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Gaseous Non-Premixed Flame Research Planned for the International Space Station

Dennis P. Stocker[1,*], *Fumiaki Takahashi*[2], *J. Mark Hickman*[1], *and Andrew C. Suttles*[1]

[1]*NASA Glenn Research Center, Cleveland, Ohio 44135, USA*
[2]*Case Western Reserve University, Cleveland, Ohio 44106, USA*

Thus far, studies of gaseous diffusion flames on the International Space Station (ISS) have been limited to research conducted in the Microgravity Science Glovebox (MSG) in mid-2009 and early 2012. The research was performed with limited instrumentation, but novel techniques allowed for the determination of the soot temperature and volume fraction. Development is now underway for the next experiments of this type. The Advanced Combustion via Microgravity Experiments (ACME) project consists of five independent experiments that will be conducted with expanded instrumentation within the station's Combustion Integrated Rack (CIR). ACME's goals are to improve our understanding of flame stability and extinction limits, soot control and reduction, oxygen-enriched combustion which could enable practical carbon sequestration, combustion at fuel lean conditions where both optimum performance and low emissions can be achieved, the use of electric fields for combustion control, and materials flammability. The microgravity environment provides longer residence times and larger length scales, yielding a broad range of flame conditions which are beneficial for simplified analysis, e.g., of limit behavior where chemical kinetics are important. The detailed design of the modular ACME hardware, e.g., with exchangeable burners, is nearing completion, and it is expected that on-orbit testing will begin in 2016.

1. Introduction

Microgravity, i.e., apparent near weightlessness, is a unique environment for conducting combustion research. Many flames are dramatically influenced by the effective elimination of buoyant convection, where the resulting effects are often advantageous. For example, it is possible to create spherically symmetric flames enabling one-dimensional analysis. More generally, the effective elimination of flicker yields quasi-steady flames. Furthermore, the length scales are increased in microgravity flames facilitating analysis of the flame structure. Microgravity flames tend to have a much stronger sensitivity to their atmosphere than normal-gravity flames and exhibit a much broader range of characteristics. For example, the long residence times in microgravity flames can lead to strong soot production, but many microgravity flames are soot free. Even neglecting soot, microgravity flames can be appropriate for studies of limit and stability behavior where chemical kinetics are important. It is also possible to study momentum-dominated flames at low velocities. And of course, microgravity is the appropriate environment for studies related to spacecraft fire safety.

Although microgravity combustion research has been conducted in drop facilities and research aircraft flying parabolic maneuvers, spacecraft like the International Space Station (ISS) offer significant advantages. Drop durations, which are ~5 s or less in NASA facilities, are too short for soot to achieve quasi-steady conditions. The drop durations are also too short to first establish a flame and then vary its flow rate, for example, to investigate stability or extinction

*Corresponding author. Email address: dennis.p.stocker@nasa.gov

limits. Meanwhile, low-momentum flames can be dramatically disturbed by the g-jitter present in the aircraft testing, which is nominally ±0.02 g for a ~20 s duration. The jitter can be avoided by floating an experiment within the aircraft, but that reduces the test duration to mere seconds. As a result, space-based testing is often necessary to get microgravity conditions of sufficient duration and quality for combustion research.

Given the many advantages of space-based combustion research, five gas-fueled non-premixed flame experiments have thus far been conducted in space, where they are listed chronologically in Table 1. Three experiments were conducted over a decade ago on the space shuttle, i.e., the Space Transportation System (STS). The other two were conducted within the last five years on the ISS. This past research was focused on gravity's effects on the flame structure, soot and stability limits, and vortex interactions. In each experiment, the flame configuration was the laminar gas-jet diffusion flame, where vortices were created in the TGDF experiment by varying the air entrainment (through mechanical control of an iris centered near the burner tube outlet). The research has included flames in both quiescent and coflowing atmospheres. The LSP and TGDF experiments were conducted in sealed combustion chambers. In contrast, the flame was enclosed within a small flow duct (with a 76-mm square cross-section) in the ELF, SPICE, and SLICE experiments. The pressure was consistently ~100 kPa, with the exception of the LSP experiment which also included testing at lower values. In all cases, the atmosphere consisted of ~21% oxygen (by volume) with a balance of nitrogen. Tests have been conducted with a variety of fuels (including dilutions) and burner diameters.

Table 1: Past space experiments investigating gaseous non-premixed flames, listed chronologically.

Experiment	Principal Investigator (PI) and Co-Investigators (Co-Is) when the experiment was conducted	Mission (year)	Refs.
Laminar Soot Processes (LSP)	PI Gerard M. Faeth (University of Michigan)	STS-83 (1997), STS-94 (1997), STS-107 (2003)	[1-6]
Turbulent Gas-jet Diffusion Flames (TGDF)	PI M. Yousef Bahadori (Science Applications International Corporation) Co-I Uday G. Hegde (National Center for Microgravity Research)	STS-97 (1997)	[7-12]
Enclosed Laminar Flames (ELF)	PI Lea-Der Chen (University of Iowa) Co-I Dennis P. Stocker (NASA Lewis Research Center) Co-I John E. Brooker (NASA Lewis Research Center)	STS-97 (1997)	[13-16]
Smoke Point In Coflow Experiment (SPICE)	PI David L. Urban (NASA Glenn Research Center) Co-I Peter B. Sunderland (University of Maryland)	ISS (2009, 2012)	[17-20]
Structure & Liftoff In Combustion Experiment (SLICE)	PI Marshall B. Long (Yale University) Co-I Mitchell D. Smooke (Yale University) Co-I Fumiaki Takahashi (Case Western Reserve Univ.) Co-I Dennis P. Stocker (NASA Glenn Research Center)	ISS (2012)	[21-22]

The SPICE and SLICE experiments were both conducted in the Microgravity Science Glovebox (MSG) using common hardware which has since been used for the Burning and Suppression of Solids (BASS) experiment. The manually-operated hardware, e.g., where the ISS crew controlled the flow with a potentiometer, was based on the preceding ELF experiment and was designed for exploratory studies. The flame instrumentation was limited to a high-resolution digital still camera, an analog video camera, and a thermopile radiometer with a manually-adjustable gain. In addition to the radiometer output, the fuel flow, the coflow fan voltage, a coflow reference velocity, and a time stamp were both displayed and recorded through a video overlay. Despite the limited instrumentation, pyrometric measurements were made in 2012 of the soot temperature and volume fraction using the innovative techniques discussed in [23-24]. While these experiments proved to be valuable, more can be accomplished on the ISS.

In 2008, the Combustion Integrated Rack (CIR) [25] was delivered to the International Space Station. The facility is similar to a vending machine in size and includes a 100-liter combustion chamber capable of operation at pressures of up to 300 kPa. The chamber features a ring of 8 sapphire windows and is equipped with reconfigurable imaging systems (described later in this paper). CIR includes a gas delivery system and provides venting, thermal control, electrical power, data handling, image processing and storage, and vibration isolation. CIR experiments are conducted using unique hardware both inside and outside of the chamber. Unlike the SPICE and SLICE experiments which were heavily dependent on the crew, the CIR experiments are commanded from the ground, limiting the crew's responsibility to set up (e.g., exchange of gas bottles) and trouble shooting. Since its launch, the CIR has been used for droplet combustion experiments, e.g., as seen in Figure 1, but future experiments are now in development.

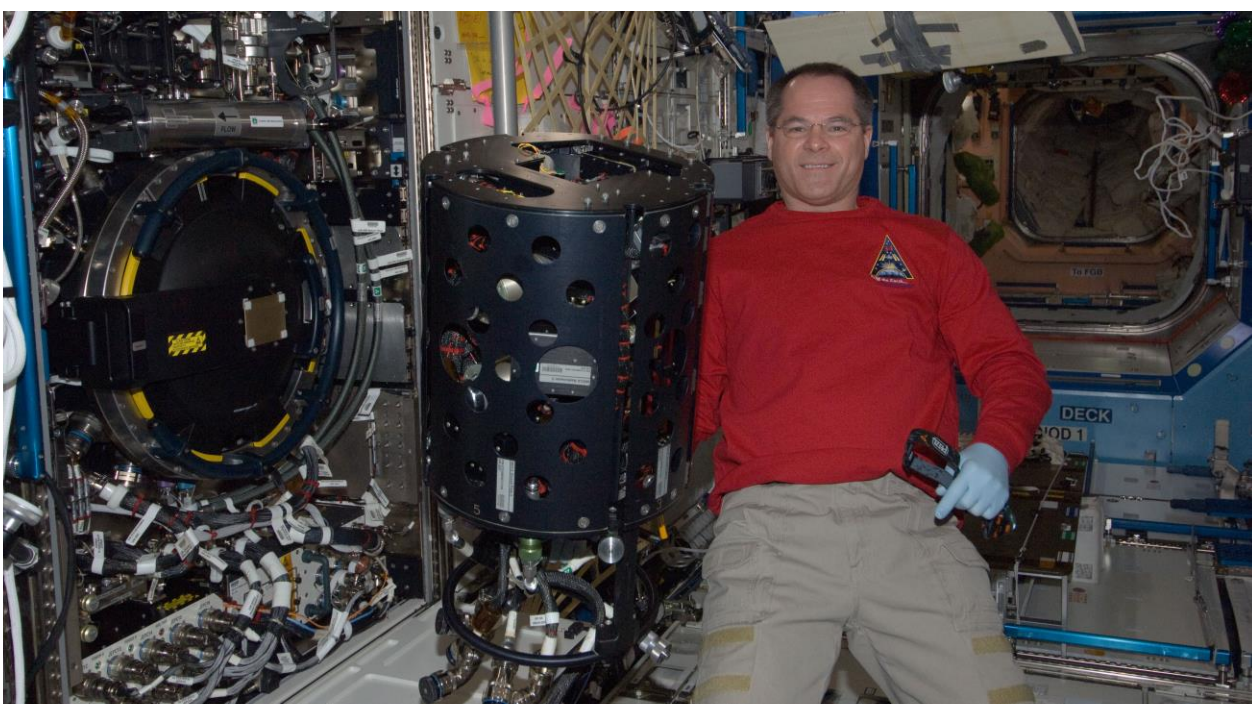

Figure 1: From left to right, the Combustion Integrated Rack (CIR) with the Multi-user Droplet Combustion Apparatus (MDCA) removed from the chamber for servicing by Expedition 34 Commander Kevin Ford. The photo was taken on Dec. 12, 2012 in the U.S. (Destiny) Laboratory of the International Space Station. [NASA photo ISS034-E-007409]

Gaseous flames will be investigated in the next set of CIR experiments as part of NASA's Advanced Combustion via Microgravity Experiments (ACME) project. ACME currently includes five independent experiments, listed in Table 2, which are each focused on advanced combustion technology through fundamental research. Although distinct, the experiments will be conducted with a single modular CIR insert similar to the MDCA seen in Fig. 1. Laminar, non-premixed flames are used in all of the current ACME experiments. To simplify analysis, the flames are either one or two dimensional, depending upon the experiment.

Table 2: Planned ISS experiments investigating gaseous non-premixed flames, listed alphabetically.

Experiment	Principal Investigator (PI) and Co-Investigators (Co-Is)
Burning Rate Emulator (BRE)	PI James G. Quintiere (University of Maryland) Co-I Peter B. Sunderland (University of Maryland)
Coflow Laminar Diffusion Flame (CLD Flame)	PI Marshall B. Long (Yale University) Co-I Mitchell D. Smooke (Yale University)
Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)	PI Derek Dunn-Rankin (University of California, Irvine) Co-I (former) Felix J. Weinberg (Imperial College London) Co-I (former) Zeng-Guang Yuan (National Center for Space Exploration Research)
Flame Design	PI Richard L. Axelbaum (Washington University in St. Louis) Co-I Beei-Huan Chao (University of Hawaii) Co-I Peter B. Sunderland (University of Maryland) Co-I David L. Urban (NASA Glenn Research Center)
Structure and Response of Spherical Diffusion Flames (s-Flame)	PI Chung K. Law (Princeton University) Co-I Stephen D. Tse (Rutgers University) Co-I Kurt R. Sacksteder (NASA Glenn Research Center)

2. Science

The current ACME experiments are primarily focused on energy and environmental concerns, but there is a secondary emphasis (with the BRE experiment) on fire prevention, especially for spacecraft. The primary objective is to gain fundamental understanding that can enable improved efficiency and reduced emissions in practical combustion processes on Earth, for example through the development and verification of 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. Some specific goals are to improve our understanding of combustion at fuel lean conditions where both optimum performance and low emissions can be achieved, soot control and reduction, oxygen-enriched combustion which could enable practical carbon sequestration, flame stability and extinction limits, the use of electric fields for combustion control, and materials flammability.

Unlike the other current ACME experiments, the Burning Rate Emulator (BRE) experiment is focused on spacecraft fire prevention. More specifically, BRE's objective is to improve our fundamental understanding of materials flammability, such as extinction behavior and the conditions needed for sustained combustion, and to 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, where measurements are made of the thermal feedback (i.e., to the burner) upon which the vaporization of condensed-phase fuels is dependent. A small number of gaseous fuels (including mixtures with inert gases) will be used to simulate the burning of fuels such as paper, plastic, and alcohol by matching properties such as the heats of combustion and gasification, the surface temperature, and smoke point.

Research, including that already conducted in microgravity, 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 goal of the Coflow 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 coflow 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 coflow. 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. The SLICE experiment was conducted as a precursor to ACME's CLD Flame experiment, in order to maximize its science, e.g., through refinement of the test matrix.

An electric field can strongly influence flames because of its effect on the ions produced by the combustion reactions. The direct ion transport 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. Outside reviewers concluded that the experiment "has great prospects of improving our understanding of nearly every practical combustion device." The experiment will be conducted with a simple gas-jet flame, where an electric field will be generated by creating a high voltage (up to 10 kV) differential between the burner and a flat circular mesh above (i.e., downstream of) the burner. Measurements will be made of the ion current through the flame and the flame's response to electric forcing as a function of the field strength, fuel, and fuel dilution.

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. An outside review panel declared that 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 with porous spherical burners. Tests will be conducted with various concentrations of both the fuel (i.e., ethylene or methane) and oxygen in order to determine the role of the flame structure on the soot inception. The effect of the flow direction on soot formation will be assessed by studying both normal flames and inverse flames, where in the latter case an oxygen/inert mixture flows from the spherical burner into a fuel/inert atmosphere. 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.

The purpose of the Structure and Response of Spherical Flames (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 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 mixtures for soot-free flames, and ethylene for sooty flames. One experiment objective is to identify the extinction limits for both radiative and convective extinction (i.e., at high and low system Damköhler numbers, respectively). Another objective is to determine the existence, onset, and nature of pulsating instabilities that have been theoretically predicted to occur in such flames with fuel/diluent mixtures that are above a critical Lewis number.

3. Experimental

As previously discussed, the ACME experiments will be conducted within the Combustion Integrated Rack (CIR) using a chamber insert, depicted in Figure 2, which was designed to accommodate gas delivery to a variety of exchangeable burners. Besides the chamber insert, other ACME-unique hardware includes a high-definition color camera and an avionics package, which is for data acquisition and control.

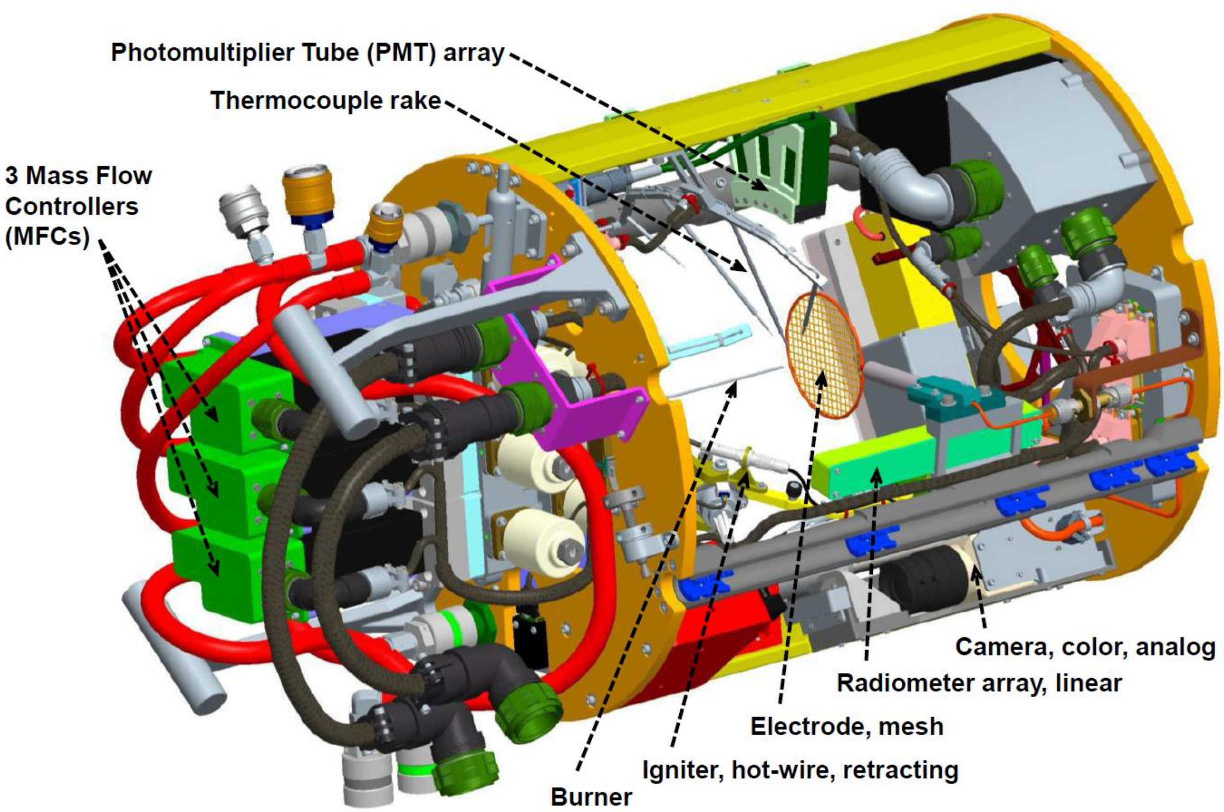

Figure 2: Design of the Advanced Combustion via Microgravity Experiments (ACME) chamber insert that will be used in the Combustion Integrated Rack (CIR) on ISS.

ACME's chamber insert, which is ~0.4 m in diameter, provides common mounting for a variety of burners on the chamber axis (but only one at a time) and includes a retracting resistive igniter. As depicted in Figure 3, there will initially be gas-jet burners (with inner diameters ranging from 0.4 to 3.2 mm), a small coflow burner (where the two concentric tubes have inner diameters of 2.1 and 25 mm), porous spherical burners (with diameters ranging from 6.35 to 12.7 mm), and two flat porous burners for the BRE experiment (with inner diameters of 25 and 50 mm). Most burners will be equipped with a surface thermocouple, and each BRE burner will have two heat flux transducers. The internal pressure of the porous burners will be measured to allow monitoring of the pressure differential across the outlet surface. The igniter will have a crew-exchangeable tip and arm (to accommodate the various burners) and its stepper-motor drive will allow for precise positioning.

Figure 3: ACME burner types, including from left to right, gas-jet burners, a co-flow burner, porous spherical burners, and flat porous burners for the BRE experiment.

The chamber insert includes three mass flow controllers (visible on the left of Fig. 2) for the delivery of fuel, oxidizer or inert (e.g., helium or carbon dioxide), and nitrogen to the burner. The maximum fuel flow is 2 slpm (on a nitrogen basis), whereas much higher flows, e.g., 10 slpm (on a nitrogen basis), are possible for the oxidizer and nitrogen lines. The crew can exchange the mass flow controllers to provide appropriate ranges that maximize the flow accuracy. The gas delivery system enables on-orbit dilution of the fuel or oxidizer (but not both simultaneously), coflow, inverse flames (e.g., oxidizer delivery to the center of a coflow burner), and premixed flames, although the latter are not planned for any of the current ACME experiments. Gases can also be delivered premixed to the space station where that is necessary in some circumstances, such as the blending of different fuel gases. CIR's standard bottle sizes are 1, 2.25, and 3.8 liters but ACME will sometimes use smaller bottles as a hazard control to limit the deficient reactant (e.g., fuel) that can be released into the combustion chamber.

ACME's primary flame diagnostics are a suite of imaging systems including five video cameras and two illumination systems, of which three cameras are part of the CIR facility and are already in use on orbit. All but one of the cameras is mounted outside of the chamber. Collectively, the imaging systems will enable color, CH*, and OH* imaging; pyrometry; measurement of the soot volume fraction; and operational support. However, it is unlikely that all functions would be exercised at any one time as will become apparent in the subsequent discussion.

Color imaging is provided by two cameras: a high-definition digital camera mounted outside of the chamber and a standard analog camera mounted on the chamber insert (with a turning mirror). Both cameras are part of the ACME hardware that is now in development. The analog camera signal will be downlinked in near real time to support the experiment operations. Light-emitting diodes within the chamber can be used to illuminate the igniter and burner to both support the operations and provide reference images. The 12-bit digital camera records at up to 30 full frames (1360x1024) per second, and is equipped with a motorized lens with independent control of the zoom, iris, and focus. The digital camera will be equipped with a filter assembly with four options, where selection of a clear "filter" allows for color imaging. Color imaging can also be carried out with a blue-green BG7 Schott glass filter, which balances the color planes to avoid saturation in the red while maintaining sensitivity in the blue and green. The natural flame color can be approximately reconstructed, but the primary purpose of the filter is pyrometry and measurement of the soot volume fraction, again via the techniques of [23-24]. Alternately, CH* imaging can be conducted with this camera because the filter assembly includes a 430-nm bandpass filter with a 10-nm full width at half-maximum transmission (FWHM). A 450-nm bandpass filter (again with a 10-nm FWHM) can be used with the CH* filter to effectively subtract interfering broadband soot emission. However, the filter assembly rotates slowly so such subtraction effectively requires a separate test with each filter and of course reproducible flame conditions.

Pyrometry can alternately be accomplished with CIR's monochrome High-Bit Depth Multispectral (HiBMs) camera, equipped with a Liquid-Crystal Tunable Filter (LCTF), which allows for imaging at multiple spectra, but requires a quasi-steady flame for measurement at each desired band. This camera has a telecentric optical system and is recorded at 512x512 and 30 frames per second (fps). Although it has a 1024x1024 pixel array, binning has been necessary because of signal loss through the LCTF. Both soot pyrometry and Thin Filament Pyrometry (TFP) are possible, where ACME is equipped with a crew-replaceable array of 5 silicon carbide (SiC) fibers. The fibers are orthogonal to the flame axis and the array can be translated along the flame axis to the desired position downstream of the burner, e.g., based on the downlink of the analog video. During set up, the crew can manually orient the array so that it is orthogonal to either ACME's color digital camera or the HiBMs camera with the LCTF. An alternate fiber array including a platinum wire will be used for inflight characterization, which in combination with preflight calibration will enable determination of the soot volume fraction [24].

CIR has a second HiBMs camera, without a filter, that will be used in combination with CIR's illumination package for alternate measurements of the soot volume fraction. This will be accomplished via an extinction technique previously employed in microgravity [3,6,26], where the camera and the collimated light source (with its two fiber-coupled laser diodes) are positioned at opposite windows. The images are recorded at 1024x1024 and 30 fps. Thus far, the primary purpose of this combined system has been the measurement of the droplet diameter for determination of the droplet burning rate.

CIR's Low-Light-Level Ultraviolet (LLL-UV) package is a monochrome camera with an intensifier (for 280-700 nm) and a 310-nm bandpass filter (with a 10-nm FWHM) for OH* imaging. Again as a result of the signal loss through the filter, binning is employed such that the OH* images are recorded at 512x512 and 30 fps.

The ACME chamber insert will also be equipped with non-imaging optical diagnostics including both thermopile radiometers and Photomultiplier Tubes (PMTs). There is a crew-exchangeable linear array of radiometers of which there are two versions supporting the initial set of experiments. The array has a fixed position which is parallel to the chamber axis and centered (along the chamber length) relative to the chamber windows and thus most of the other instrumentation. One array is equipped with a single wide-view radiometer with two narrow-view radiometers that are downstream and two more that are upstream, where all views are orthogonal to the chamber axis, as depicted in Figure 4. The narrow-view radiometers are intended to support studies of gas-jet flames, where ACME can accommodate shorter burners, making the "lower" detectors useful. The other array, also seen in Fig. 4, provides for three wide-view measurements of the flame, where one view is masked to nominally block radiant emission from the burner. It was specifically designed for the BRE experiment but will be a resource available to other ACME experiments. Given that the radiometer array can be exchanged by the crew, alternate arrays could be developed.

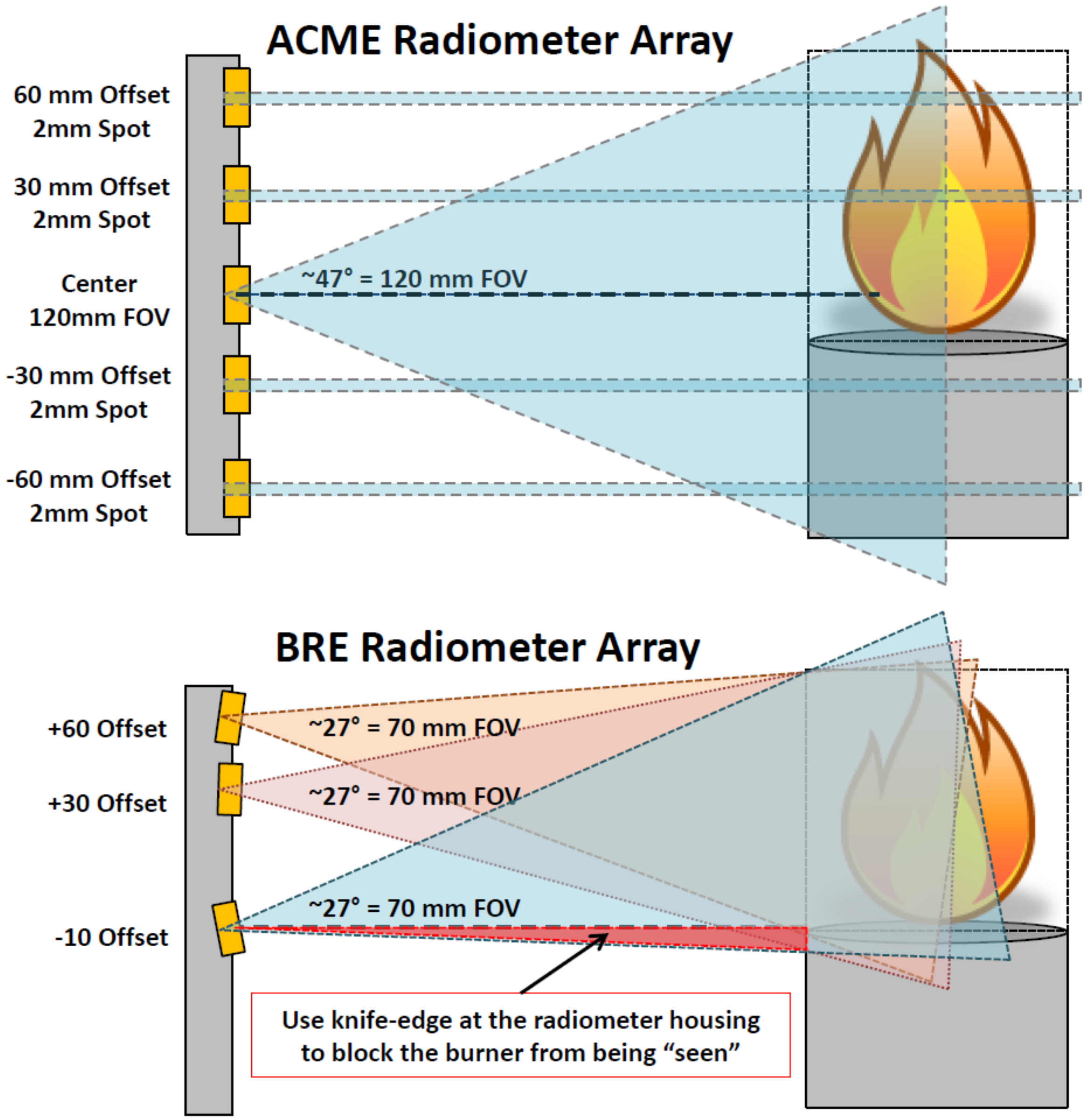

Figure 4: Crew-exchangeable radiometer arrays on the ACME chamber insert: (top) standard (ACME) array of 5 radiometers, and (bottom) array with three radiometers, designed for the BRE experiment, where the lowest detector is masked to avoid view of the burner.

An additional wide-view radiometer, that is fixed and not crew exchangeable, is positioned downstream of the burner and flame at 30^o from the chamber axis. This detector is primarily intended to support the spherical flame experiments and will have a quicker response than the more sensitive detectors that will used in the linear arrays. Like the radiometers on the two linear arrays, it will have a spectral range of nominally 0.2-11 micron and its field of view will be established by an appropriately selected aperture.

To detect the quenching of dim flames, the chamber insert will be equipped with a set of three PMTs. Each PMT will have a wide-angle view, a sight line that is orthogonal to the chamber axis, and will be centered (along the chamber length) relative to the chamber windows so that it is aligned with most of the other instrumentation. The PMTs' spectral range will be 230-700 nm, i.e., visible and near ultraviolet, but one will have a 310-nm bandpass filter and another will have a 430-nm bandpass filter (where both are with a 10-nm FWHM). The pair of detectors will enable measurement of OH* and CH* emission, respectively. The third PMT will be equipped with a neutral density filter to prevent saturation. Like many other components, the PMT array can be removed from the chamber insert by the crew.

The chamber insert is also equipped with six far-field thermocouples to measure the spread of the thermal field in the spherical flame experiments. They are of limited utility for other experiments because they are positioned upstream of the burner tip. Therefore, they will generally not be installed by the crew to reduce the chance of accidental damage. There will be two versions of a four-thermocouple rake to allow a choice of near and far measurements. Other arrays could be designed to support future experiments, but they cannot extend downstream of the burner tip without interfering with other (e.g., optical) measurements.

Experiment-unique hardware is also mounted on the chamber insert. For example, to accommodate the E-FIELD Flames experiment, the insert is equipped with a high-voltage supply and a crew-removable electrode mesh which can be set between +10 and -10 kV. The circular mesh is orthogonal to the chamber axis and is positioned (during set up) at either ~35 or ~50 mm downstream of the insulated burner. The ion current between the burner and electrode mesh will be determined via measurement of the voltage drop across a known resistor and application of Ohm's Law.

Additional supporting measurements will be made, where the chamber pressure is a simple example. The ACME experiments will use the CIR's gas chromatograph for pre- and post-test analysis of the chamber atmosphere, e.g., for oxygen, nitrogen, carbon dioxide, carbon monoxide, and fuel gases. Acceleration measurements will be provided by the Space Acceleration Measurement System (SAMS) [27], which is the primary instrument for such measurements on ISS and previously served that role for the space shuttle.

All ACME experiments will be constant volume (i.e., rather than constant pressure) studies, where the chamber's free volume will be about 90 liters. Burner flows will generally be constrained to limit the pressure rise, and tests will typically be 0.5-2 minutes in duration.

The ACME experiments will be configured, but not conducted, by the ISS crew. Instead, the experiments will be commanded from the ground, specifically from the Telescience Support Center (TSC) at the NASA Glenn Research Center in Cleveland, Ohio. They can be conducted in a nominally automated mode using pre-programmed scripts. However, it will also be possible to effectively operate the experiments in a "manual" mode, where changes can be made in response to the analog video downlink and the numerical data available in the telemetry stream.

For example, a flow rate could be adjusted to approach a stability or soot limit. Step and ramp changes can be made in the flow rate(s) or electric field potential. The TFP fiber array can be translated uniformly through a soot-free flame to get a continuum measurement of the temperature field. In summary, ACME's experiment control will allow for broad flexibility.

4. Concluding Remarks

In January 2014, the Obama administration announced that ISS operations will continue until at least 2024. It is currently expected that the five ACME experiments will be conducted from 2016 to 2019. While there are plans for subsequent CIR experiments, e.g., to study flame spread across solid fuels, future experiments could be conducted using the ACME hardware. Although the current ACME experiments are limited to laminar non-premixed flames, turbulent and burner-stabilized premixed flames could also be studied using the ACME chamber insert. Many of the hardware elements are exchangeable on orbit, including for example, the burner, igniter arm and tip, video cameras, radiometer array, PMT array, TFP fiber array, thermocouple rake, high-voltage supply, electrode mesh, and the gas chromatograph. As such, the hardware can be customized to support a wide variety of future experiments. Gaseous flames could continue to burn brightly on the ISS.

Acknowledgments

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