help to develop verified detailed and reduced-order models of droplet combustion, particularly with flow-field and droplet-droplet interactions*
- Fuels, pure and mixed
 - n-decane, ethanol, heptane-hexadecane, propanol-glycerol, decane-propylbenzene mixtures, n-heptane-toluene mixtures, pure propylbenzene, and pure toluene

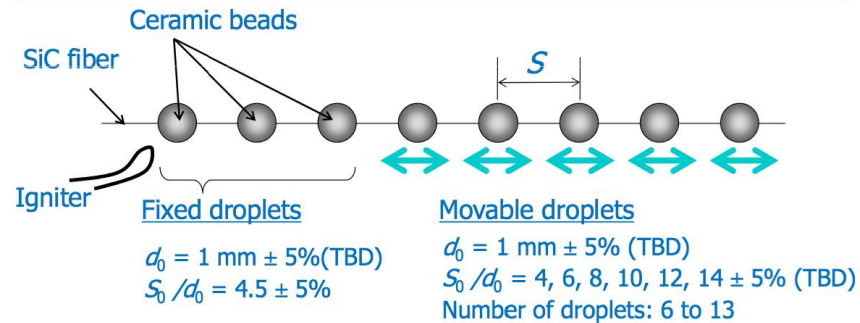


- International collaboration with Italian Space Agency, ASI
- Investigation of ignition and combustion of a surrogate bio-fuel
- Results will lead to development and validation of models of bio-fuel combustion, focusing on
 - Finite-rate gas-phase chemistry
 - Multi-component-species gas- and liquid-phase transport processes
 - Production of soot and other pollutants
 - Phase-change processes
 - Liquid-phase species separation and fluid motion
 - Radiation and conductive energy transfer
- Measurements of burning rate, burning time, soot aggregate-size, extinction diameter, and flame luminosity
- Flight fuels: 50%-50% mixtures of n-heptane/ethanol and 50%-50% n-hexanol/n-decane



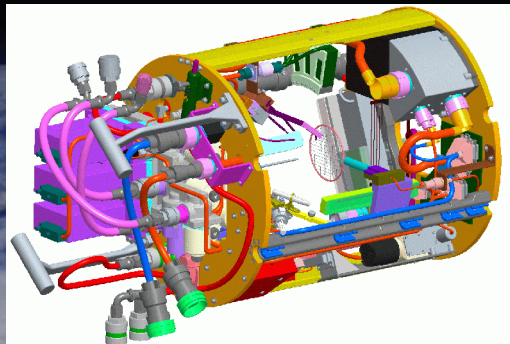
- International collaboration with Japan Aerospace Exploration Agency, JAXA
- Investigation of fuel droplet motions during flame spreading along a one-dimensional droplet array
 - Velocities of the free droplets before and after flame spread are measured
 - The experiment will obtain the history of flame leading edge position and flame spread limit span, as well as the growth process of the group flame along the fuel droplet array
 - The experiment will measure burning rate, burning time, flame spread and droplet motion as a function of inter-droplet spacing, ambient pressure and gas composition
 - Uses n-Heptane fuel

Flame is ignited at initial bead location and spread across the fixed bead site and to the free (moveable) droplet locations. Spacing and number of free droplets is varied through the test matrix





- Suite of 5 independent, fundamental gas combustion experiments
 - Burning Rate Emulator (BRE)
 - *Improve our fundamental understanding of materials flammability, such as ignition and extinction behavior, for prevention for solid materials fires using gas burning emulator*
 - Coflow Laminar Diffusion Flame (CLD Flame)
 - *Develop chemical kinetic and soot formation models for dilute and sooting conditions*
 - Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)
 - *Understand flame ion production and how ions can be used to control non-premixed flames*
 - Flame Design
 - *Improve understanding of soot inception and control for less polluting combustors*
 - Structure and Response of Spherical Diffusion Flames (s-Flame)
 - *Advance our ability to predict the structure and dynamics of soot-free and sooty flames*



Engineering concept of ACME Chamber Insert Assembly (left) and Color Camera Package (right)



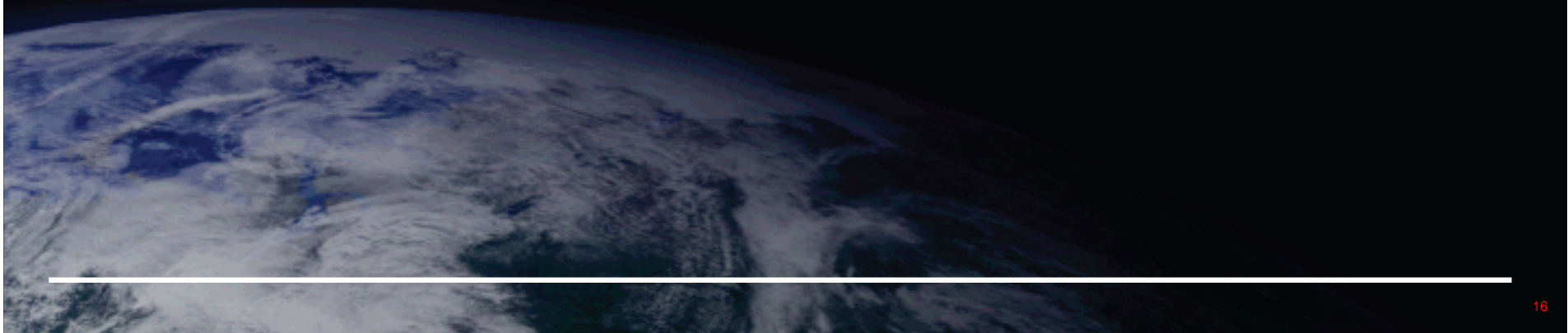


A [redacted]

- Suite of 5 independent, fundamental gas combustion experiments
 - **Burning Rate Emulator (BRE)**
 - *Improve our fundamental understanding of materials flammability, such as ignition and extinction behavior, for prevention for solid materials fires using gas burning emulator*



Image of a normal-gravity flame extending from a flat burner facing downward at an angle. In this conceptual test, a liquid fuel is being burned with a porous wicking burner.





A [redacted]

- Suite of 5 independent, fundamental gas combustion experiments
 - Coflow Laminar Diffusion Flame (CLD Flame)
 - *Develop chemical kinetic and soot formation models for dilute and sooting conditions*



Image of a lifted flame of 50% propylene in a coflow of air (at ambient pressure) from an exploratory test conducted on the International Space Station in 2009 as part of the Smoke Point In Coflow Experiment (SPICE).

- Generation of modified kinetic mechanisms for hydrocarbon fuels that are able to effectively model diffusion flame structure under a larger parameter range than existing mechanisms
- Development of submodels for soot formation that are capable of predicting both high and low soot loading levels in hydrocarbon flames of various fuels



A [redacted]

- Suite of 5 independent, fundamental gas combustion experiments
 - Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)
 - *Understand flame ion production and how ions can be used to control non-premixed flames*



Image of a gas-jet diffusion flame (in air at ambient pressure) from a test conducted in NASA's 2.2 Second Drop Tower. The flame is being forced downward by the electric field between the burner and an electrode mesh, which is at +2 kilovolts and is down-stream of the burner.

- *Controlling flames near operational limits can improve system performance substantially*
- *Characterizing flame behavior with ion current will improve performance of control system*
- *Maintaining flame stability will increase the time that combustion performance can be studied near extinction limits*



A [redacted]

- Suite of 5 independent, fundamental gas combustion experiments
 - Flame Design
 - *Improve understanding of soot inception and control for less polluting combustors*



Image of a spherical diffusion flame on a porous burner (which is also visible) at the end of a test conducted in NASA's 2.2 Second Drop Tower. From the burner, there was 1.51 mg/s of 100% ethylene flowing into air at atmospheric pressure.

- *Advances in separation technology may allow oxygen enrichment in large-scale combustors leading to permanently blue flames, opening unexplored opportunities in "flame design"*
- *Soot and NO_x control are critical to combustor design and they can be reduced by improved "flame design"*



A [redacted]

- Suite of 5 independent, fundamental gas combustion experiments
 - Structure and Response of Spherical Diffusion Flames (s-Flame)
 - *Advance our ability to predict the structure and dynamics of soot-free and sooty flames*

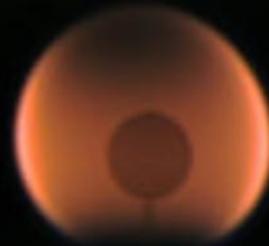


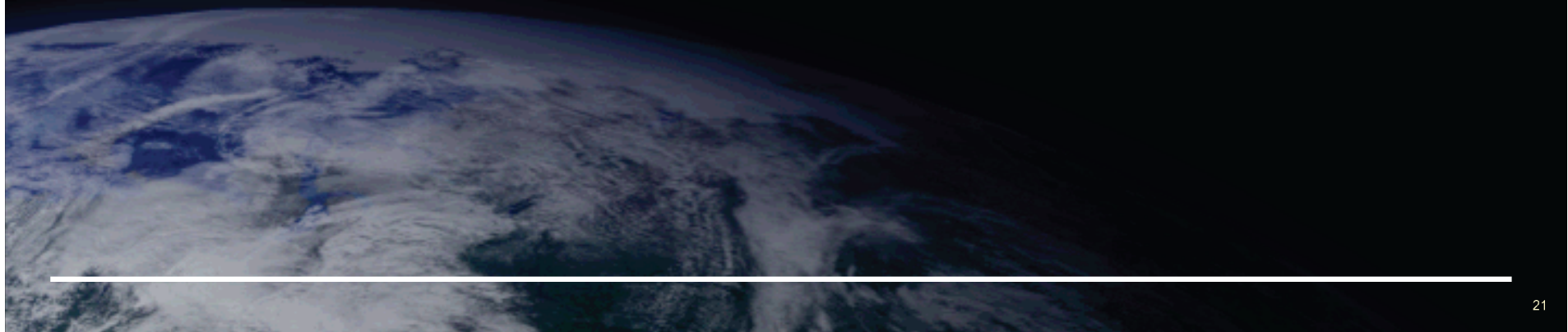
Image of a partially-premixed spherical flame on a porous burner (which is also visible). The microgravity test was conducted in a NASA drop facility. The gas issuing from the burner was 25% propane, 2% oxygen, 49% argon, and 24% nitrogen.

- Improved energy efficiency and emission reduction from practical combustion systems due to verified chemical kinetic and transport models in computational simulations
- Reduction of design costs due to improved ability to predict system performance numerically



A [redacted]

- Improve efficiency and reduce emissions in Earth-based combustion processes
 - Development and verification of models for chemical kinetics and transport processes in computational simulations
 - *Improved modeling capability can lead to reductions in the time and cost for combustor design*
 - Microgravity investigations of non-premixed flames could lead to eco-friendly combustion systems providing our nation with green power for the future





- **Flammability Assessment of Materials for Exploration (FLAME)**
 - First solid-materials combustion experiment planned to operate in the CIR
 - *This suite of investigations is still in the preliminary planning stage*
 - *The experiments under the FLAME umbrella will study the ignitability and flammability of spacecraft materials*
 - *Experiments could include ignition studies of materials representing cabin materials and EVA suit designs*
 - *Investigations could study the suppression of burning materials by diluents, airflow reductions, and habitat air venting*
 - FLAME will improve our understanding of early fire growth behavior and help validate material flammability numerical models for reduced gravity environments

- **Premixed Flames (P-Flames)**
 - Research focused on the fundamental unit of combustion in practical engines, the premixed gas flame
 - *Obtain measurements of flames and velocities in a microgravity environment*
 - *Determine the limits of flame combustion for fuel-lean mixtures*
 - *Improve the fuel consumption by combustion engines, with significant benefits to automotive and aerospace industries.*
 - Substantially improve emission of pollutants from automobile and other engines



- NASA's Combustion Science Program is robust and extends into the next decade
- FLEX has completed primary tests and is analyzing hundreds of data points
 - Early results show that μg conditions can sustain flaming combustion at lower O_2 concentrations than 1-g
 - Quasi-steady models require updating with FLEX data
 - Discovery of new Cool Flames chemistry
- Droplet combustion tests continue to 2015 with international collaboration
- Fundamental and applied combustion investigations will continue with gaseous, premixed gaseous flame, and solid materials combustion experiments
- Many new discoveries lie in wait