AIAA 2001-5046

MICROGRAVITY GASEOUS COMBUSTION FLIGHT HARDWARE

J. A. Jones and A. P. Over
NASA Glenn Research Center
Cleveland, OH
G. Funk
Zin Technologies
Cleveland, OH

International Space Station Utilization Conference
15-18 September 2001
Cape Canaveral, Florida

Abstract
The NASA Glenn Research Center has led NASA in the development and flight of microgravity combustion flight hardware for over a decade. Combustion research is generally broken into three areas by fuel type: gasses, liquids and solids. This paper focuses on the evolution, current and future state of the facility level gaseous combustion flight hardware systems, from Combustion Module-1 through the Fluids and Combustion Facility (FCF) Combustion Integrated Rack (CIR), planned to become part of the Destiny Laboratory. As part of the future CIR research, this paper includes a particular focus on the Multi-user Gaseous Fuels Apparatus (MGFA) "mini-facility" hardware which complements the capabilities of CIR to accommodate Principle Investigators for a wide range of gaseous combustion experiments.

Introduction
The NASA Glenn Research Center (GRC) has been developing ground-based and space flight combustion hardware for over a decade. A combination of platforms including the Space Shuttle, Spacelab, Sounding Rockets, and ground facilities has been utilized to study the combustion of solids, liquids and gaseous fuels. The next generation of combustion research on-board the ISS has already accumulated a significant history, even though no combustion flight hardware has been delivered to ISS.

Historically, when the ISS program suffered delays and schedule stretches, NASA Glenn was able to design and build precursor facility-level hardware. For example Combustion Module-1 (CM-1), a precursor to the Glenn developed ISS Fluids and Combustion Facility (FCF) Combustion Integrated Rack (CIR) successfully flew twice in 1997. CM-2, scheduled for a mission in 2002, is a re-flight of CM-1 and includes changes that furthered the evolution of hardware development for the FCF as well as PI-unique combustion hardware. Part of the wealth of "lessons learned" from CM-1 and CM-2 are summarized below and specific areas are highlighted that apply directly to the CIR gaseous combustion hardware development.

The term "mini-facility" refers to the hardware (and resident software) systems that are mounted inside and outside of the Fluids and Combustion Facility (FCF) Combustion Integrated Rack (CIR) chamber, part of the ISS *Destiny*. These mini-facilities are being developed to accomplish PI-unique combustion research in solids, liquids and gaseous fuels. [1,2] The most notable portion of the mini-facility is the multi-user chamber insert which includes burners, ignitors, sensors, and diagnostics (even cameras) unique to the Principal Investigators' (PI) needs. However mini-facilities also include external diagnostics, avionics, software and other hardware. The first of these planned mini-facilities is the Multi-user Droplet Combustion Apparatus (MDCA), which will be available for investigators to study the burning of liquid fuels in the form of droplets.[3] The next scheduled mini-facility is the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS). [4] This apparatus will provide the hardware needed to study combustion of both thick and thin solid fuels in microgravity. The final planned combustion mini-facility is the Multi-user Gaseous Fuel Apparatus (MGFA). The MGFA mini-facility (like MDCA and FEANICS) provides modularity and cost efficiency, while still meeting the science requirements of current (and future) Principal Investigators.

This paper will describe the CM-1 and CM-2 facility hardware, accomplishments/lessons learned and the current state of the next generation CIR/MGFA hardware concept under development to accommodate an initial set of gaseous experiments. Both CM-2 and MGFA are managed within the Combustion Flight Projects Branch, located in the Microgravity Science Division at NASA GRC.

Combustion Module

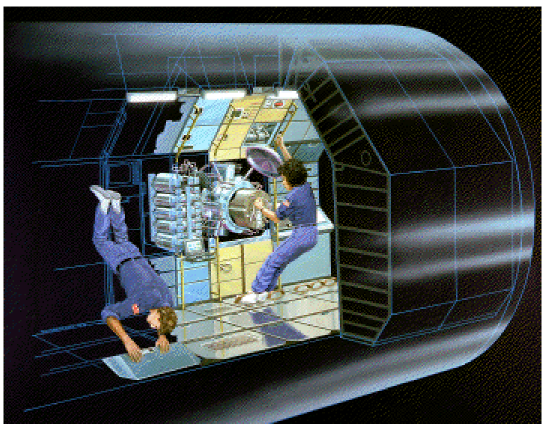
CM-1 History

In 1989 a NASA Research Announcement was published and proposals were accepted for six flight PI's in the FCF. In late 1992 the International Space Station went through a major redesign effort including a large delay to the deployment of the US Lab and its facilities. That year the Combustion Program decided to accelerate two of its highest priority experiments to a new "Combustion Module" to be flown in a

Shuttle/Spacelab carrier called Microgravity Science Laboratory-1 (MSL-1). These two experiments were:

a) Laminar Soot Processes (LSP), G. M. Faeth Principal Investigator
b) Structure of Flame Balls at Low Lewis-number (SOFBALL), P. D. Ronney Principal Investigator

In addition, the Droplet Combustion Experiment (DCE) was also accelerated to be flown on MSL-1 in a partial rack facility, which served as a precursor to the MDCA program.[2] Combustion Module was charged with the task to not only accommodate the requirements of two PI's, but to also develop hardware designs and operations to be utilized by FCF.



CM-1 Artist's Concept

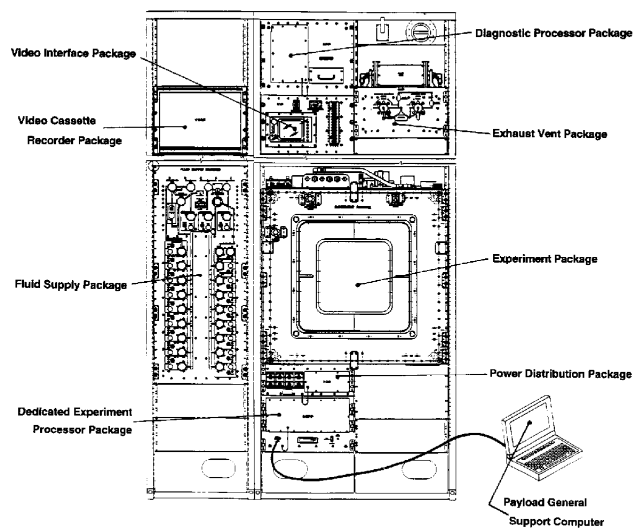
From 1989 through 1993, the CM-1 concept was developed. From late 1993 through 1996 CM-1 completed development, build and testing culminating with a shipment of flight hardware to the launch site in September of 1996. In April of 1997, CM-1 flew on STS-83/MSL-1, however this mission was called back and landed after only four days due to orbiter fuel cell problems. CM-1 flew again with the reflight of MSL-1 in July 1997 with a fully functioning Columbia Space Shuttle for a 16-day mission.

CM-1/CM-2 General System Overview

The CM-1 and CM-2 hardware consists of eight hardware packages mounted in two racks, three chamber inserts (Experiment Mounting Structures) and other stowage, 18 external electrical harnesses, and over 30,000 lines of software. The rack-mounted subsystems are loaded in a volume approximately 2.0 x 1.5 x 0.8 m, and have a total mass of over 620 kg (or 1375 lb). Its overall size and range of capabilities make it a fitting precursor facility to the CIR.

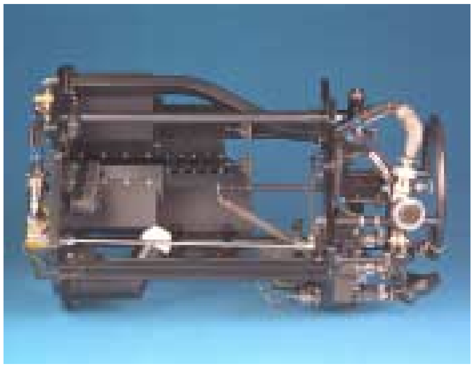
The following is a very brief description of each subsystem or package in the CM-2 configuration:

Experiment Package (EP) - 90 liter combustion chamber w/ six ports for three intensified near IR, one color, and three B&W cameras (used for laser extinction and multi-line emission measurements), a gas chromatograph, crew switches, thermistors
Fluid Supply Package (FSP) -Complex, safety critical gas control and distribution system containing 20 composite overwrapped bottles for gas storage
Video Cassette Recorder Package (VCRP) - Four Hi-8 video recorders
Exhaust Vent Package (EVP) - Blower, canister, other fluids components for clean-up of chamber gas products and control of evacuation
Dedicated Experiment Processor Package (DEPP) - Main processor for experiment command & control; DEPP software interfaces with the crew PGSC (control/monitoring) and DPP (image acquisition) software
Video Interface Package (VIP) - Main video interface for switching, routing, and display of analog & digital video; includes crew gain switch



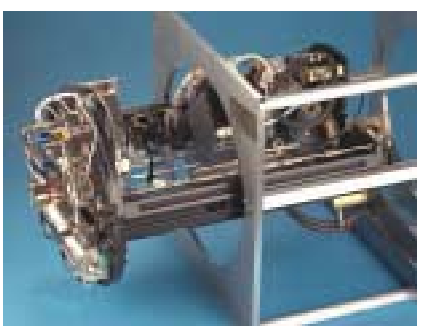
CM-1 System Layout

Diagnostic Processor Package (DPP) - Video frame grabber and storage system for digital data with its own custom S/W to control image acquisition and storage
Power Distribution Package (PDP) - Power conditioning and transfer from carrier to all CM-2 packages
Harness - Package to package and package to SPACEHAB interface harness for power, control, data, and video
Experiment Mounting Structures (EMS) (chamber inserts launched in stowage):



LSP EMS - Unique LSP H/W: Retractable hot wire igniter, thermocouple rake, soot samplers, radiometer, and thermistors (Note: many capabilities of this EMS are similar to those needed for MGFA increment A as described below.)

SOFBALL EMS - Unique SOFBALL H/W: Spark igniter, thermocouple rake, radiometers, thermistors, and mixing fan



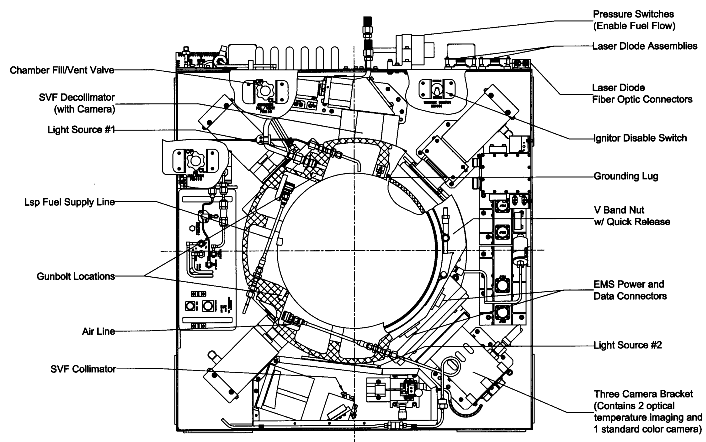
Mist EMS - Unique Mist H/W: Flame tube with iris, gate valve, flame speed photo diode, laser extinction, and hot wire igniter; fuel/air bottles & fluid fill control, clean-up canister, ultrasonic mist generator systems

CM-1/CM-2 Operations

Once on-orbit, the CM facility is configured for the first power-up and the combustion chamber is evacuated and filled with fresh air. After power-down, the crew opens the chamber and installs the EMS for the first experiment. The chamber is then resealed and experiment operations can begin via flight software under control of the crew or the ground (CM-2 only). For LSP and SOFBALL, the pre-combustion gases are provided to the chamber from the FSP and for Mist, they are provided from the EMS gas supply system. The EMS ignitor starts combustion and the flame/s are observed using the on-board suite of diagnostics. During the actual combustion event the crew can control test conditions (via the VIP Gain Switch) such as the LSP flame height (fuel flow control) and SOFBALL camera gains.

For imaging, CM includes a choice of seven cameras of which subsets can be routed as follows:

- Hi-8 recorders (up to four cameras)
- VIP Monitor (crew selects one of active cameras)
- DPP (up to three cameras can be digitized with programmable frame grabber for downlink later)
- Downlink (up to two analog camera signals)



CM-2/LSP EP Layout/Diagnostics

Once combustion is completed, the post-combustion gases are evacuated and cleaned-up as needed by the CM EVP (or Mist clean-up system for Mist) and the process starts again. For CM-1, a total of 29 test burns were planned and 40 tests were completed between the two experiments on two missions. For CM-2, a total of 66 test burns are planned for the three experiments.

CM-1 Lessons Learned

The flight of CM-1 on STS-83 and STS-94 offered many lessons learned, both positive and negative. The LSP and SOFBALL Science accomplishments are well documented in journals and conference proceedings.[5,6] With regard to the hardware systems, the engineering team touted many accomplishments which were “firsts” for NASA. The following are those key engineering accomplishments:

a) First time that a pressure vessel has been breached and re-certified on-orbit to contain hazardous gases

under pressure, which validated concept of multiple combustion investigations in one facility (a critical pathfinder for the FCF)
b) First hardware to produce pre-mixed (SOFBALL) and gaseous diffusion flames (LSP)
a) First Gas Chromatograph on-orbit analysis and downlink for real time PI evaluation
c) First non-obtrusive measurement of soot in a flame (using soot volume fraction)
d) First on-orbit clean-up of sulfur hexafluoride and other post-combustion products, before safely venting into space
e) First on-orbit false coloring for crew adjustment of science camera gain

CM-1 also had many small issues and problems associated with the final development phases and on-orbit operations:

- LSP: Weak and unstable laser diode for Soot Volume Fraction and flame disturbances caused by soot sampler system
- SOFBALL: Intensified near-IR cameras had high background noise and synch issues,
- EP: Gas Chromatograph measurements degraded/lost due to water vapor in columns
- EVP: Safety concern about LiOH dust "puffing" back into the chamber
- EMS connectors difficult to mate
- Fluid system leaks/performance faults
- Software: one-time error in data storage and excessive software patches
- Crew time: did not maximize ground commanding

Each of these issues was addressed for CM-2.

STS-83 & 94 Mission Specialist Roger Crouch working on the LSP EMS

CM-2 Overview

The LSP and SOFBALL experiments contain peer-reviewed science requiring two flights. Due to an ISS/FCF-CIR delay and the new flight opportunity to accommodate these experiments in a proposed reflight of CM-1 (or CM-2) on SPACEHAB, CM-2 was given the preliminary authority to proceed in February of 1998. In addition, CM-2 was given the nod to integrate a third experiment called Water Mist Fire Suppression Experiment (Mist). Mist is sponsored by the NASA Space Product Development organization and includes commercial sponsorship through the Center for Commercial Applications of Combustion in Space (CCACS).

CM-2 was charged with three main challenges:

1. Complete the test matrices for LSP and SOFBALL, correcting any issues from CM-1.
2. Add a third experiment (Mist).
3. Convert the hardware from the Spacelab to the SPACEHAB carrier.

CM-2 Engineering Objectives

The CM-1 facility had numerous engineering objectives for its first flight to show proof of concept for designs to be incorporated into the NASA Glenn FCF Facility and mini-facilities like MGFA. For CM-2, new technical objectives include:

a) Highly Accurate (within +/- 2% of smallest constituent) Gas Chromatograph Measurements
b) Successful operation of new high energy spark igniter for SOFBALL
c) Verified On-orbit Gas Mixing within the Mist EMS which includes separate fuel and air bottles for on-orbit pre-mixing of combustible gasses
d) Use of System level dynamic testing for package qualification (using flight rack vibration testing to verify loads and mitigate the risks of package level testing)
e) Extensive ground commanding, control, and data flow of the most complex safety critical payload ever flown on SPACEHAB or any carrier
f) Successful integration and flight operations of the complex, commercially developed Mist experiment

CM-1/CM-2 Lessons Learned for MGFA

Most of the technical accomplishments listed above have already been folded into the design and development of CIR. In addition the following approaches or lessons learned from CM-1/CM-2 are being applied for MGFA in the following areas:

Chamber Insert or EMS:

For CM-1 and CM-2, the EMS's are one of a kind; this saved costs but made testing opportunities difficult in terms of scheduling and risk. For Mist, a functional model EMS was built which simulated all EMS functions for software development, which was critical to mitigate both schedule and technical risk. It was also learned that EMS's should be more modular to be both flexible in functionality and cost effective when changes need to be made. A functional or engineering model EMS should be planned from the start. Finally, especially since MGFA is anticipated to be flown several years after the CIR's first operation, it is believed that the relatively complex Mist EMS may be representative of future experiment-specific hardware. For Mist, the CM-2 facility capabilities were essentially frozen (cost/schedule constraints) and any new capabilities were supplied by the EMS.

Diagnostics:
Based on CM-1 and CM-2 experience, unique diagnostics require some significant initial investment but the testing/verification phase can be even more costly if it includes items like target development and parametric studies. In this era of cost efficiency as a necessity to fly, there should be early review and tough criteria to allow any unique diagnostics.

PI Avionics/Software/Test Parameters:
CM-1 and CM-2 proved that on-orbit replacement of circuit boards is feasible. Although ISS is expected to have tight crew time and up-mass constraints, accommodating an off-nominal on-orbit replacement of critical board is recommended. Given the history of schedule slips, CM-2 has also learned that built-in batteries with limited lives create potential issues.

Like the hardware, MGFA software should be as modular as possible with well tested generic capabilities. The PI unique code should be minimized. Human factors risk mitigation was employed in the development of Mist software by utilizing mostly automated sequencing during critical phases. By comparison to LSP and SOFBALL, the benefit of this approach became apparent during pre-flight testing because there were fewer times that the team had to use off-nominal software/procedures to get back on a nominal track. This philosophy must be balanced with flexibility of operations for a given experiment. Software code should accommodate both ground command and crew, but conflicts caused by mixing the two control options need to be avoided. CM-1 and CM-2 relied on the PI unique teams to fully test the range of their test parameters; this lacked the rigor of formal software verification and probably should have been done by the software team. One final point that is obvious to any experienced developer is to make sure that adequate system testing time is allocated for system level hardware <u>and software verification</u> for both nominal and off-nominal conditions; for CM-1 and CM-2 the software element tended to be underestimated. Also related to system/software testing, to mitigate risks, Mist simulated all the CM-2 software interfaces, enabling EMS stand-alone testing. MGFA may wish to consider having surrogate facility systems (simulated hardware or software or a combination) like Mist did to test all interfaces adequately, especially if time on the CIR ground system is limited.

Fluids:
The single most important issue in fluids is contamination control because it causes leaks and fluids component failures. In the early phases of CM-1, some of the fluids hardware had a problem with contamination and it was difficult to clear the fluids system without complete disassembly; in particular CM-1 learned the lesson to carefully check all ground support equipment. Much has been learned about the behavior of mass flow controllers in microgravity conditions from CM-1 and other Glenn experiments. The understandings gained in CM-1 and CM-2 of gas mixing and gas chromatography requires its own paper. In particular the SOFBALL experiment pushed the methods and technology to the limit. Improvements such as vacuum purge of the sample lines and on-orbit bake-outs allowed CM-2 to meet the stringent SOFBALL requirements such as +/- 2% measurement accuracy of the smallest component delivered to the chamber. Finally, gas resources such as air need to be carefully managed and margins should be established. CM-1 was short on air reserves but with CM-2 and careful management, the third experiment was added and more air reserve was made available for off-nominal chamber access by the crew. This also applies to other gasses since MGFA may be dealing with a different paradigm on the most critical resource.

CM-2 Flight System

Systems:
As mentioned previously, systems testing should be planned carefully and it should start by having all of the requirements well documented. MGFA needs to include requirements that will lead to end-to-end testing and post-testing analysis of the results. From CM-1 and CM-2 it was learned that a successful test in the clean room did not always lead to a full success once the report was written. Systems as complex and CIR/MGFA are impossible to fully monitor and analyze real time. The Systems area would also lend well to a separate paper, however the final important point to be stressed here is: that careful documentation and control of the requirements needs to be implemented from the conceptual design stage through flight. This is particularly important for any safety critical system like the CIR and its experiments.

Multi-user Gaseous Fuels Apparatus (MGFA)

MGFA Overview

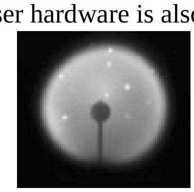
The MGFA is a set of hardware and software elements integrated on orbit with the FCF/CIR Systems for conducting specialized research in gaseous combustion phenomena. The CIR provides a sealed test chamber and support facilities for conducting a variety of combustion science research including combustion of liquid droplets, solid materials, and gasses. As mentioned earlier, CIR is part of the FCF, which is a three-rack ISS experiment facility that supports microgravity research of fluid science, combustion science and biotechnology.

FCF Mock-up: CIR/Science Accommodations Rack /Fluids Integrated Rack (FIR) (left to right)

The MGFA includes an insert that fits inside of the CIR chamber, an avionics package that is mounted inside the CIR rack, and diagnostic packages unique to gaseous combustion research.
The MGFA is currently in the conceptual phase of development. Its mission is to perform microgravity experiments in gaseous combustion science over the life of the CIR in order to better understand the combustion processes that occur on Earth. MGFA, in conjunction with the CIR, will allow experimenters to use various gaseous fuels in flow or quiescent environments and at various pressures, oxidizer compositions, and oxygen concentrations. The microgravity environment allows for measurement and observation of combustion processes that cannot be made in sustained gravity on Earth. The modular design of MGFA allows for flexibility in configuring for specific experiments, easy maintainability of the hardware and should result in lower hardware launch mass.

The MGFA is designed to accommodate, at a minimum, four PI's initially funded through the conceptual phase:
1) Structure and Response of Spherical Diffusion Flames (s-Flame, PI: C.K.Law)
2) Flame Design Experiment (PI: R.L. Axelbaum)
3) Pulsed-Fully Flames Experiment (PUFF, PI: J.C. Hermanson)
4) Field Effects of Gravity on Lean Premixed Turbulent Flame (V-Flames, PI: R.K. Cheng)

s-Flame test flame in Glenn 2.2 second drop tower



The MGFA multi-user hardware is also called a mini-facility because it is analogous to the CIR facility, which also accommodates multiple users with minimal changes to a single set of hardware (i.e. MGFA is a facility within a facility, hence mini-facility). The major planned subsystems are defined as follows:
1. Structure —CIR chamber insert structure; when fully outfitted with equipment the insert is called an Experiment Mounting Structure (EMS)
2. Burner/Ignitor — Consists of PI unique burner or nozzle and ignition system mounted on the EMS
3. Fluids Control — Fluids system for gas regulation provided by the combination of the MGFA EMS, MGFA supplied components (if required) and the CIR Fluids Oxidizer Management Assembly (FOMA); may include flame verification system for safety, possibly mounted on the EMS
4. Internal Diagnostics/Sensors — Includes hardware mounted on the EMS to support external diagnostics such as mirrors, lasers, PIV seeders (see description below) and the various analog sensors such as thermocouples and radiometers
5.External Diagnostics — Includes the MGFA provided diagnostics to be mounted outside the CIR chamber at

Universal Mounting Locations (UML's) such as cameras, illumination sources (lasers), and other optical systems

6.Experiment Avionics — Includes the MGFA unique electrical systems and software required to command, control, and power the MGFA insert and diagnostics

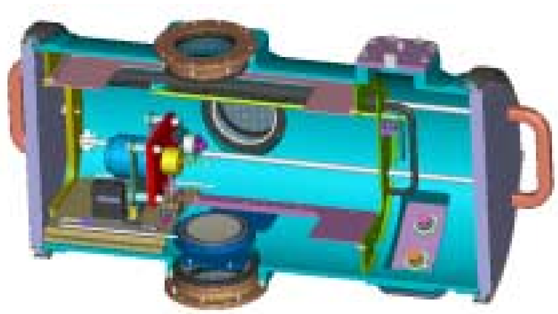
MGFA Flight Increments

MGFA is planned to be delivered to the ISS in two flight increments, designated MGFA-A and MGFA-B. The first increment is planned to include the s-Flame and Flame Design experiments, and the second increment is planned to include the PUFF and V-Flames experiments. Although there are two separate flight increments, the overall MGFA-A EMS design is planned to accommodate the later MGFA-B experiments without significant modifications.

MGFA Flight Increment A: MGFA-A

The s-Flame and Flame Design experiments share a common burner type and size. This commonality extends to the overall CIR chamber insert design and little or no modifications should be required on-orbit between the performance these two experiments. This, in combination with their relative maturity and complexity, make them most likely to be flown together in MGFA Increment A. It should be noted that unique diagnostics are required for each experiment however MGFA is working with the science teams to minimize the changes required for MGFA-A diagnostics to save crew time.

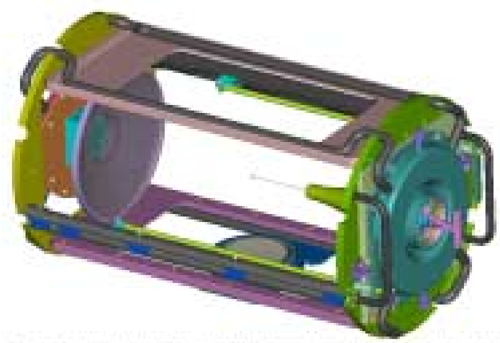
As mentioned above, MGFA can be broken into major subsystems and each will be discussed in turn for MGFA-A: Structure, Burner/Ignitor, Fluids Control, Diagnostics and Avionics/Software.



Cut-away view of one MGFA concept with s-Flame

MGFA-A Structure

The baseline concept for the structure of the MGFA-A consists of a pair of plates, one forward (aisle end) and one aft, connected by structural rails that will interface with the CIR chamber guide rods. Currently, there is no requirement to rotate the structure to any orientation other than its initial, nominal insertion configuration. The burner mechanisms as shown above are mounted on the aisle end of the EMS, and the opposite side of that plate will provide support for specialized components and controls. The aft plate will serve to mount diagnostic equipment and any other experiment specific hardware requiring that location. This EMS structure is relatively simple and open, much like the CM-1/CM-2 LSP EMS.



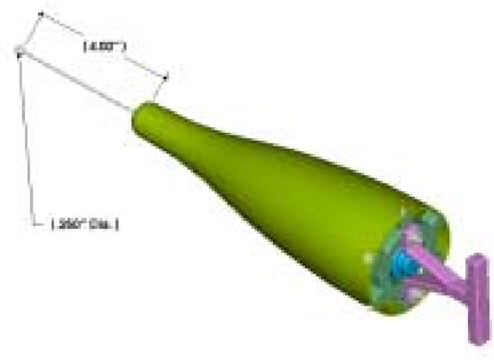
S-FLAME CONCEPT BURNER INSERT ASSEMBLY IN CO-FLOW EMS ASSEMBLY

An alternate design approach has very recently been considered for the EMS. Based on the development of an EMS design to support the MGFA-B increment, an EMS with built-in hardware elements to support air co-flow, oxygen replenishment, chamber gas recirculation, and other conditions is being considered for both increments.

MGFA-A Burner/Ignitor

The burner required for the experiments planned for this increment contains a small spherical tip mounted on a narrow diameter support/supply tube. Currently, this tip is under development and its material type and configuration are not well defined. However, the desired tip size is approximately 6 mm, and the support tube will be approximately 1.5 mm OD and 100 mm in length. It is planned that this tip will be replaceable on orbit.

The s-Flame experiment requires that this burner tip rotate during some test points, and therefore it is planned that it will be directly supported by a variable speed electric motor and that the combustion gas connection must not inhibit that rotation. This burner requires a controlled gas input that varies with time over the course of a single test point. Ignition will be accomplished by means of a hot wire coil attached to a movable arm similar to that used on the CM-2 LSP Experiment.



S-FLAME CONCEPT BURNER INSERT ASSEMBLY (10-04-2001)

MGFA-A Fluids Control

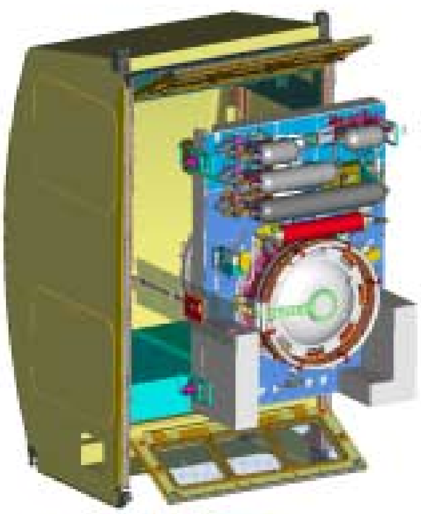
The basic experiment operation for s-Flame and Flame Design is similar to CM-2/LSP. Namely, the chamber is filled with quiescent air, fuel is flowed from the CIR FOMA through the MGFA experiment burner and ignited with a hot wire ignition system. However the flow rates are higher and given the higher amounts of fuel entering the chamber, the safety approaches from CM-1/CM-2 will need to be modified for CIR. In addition, Flame Design also has a special inverse burn case in which the chamber is filled with fuel, and then air is flowed through the nozzle and ignited. Given these ranges of test conditions, the current CIR design, and the flight safety restrictions, there are several design issues that are unresolved at this time. However, there are some basic fluid system components/functions that are required as a minimum for MGFA-A:

• Two solenoids to stop and start the flow of combustible and inert gas supplied by CIR.
• One auxiliary gas supply system, including solenoids, a Mass Flow Controller (MFC), regulator, manual shutoff, quick disconnects and storage bottle(s)
• One in-line mixing chamber, to assure complete blending of separate source gasses
• A flame verification system is currently under development, which is intended to control the timing system which regulates the amount of combustion gas that may be delivered to the CIR chamber, in order to extend the allowed burn times. This will ultimately be a Fluids Control system, mounted on the insert and interfacing with the CIR regulation system.
• Pressure transducers, relief valves, oxygen sensors, fittings, hand valves and quick disconnects as required to achieve the desired conditions.

MGFA-A Diagnostics

Several of the diagnostic devices required for obtaining the Science data will be mounted on the MGFA-A insert. Thermocouples will be installed at various locations, and a radiometer will be placed at a location suitable for good flame response. In some respects, the flame detection is also a diagnostic system, since it will rely on radiant energy to generate a known response.

The s-Flame experiment currently requires a Rainbow Schlieren system to verify flame extinction. This system will consist of a light source, some beam splitting and focusing apparatus and a three-chip color camera. An adjustable mirror will be mounted on the insert to support the proposed Rainbow Schlieren system. This will be experiment specific hardware that will be required to interface with the UML standard interfaces.



CIR with Optic Bench fully extended

Flame Design also desires an independent measure of the soot-inception limit that is not dependent on temperature. MGFA is currently considering using a diagnostic called Polycyclic aromatic hydrocarbons (PAH). This requires a laser light sheet (MGFA-provided) and low light level IR camera (CIR-provided) to induce a laser fluorescence of the molecules inherently present at the soot-inception limit. The Flame Design PI Team has also been studying photo multiplier tubes (PMTs) during ground based testing that may offer a simpler diagnostic solution compared to the PAH system.

S-Flame and Flame Design will also utilize many of the standard CIR camera packages. At this time, s-Flame is expected to utilize all eight UML locations and Flame Design will need five to seven UML's for the combination of cameras, lasers, and image acquisition systems.

MGFA-A Avionics/Software

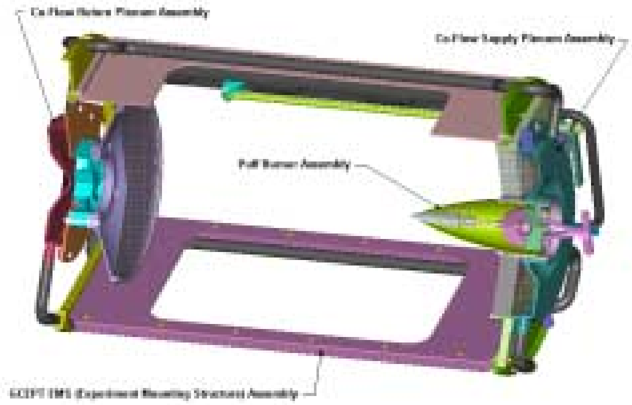
MGFA will provide the command and data management for all of its experiments through the MGFA Avionics Box. This box will have to work in conjunction with the MGFA EMS through the CIR chamber interface, and the following CIR subsystems: Input/Output Processor (IOP), Image Processing Packages (IPP), Image Processing and Storage Units (IPSU), and the Fuel and Oxidizer Management Assembly (FOMA). MGFA will employ the CIR standard control systems. Test parameter uplink and real time ground commanding are also part of the baseline approach. The management of image data is of particular concern due to the relative quantity.

MGFA Increment B

The second increment for the Multi-user Gaseous Fuels Apparatus is planned to support the performance of PUFF and V-Flames, each of which will require its own, separate burner mechanism. It is currently planned that the design of the structure will be sufficiently advanced and adaptable so that only the burner mechanism and some fluids and control devices will require installation and/or replacement. The MGFA-B subsystems are described below.

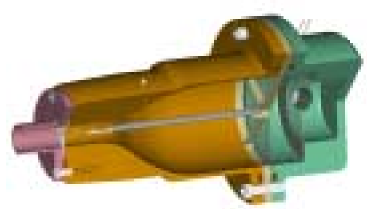
MGFA-B EMS and Fluids Controls

The MGFA-B EMS (Structure, Burner/Ignitor, etc.) and Fluids Controls are designed to accommodate the PUFF, V-Flames, and future combustion PI requirements. For example, PUFF currently requires a co-flow of replenished air to surround the burner. PUFF also requires the pulsed release of the gaseous fuel at rates ranging from 0.1 — 100 Hz. It is required that this gas flow be delivered in a rectangular wave with sharply defined on/off flows each time to generate a pulse or puff of flame when the fuel is flowing. This gas is to be ignited by a steady state hot wire located just outside the confines of the burner nozzle, which is designed to specific constraints. It is envisioned that a special burner, with a high-speed response solenoid will be designed, built and carried in stowage with the rest of the MGFA-B increment.



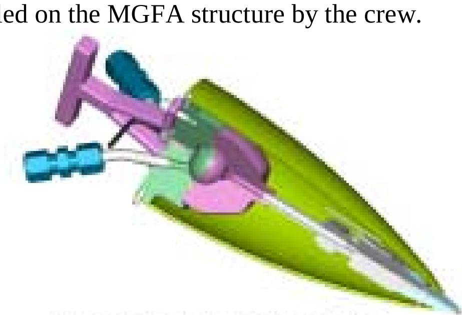
PUFF CO-FLOW ASSEMBLIES & BURNER ASSEMBLY INSTALLED ON THE GCEPT EMS (09-04-2001)

V-Flames also requires a specialized burner with an internal, constantly activated ceramic heater (in this case called a bluff body). The heated bluff body acts as a flame anchor, which gives the flame a characteristic, cone shape, or V-shape as viewed from the side of the burner nozzle. A retractable spark ignitor is required for ignition of the pre-mixed gasses. (Due to the flow velocities in the burner nozzle, hot wire ignitors alone



V-FLAME BURNER CUT AWAY (08-13-2001)

do not work.) V-Flames has a constant velocity burner that requires relatively high flow rates of fuel and oxidizer, and will require some modification of the CIR Safety Package to support its implementation (based on the current understanding of the CIR Safety controls). It is planned that this burner will be shipped to the ISS in much the same manner as the PUFF burner, and be installed on the MGFA structure by the crew.



PUFF BREADBOARD BURNER ASSEMBLY CONCEPT (08-21-2001)

PUFF requires that a tubular shell of oxygen-replenished air, or co-flow surround its burner, traveling in a laminar, discrete fashion at a specified distance from the flame. This co-flow system will utilize both recirculated chamber air and fresh input gasses from the CIR using a circular gas distribution system that will concentrically surround the combustion volume. One concept under consideration is using a flow tunnel which is optimal for science analysis, but is much more difficult to implement in terms of engineering design, build, and resources. A newly proposed concept includes supply and return plenum assemblies on either end of the EMS to accommodate this requirement, theoretically without adding a flow tunnel. However, as in any challenging conceptual design there are open issues such as velocity profiles (vs. almost constant velocity) and the need for flow straighteners and/or the effectiveness of the return plenum. These and other concerns are currently in work.

V-Flames may also require a co-flow of nitrogen gas, pending outcome of ground tests of the pressure control system. Both experiments will require controlled continuous venting to maintain pressure within tolerance bands specified in their respective Science Requirements Matrix. This has been achieved by the CIR team during ground based testing by use of a mass flow controller on the vent line.

MGFA-B Diagnostics and Avionics/Software

MGFA-B will include similar EMS-mounted diagnostic sensors as MGFA-A: thermocouples, radiometers, etc.

Both PUFF and V-Flames require a special diagnostic called Particle Image Velocimetry (PIV) to obtain flow stream velocities and flow paths. The PIV velocity imaging is to be accomplished over a relatively small area utilizing individual digitized frames and a carefully timed laser pulse. This will allow the velocity vector of each individual particle to be determined as to both length and direction from a single image. Both the light source and camera will be specialized devices, closely coupled with respect to time. These camera and illumination system requirements are currently deemed outside of the scope of present and future planned capabilities of the CIR diagnostics, hence are planned to be provided by MGFA. In addition to PIV, each experiment will utilize some of the standard CIR camera packages.

The PIV particle injection system needs to inject 2 — 10 micron non-toxic silicon dioxide (or aluminum oxide) particles into the combustion gas flow stream. These particles will be released from the co-flow supply plenum area of the EMS. Due to their vectoral inertia, most of these particles will be deposited onto the EMS return plenum assembly.

PUFF and V-Flames will also utilize many of the standard CIR camera packages. At this time, PUFF is expected to utilize 7-8 UML locations and V-Flames will need six UML's for the combination of cameras, lasers, and image acquisition systems.

MGFA-B avionics and software are planned to utilize all of the MGFA- A subsystems; a unique set of software will be required for some PI unique experiment control and data.

Conclusion

NASA is building a highly successful microgravity gaseous combustion research program. The CM-1 experiment successfully achieved all of it science objectives and demonstrated the high value of space-based microgravity research for both science and engineering. The CM-2 experiment is poised to expand the work started with CM-1 with a launch scheduled for 2002. These efforts have evolved to help develop the future gaseous combustion mini-facility MGFA, in combination with the FCF/CIR facility, that will provide investigators with unparalleled access to space-based combustion research.

References

1. O'Malley, Terence and K. Weiland, "The Fluids and Combustion Facility Combustion Integrated Rack: Microgravity Combustion Science on Board the International Space Station", AIAA 2001-4927, Conference on International Space Station Utilization, Cape Canaveral, FL, 2001.
2. Otero, Angel M., "Multi-User Hardware Solutions to Combustion Science ISS Research", AIAA 2001-6527, Conference on International Space Station Utilization, Cape Canaveral, FL, 2001.
3. Myhre, Craig, "The Multi-user Droplet Combustion Apparatus", AIAA 2001-5043, Conference on International Space Station Utilization, Cape Canaveral, FL, 2001.
4. Frate, David T., "FEANICS-A Multi-user Facility for Conducting Solid Fuel Combustion Experiments on ISS", AIAA 2001-5079, Conference on International Space Station Utilization, Cape Canaveral, FL, 2001.
5. Urban, David L., "Structure and Soot Properties of Nonbuoyant Ethylene/Air Laminar Jet Diffusion Flames," AIAA Journal, Vol. 36, No. 8, August 1998.
6. Ronney, Paul D., "Experimental Study of Flame Balls in Space: Preliminary Results from STS-83," AIAA Journal, Vol. 36, No. 8, August 1998.