Results from on-board CSA-CP and CDM Sensor Readings during the Burning and Suppression of Solids – II (BASS-II) Experiment in the Microgravity Science Glovebox (MSG)

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For the first time on ISS, BASS-II utilized MSG working volume dilution with gaseous nitrogen (N_2). We developed a perfectly stirred reactor model to determine the N_2 flow time and flow rate to obtain the desired reduced oxygen concentration in the working volume for each test.   We calibrated the model with CSA-CP oxygen readings offset using the Mass Constituents Analyzer reading of the ISS ambient atmosphere data for that day.   This worked out extremely well for operations, and added a new vital variable, ambient oxygen level, to our test matrices.   The main variables tested in BASS-II were ambient oxygen concentration, ventilation flow velocity, and fuel type, thickness, and geometry.

BASS-II also utilized the on-board CSA-CP for oxygen and carbon monoxide readings, and the CDM for carbon dioxide readings before and after each test. Readings from these sensors allow us to evaluate the completeness of the combustion.   The oxygen and carbon dioxide readings before and after each test were analyzed and compared very well to stoichiometric ratios for a one step gas-phase reaction. The CO versus CO_2 followed a linear trend for some datasets, but not for all the different geometries of fuel and flow tested. We calculated the heat release rates during each test from the oxygen consumption and burn times, using the constant 13.1 kJ of heat released per gram of oxygen consumed. The results showed that the majority of the tests had heat release rates well below 100 Watts.   Lastly, the global equivalence ratio for the tests is estimated to be fuel rich: 1.3 on average using mass loss and oxygen consumption data.

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Nomenclature

BASS-II	= Burning and Suppression of Solids – II experiment in the MSG aboard ISS [1, 2]
C_{in}	= concentration of oxygen entering work volume, = 0 (pure nitrogen)
C_o	= initial concentration of oxygen in the work volume
C_{out}	= concentration of oxygen exiting the work volume, = c(t), a CSTR property
$C(t)$	= concentration of oxygen in the work volume as a function of time
CDM	= Carbon Dioxide Monitor, sensor aboard ISS (CO_2) [3]
CSA-CP	= Compound Specific Analyzer-Combustion Products, sensor aboard ISS (O_2, CO, others) [4, 5]
CSTR	= Continuously Stirred Tank Reactor
HRR	= Heat Release Rate, Watts
GMT	= Greenwich Mean Time, standard time on ISS
ISS	= International Space Station
LPM	= Liters Per Minute
MCA	= Major Constituents Analyzer, a mass spectrometer based system that measures the major atmospheric constituents on ISS, calibrated O_2 reference [6, 7]
MMA	= methylmethacrylate, monomer of PMMA released during material pyrolysis
MSG	= Microgravity Science Glovebox, a facility aboard ISS [8]
PMMA	= polymethylmethacrylate, (acrylic)
SMAC	= Spacecraft Maximum Allowable Concentration
V	= volume of MSG working volume, 0.25 m^3
r	= flow rate of gaseous N_2, 0.0005 m^3/min maximum, adjustable
t	= time, minutes
Φ_{global}	= global equivalence ratio, (Eq.(3)
τ	= residence time of the working volume, = V/r, minimum of 500 minutes

I. Introduction

THE Microgravity Science Glovebox (MSG) in the Destiny Lab of the International Space Station (ISS) provides a contained atmosphere in which we can conduct fire safety experiments [8]. The MSG has a set of filter banks that capture particulates and convert the CO (carbon monoxide) to CO_2 (carbon dioxide) using an ambient temperature catalyst. The Burning and Suppression –II (BASS-II) hardware is shown inside the MSG working volume in Figure 1. The BASS-II hardware consists of a flow duct, still camera, video camera, video and power boxes, external control box and associated plumbing and mounting systems. The black anodized 7.6 cm x 7.6 cm x 17 cm rectangular flow duct with rounded corners was originally built to perform gas jet diffusion flame studies [9], and was adapted to accommodate solid samples for the BASS experiments.
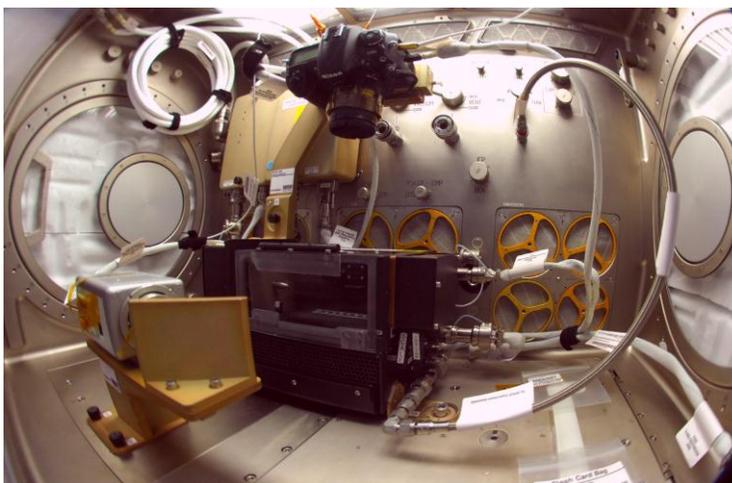
Figure 1. Microgravity Science Glovebox Facility (MSG) working volume aboard the International Space Station (ISS) , with the Suppression of Solids – II (BASS-II) experiment hardware installed. *The working volume of the MSG was diluted using ISS nitrogen gas. The CSA-CP (O_2 and CO) and CDM (CO_2) sensors were used to obtain before and after burn gas concentrations.*

The flow was blown through the duct using a small variable speed fan. In addition, up to two additional flow restrictors could be used at the fan inlet to increase the pressure drop and thus reduce the flow through the duct to the desired value for the test point. With no restrictors, the maximum flow velocity was ~55 cm/s, and with two restrictors this was reduced to ~35 cm/s. The flow then passed through a honeycomb flow straightener and an inlet screen to reduce swirl. An omnidirectional spherical air velocity transducer (TSI™[8] # 8475) was positioned between the honeycomb and the screen, and was used to measure the steady-state flow through the duct. The air velocity transducer probe had a response time of approximately one minute.
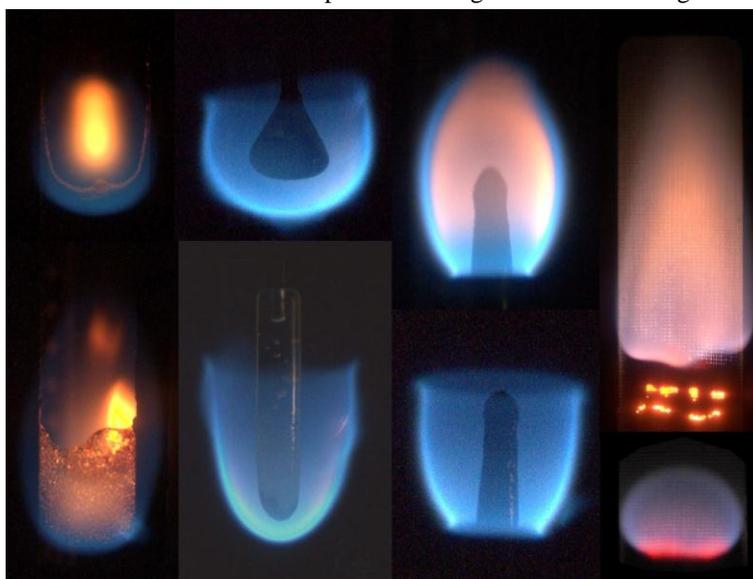
The test section was 17 cm long. Inside the test section was a nozzle for nitrogen flow, a moveable scale, and an Oriel™[8] #71768 thermopile detector with a CaFl windows (spectral range of 0.13 to 11 microns) in the downstream top back corner of the duct. The test section of the duct had two orthogonal windows; the top one was replaced for BASS to provide a mounting rail system for the solid samples. The top window was used by a Nikon™[8] D300 12.3 megapixel digital color still camera with a 60 mm lens that provided 4320 x 2968 pixel images. The duct exit contained a perforated copper plate followed by a brass screen to provide heat rejection and a cold surface for soot deposition. The flow turned ninety degrees to exit the duct, which facilitated mixing of the hot combustion gases with the cool ambient air.

The front window opened to provide access to the test section for sample and igniter change out. The front window also had interlocks for the igniter and nitrogen flow in the lower downstream corner. A Panasonic color video camera WV-CP654 (760 x 480 pixel array) with a turning mirror looked in the front window. The video camera had a built-in digital overlay that displayed the nitrogen flow rate (cm^3/min), fan voltage (10xV), air velocity transducer reading (cm/s), and the radiometer signal. The fan voltage was calibrated with the air velocity transducer at the end of every operations day. The radiometer signal was not calibrated, but provided a measure of the flame dynamics and steadiness. The external control box had controls for the fan voltage, nitrogen flow rate, enable switches for the igniter and nitrogen flow, and a radiometer gain level setting.

A number of sample geometries were used for BASS-II: Cast PMMA (polymethylmethacrylate) samples were shaped as rods of various diameters (6.35 to 12.7 mm), thin to thick slabs (0.125 to 5 mm), or a section of a 4 cm diameter sphere. In addition, flat cotton-fiberglass fabric samples were also burned. These samples could generally be mounted so that they could be burned in either the opposed or concurrent flow direction. The flat samples were 1 cm or 2 cm wide. The samples were manually ignited with a Kanthal™[8] A-1 29 gauge hot-wire igniter with a nominal hot wire resistance of 0.8 to 1 ohms, powered by 3.5-3.8 amps when the astronaut manually pulled the deployment lever to move the igniter into position. Samples were burned within the duct and the combustion products exited the duct and mixed with the gas in the work volume. Example flame images are shown in Figure 2.

Many samples are still on orbit, but 34 samples were returned and evaluated for mass loss.

To evaluate the levels of combustion products produced during microgravity fires, BASS-II requested the use of the on-board sensors to measure the O_2 (oxygen) depletion and the completeness of combustion (CO, CO_2) for microgravity combustion tests under spacecraft ventilation flow rates to provide scientific data on the stoichiometry of the diffusion flame reactions and heat release rates. The request was approved, and the data reported here is the first extensive data on the stoichiometry and toxicity of combustion products in microgravity.

Figure 2. Flame geometries tested in BASS-II. *Sample images from the different geometries, from top left to bottom right: opposed thin slab, spherical section, opposed rod higher flow, flat fabric sample at higher flow, opposed thick slab, concurrent rod, opposed rod at low flow with open tip (similar to concurrent rod), flat fabric sample at low flow). The forced flow is up in all images.*

The O_2, CO_2, and CO measurements required two portable, battery powered instruments in the working volume during testing: CDM (Carbon Dioxide Monitor), and CSA-CP (Compound Specific Analyzer-Combustion Products) [3-5]. The oxygen sensor (CSA-CP) is not recalibrated

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[8] Mention of trade names or commercial products is for descriptive purposes only and does not constitute endorsement or recommendation for use by the U.S. Government.

on orbit, so we also used the Major Constituents Analyzer (MCA) [6-7] data to determine the oxygen sensor offset on a daily basis. The resolution of the oxygen sensor in the CSA-CP was 0.1% O_2. Oxygen concentrations in the MSG working volume were varied during the testing from ambient ISS oxygen levels (~ 21% O_2) down to ~ 14% O_2 for very near-limit flames. The CO sensor in the CSA-CP is zero calibrated every 60 days, with a range of 0-1000 ppm and a resolution of 1 ppm. The CO_2 sensor was within its calibration window, and had a range of 0-5% and a resolution of 0.1% by volume of CO_2. The sensor data provided initial and final conditions for repeated tests in a sealed working volume, and allowed us to determine when the working volume needed to be purged. The O_2 decreased during each burn and the CO and CO_2 increased accordingly.

   Many of the BASS-II tests also required a diluted atmosphere, which typically took one to three hours to achieve by dilution of the MSG working volume using ISS nitrogen (from the hose connecting BASS-II duct to back wall of MSG in Figure 1).   The nitrogen was regulated with a small (< 0.5 liters per minute (LPM)) MKS™8 179A mass flow meter and entered the flow duct through a small nozzle just downstream of the fan. The fan in the flow duct was turned to maximum (>100 LPM) during the nitrogen flow to mix and blow the gas into the working volume and circulate it continuously throughout the hours-long dilution.

II.   Validation of MSG Dilution - Continuously Stirred Tank Reactor (CSTR) Model

To utilize the capabilities of MSG to reduce the oxygen in the working volume in a controlled manner, we developed a dilution model based on a Continuously Stirred Tank Reactor (CSTR) model. In this model, the mixing in the working volume (via the BASS-II duct fan) is assumed to be 'instantaneous', so that the outflow 'leak' concentration from the MSG work volume to the ISS cabin is the perfectly mixed instantaneous concentration. This perfect mixing approximation is valid as long as the residence time (V/r) is 5-10 times as long as the mixing time, which is easily the case for the 100 LPM flow rate during dilution (250 liters/100 LPM ~ 2.5 min mixing time). For the MSG volume and N_2 flow rates, the working volume residence time is V/r=500+ minutes, and the mixing time is certainly shorter than 50 minutes, so the assumption is valid.   The model assumes the work volume is at constant pressure and temperature, and constant volume. Thus the leak rate out of the work volume is equal to the rate of N_2 supplied (r).

The model is based on a mole balance on O_2 as follows:

   The control volume is the working volume, with an input of nitrogen and a leak rate of well-mixed gas.

   Boundary and conditions:

   C_{in} = 0 (pure N_2),

   C_{out} = c(t) (CSTR property),

   C(0) = C_o

The rate equation is given by

$$\frac{dc}{dt}V = r(c_{in} - c_{out}) = -rc_{out} = -rc \qquad \text{Eq.(1)}$$

Integrating and applying initial conditions:

$$c(t) = C_o \exp(\frac{-r}{V}t) \qquad \text{Eq.(2)}$$

Astronaut Chris Cassidy conducted a calibration test on the morning of GMT (Greenwich Mean Time) 2013-095 in the MSG using a CSA-CP sensor taking oxygen readings of the MSG working volume at intervals during the dilution. During dilution, the BASS duct fan was turned to maximum, and the working volume air circulation was deactivated. To validate the model, we used the following values in the model based upon the test conditions:

MSG working volume [8] = 0.255 m^3
BASS-II hardware = ~0.005 m^3
Net volume V ~ 0.25 m^3
N_2 flow rate in = 493 cm^3/min
(0.000493 m^3/min)
Initial O_2 concentration c(0) = C_o
CSA-CP sensor C(0)=20.9% O_2
ISS MCA = 21.48 % O_2 [10]

Figure 3 shows the calibration data compared to the model predictions for both the CSA-CP readings and corrected for the offset from the MCA. The model agrees very well with CSA-CP readings directly and corrected for the offset to provide a calibrated oxygen level with time. The curvature is minimal due to the slow rate of nitrogen flow into the large volume.

This model was used for subsequent BASS-II operations to determine the nitrogen flow rate and flow time to achieve the desired test oxygen concentration based upon the initial oxygen concentration and operational crew time constraints. It worked very well, and post-dilution CSA-CP readings agreed extremely well with the model predictions over a range of dilution rates, as shown in Figure 4. The out of calibration CSA-CP readings were then corrected for the offset from the MCA readings for that day to provide a calibrated oxygen reading for each test.

III.   Combustion Products

Sensor readings were taken before and after each BASS-II test. The sensor data is used to measure the O_2 depletion and the completeness of combustion (CO, CO_2) for each microgravity combustion test under spacecraft ventilation flow rates.

The oxygen depletion data is compared to the CO_2 production for each BASS-II test that used PMMA as the fuel.
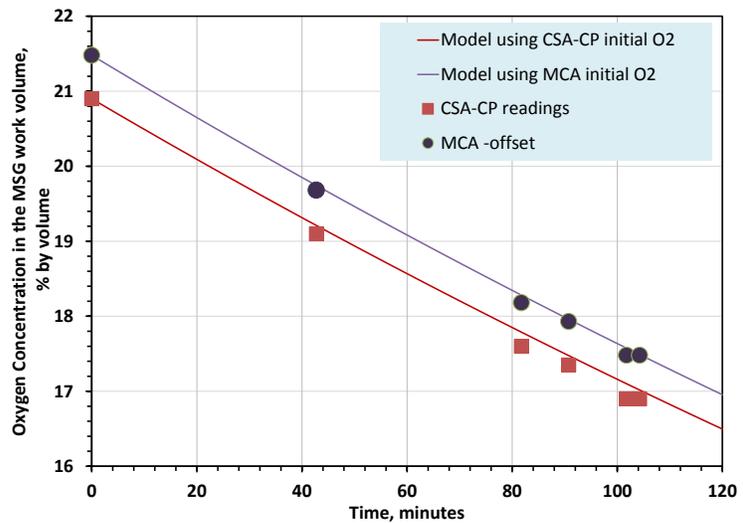
Figure 3.   Model verification of the CSTR modeling the MSG dilution using the CSA-CP sensor oxygen readings. *Sensor data taken at intervals during the dilution show how the measurements agree with the model curve(Eq.5). Data symbols are sized to ± 0.1% O_2, the resolution of the sensor. Raw CSA-CP data and corrected data for the MCA offset are shown with the model predictions using the initial reading as the starting value.*
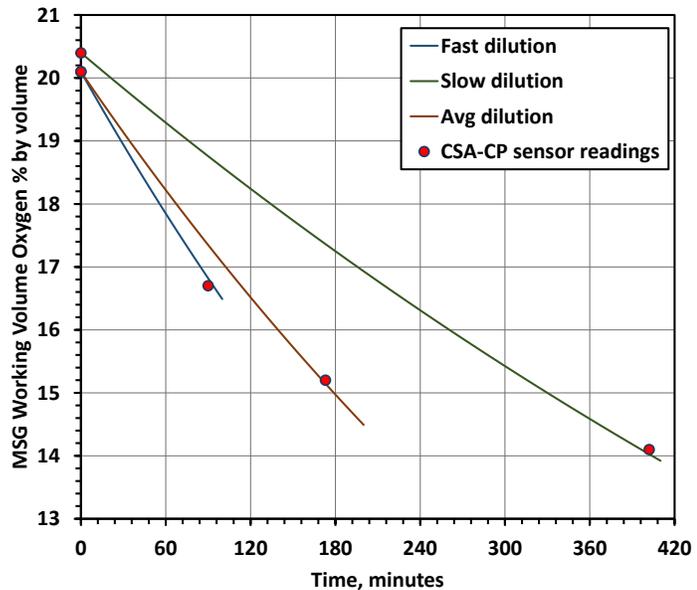
Figure 4.   Dilution model compared to fast, slow and average dilution rates during BASS-II operations. *Data from three BASS-II tests and CSTR model (Eq.2) results that show the range of dilution times and oxygen levels obtained. The control of both flow rate and dilution time allowed us to work around the crew's schedule while still obtaining the desired working volume oxygen concentration for the test.*

The PMMA stoichiometric equation is:

$$C_5H_8O_2 + 6\,O_2 > 5\,CO_2 + 4\,H_2O \qquad Eq.(3)$$

The data, taken over a wide range of initial oxygen concentrations, forced opposed or concurrent flow velocities, and using various sample geometries, is compared with this stoichiometric ratio ($6O_2 : 5\,CO_2$) in Figure 5. As shown, the data agrees very well with stoichiometric ratios, indicating that despite the varied test conditions, the vast majority of the oxygen consumed did indeed go into carbon dioxide.

Other than unburned fuel (primarily MMA (methylmethacrylate) vapor), which does contain some oxygen as shown in Eq. 6, the only other potential species with oxygen is carbon monoxide, which was also measured, as shown in Figure 6. The concurrent rods produced on average 550 ppm of CO for every 1% of CO_2. The opposed rods had a very non-linear response, which may be indicative of a flow effect.

The longer the burn, the more CO_2 was formed, and the nominal test procedure for most samples was to turn the flow down in increments. At very low velocities, the tail region of the opposed flow flames opened up, which presumably allowed incomplete combustion products to escape the flame zone. Interestingly, the concurrent procedure was very similar, but the concurrent flame always had an open tail, allowing incomplete combustion products to exit throughout the burn. The opposed thick slabs fall somewhere in between, producing on average 370 ppm of CO for every 1% of CO_2.

The one outlier point from Figure 5 at 2.8% CO_2 is not included on Figure 6 since the CO sensor was over-ranged for this test (> 1000 ppm), so we have no quantitative value for CO for this test. During this test, the long burn of the relatively strong flame caused some overheat damage to the downstream lower corner of the front window in the area where a leak was occurring. The leak was repaired and operations proceeded without further incident.
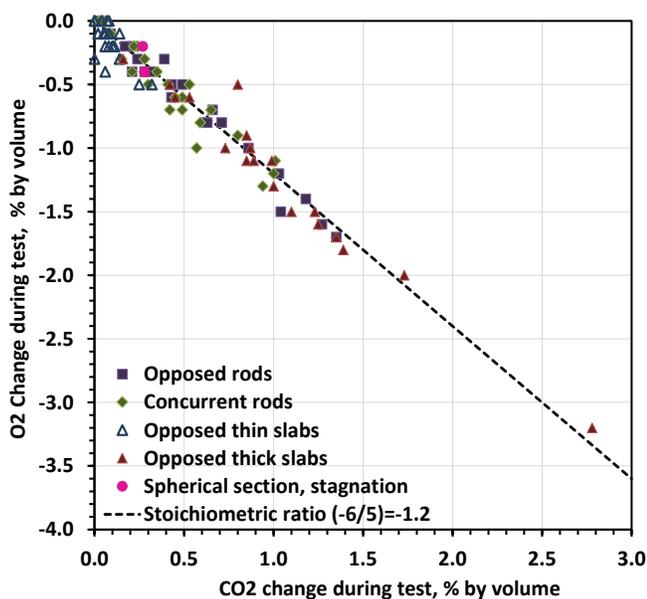
Figure 5. Oxygen depletion and Carbon Dioxide production during BASS-II tests with PMMA fuel. *The data from different geometries, flows, and initial oxygen concentrations all agree with the expected stoichiometric trend (shown by the dashed line).*
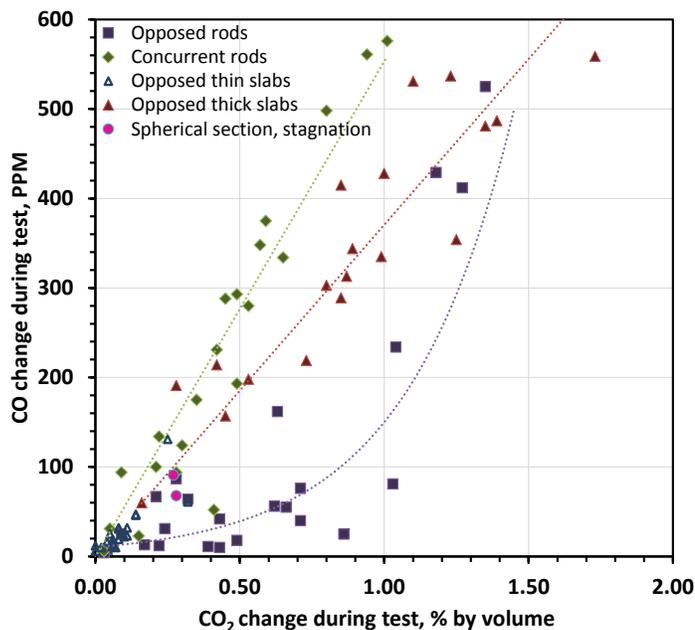
Figure 6. Carbon monoxide generated compared to Carbon Dioxide generated in each test. *The CO generated appears to be clustered by geometric and flow configurations. The concurrent rod geometry produced the most CO per CO_2, and the opposed rods showed a very non-linear trend of CO versus CO_2 production. Thick opposed flow slabs fell in between the two.*

Of interest to the combustion community is the ratio of CO to CO_2, a measure of completeness of combustion, which is plotted in Figure 7 as a function of the initial oxygen concentration in the working volume. For efficiently burned flue gasses (boilers, furnaces, etc.), this ratio is on the order of 0.002. As can be seen most of our data is an order of magnitude above that. This indicates that microgravity flames are not very efficient.

Although the absolute values of CO are very high in the 250 liter MSG working volume, the MSG contained and converted the CO to CO_2 during the post-test work volume purge. Since the ISS is quite large, the combustion products from a fire of the scale of a BASS-II test would quickly be diluted, so that even within just the US Lab (106 m^3 pressurized volume), the CO levels in the lab would only be 1.5 ppm, well below SMAC (Spacecraft Maximum Allowable Concentration) values for even long term exposure (10 ppm), let alone the 1 hour SMAC of 55 ppm [11].

Lastly, the heat release rates (HRR) from these small microgravity fires can be estimated using Huggett's oxygen consumption calorimetry [12] and the burn time for each test. Using his constant of 13.1 kJ/g O_2, we estimate the heat release rate to be typically well below 100 W, as shown in Figure 8. There is a trend of increasing HRR with increasing ambient oxygen concentration, and the scatter is attributed to the different duct flows between and even within the tests.

The one long opposed thick slab test that caused the lower downstream corner of the front window damage released close to 100W. A prior relatively brief concurrent rod test that released almost 110 W did not cause any damage.

IV. Global Equivalence Ratio

To date, 34 burned BASS-II samples have been returned to Earth for post-flight analysis. Eight of those samples had been used for multiple tests, and were altered on
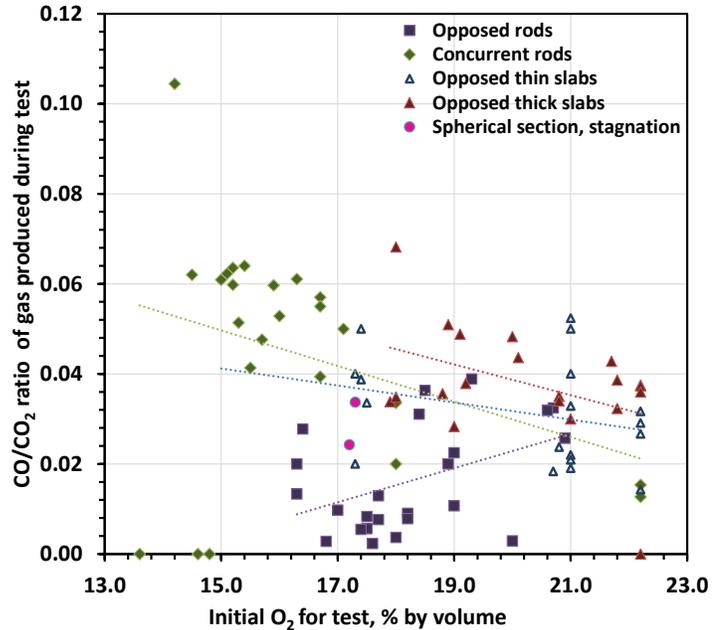
Figure 7. CO / CO_2 ratio as a function of the initial oxygen concentration for each test. *There is some clustering apparent in the data, which shows that lower oxygen concentrations produce higher levels of CO per CO_2 for concurrent rods, especially when compared to the opposed rods which shows the opposite trend. The opposed slab data has a similar trend to the concurrent rod data, although the scatter is large.*
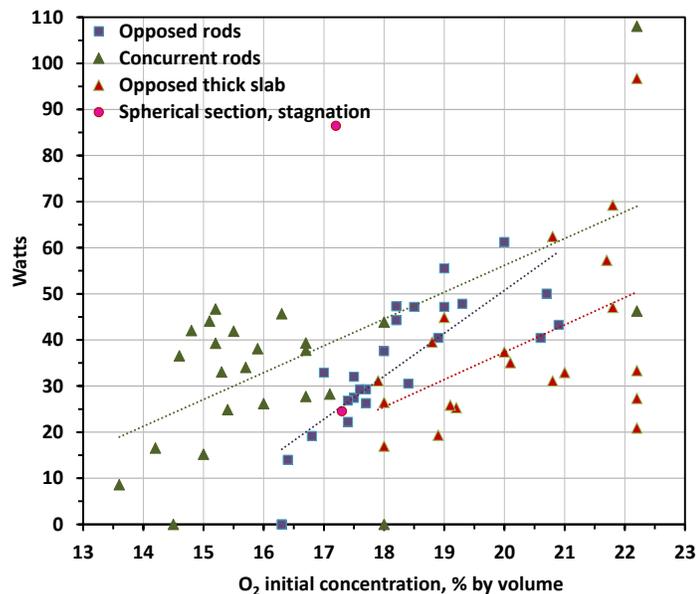

Figure 8. Heat release rate during each test using oxygen consumption calorimetry. *The data from Figure 5 is converted to Watts using the burn time and Huggett's constant, plotted against initial O_2, showing the heat release rate generally increases with increasing ambient oxygen concentration. The magnitude of the heat release rate is modest for these small flames.*

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orbit by having their burned fuel cut off and/or their built-in igniter leads removed. As a result, the pre and post-flight weights for these modified samples cannot be used to determine the mass loss due to combustion. Also, seven additional samples had burns that were so short that no oxygen consumption was measured, and so are not usable for the global equivalence ratio estimates.

For the remaining 19 samples, mass loss is compared to oxygen consumption, as shown in Figure 9.

There are clear trends observed for O_2 consumption and CO_2 generation relative to measured fuel mass loss. Given the previous stoichiometric relation between O_2 and CO_2, it is not surprising that the two trends mirror each other. The CO data is more scattered, but CO generation generally increases with increasing fuel mass loss.
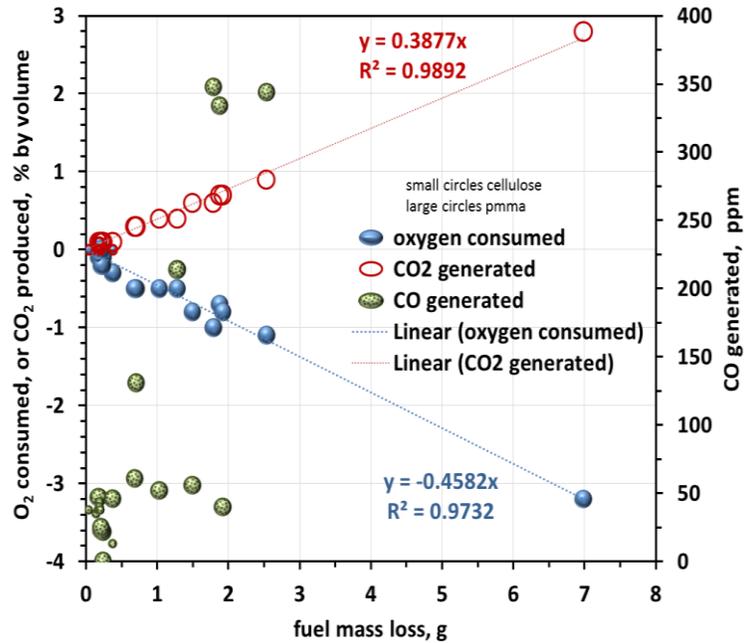
Figure 9: *Oxygen consumed, Carbon Dioxide and Carbon Monoxide generated per gram of fuel mass loss for two different fuels tested (cellulose and pmma).*

We can evaluate the fuel/oxygen ratio based upon these test results. The global equivalence ratio can be expressed for either cellulose or PMMA fuel stoichiometry as

$$\Phi_{global} = \frac{gmol\ fuel/gmol\ O_2}{1/6} \qquad \text{Eq.(3)}$$

Using the ideal gas law, the free volume of MSG of V=250,000 cc, ideal gas constant R=82.05 cc-atm/gmol K, P= 1 atm, and T=300 K, the gmol of O_2 consumed is calculated as

$$gmol\ O_2\ consumed = \frac{RT}{PV} = \frac{82.05 * 300}{1 * \% O_2\ by\ vol/100 * 250,000} \qquad \text{Eq.(4)}$$

The gmol of fuel consumed is simply

$$gmol\ fuel = \frac{g\ fuel}{molecular\ weight} \qquad \text{Eq.(5)}$$

Using the observed slope of 0.4582 O_2% by vol / g fuel, and the molecular weight for pmma of 100 g/gmol for the majority of the data, we can use the above equations to solve for the effective equivalence ratio for the tests: Φ_{global} = 1.3, which is fuel rich. So in general, the flames were under-ventilated and did not burn all of the vaporized fuel. Some fuel ended up as soot, some as CO, and some as unburned hydrocarbons.

V. Conclusions

As part of the BASS-II experiment, we conducted a number of tests with different geometries, flow velocities, and initial oxygen concentrations. The last variable was enabled by the use of gaseous nitrogen to dilute the working volume. To adequately characterize this dilution, we developed a CSTR model and verified it against sensor readings.

Sensor data from the tests showed that the oxygen was burning nearly stoichiometrically to CO_2, and that CO levels appear to be a function of geometry and, in some cases, the flow velocity/geometry combination. The CO/CO_2 ratios for these fires are an order of magnitude higher than for efficient flue gases, indicating that these flames are not efficient. The heat release was estimated for the tests using oxygen consumption calorimetry. This showed that most of the tests released well below 100 Watts. In the one long test that released close to 100W, we did sustain some damage to the downstream corner of the front window, due to a leak that directed the heat from this energetic flame to that location during the prolonged burn. Using the mass loss data and oxygen consumption data, the global equivalence ratio for the tests is estimated to be 1.3 on average, which indicates the flames were burning fuel rich under the low velocity forced flow conditions.

VI. Acknowledgments

VII. References

[1] Olson, S. L., Ferkul, P. V., Bhattacharjee, S., Miller, F. J., Fernandez-Pello, A. C., and T'ien, J. S.; "Burning and Suppression of Solids – II Fire Safety Investigation for the Microgravity Science Glovebox", presented at the 29th annual meeting of the American Society for Gravitational and Space Research (ASGSR) and the 5th International Symposium on Physical Sciences in Space (ISPS), Orlando, FL, Nov. 3-8, 2013.

[2] http://www.nasa.gov/mission_pages/station/research/experiments/1262.html; http://www.nasa.gov/mission_pages/station/research/experiments/735.html

[3] Limero, T., Beck, S., and James, J., "Evaluation of a Portable Carbon Dioxide Monitor for Use Aboard the International Space Station," SAE Technical Paper 2000-01-2433, 2000, doi:10.4271/2000-01-2433.

[4] Limero, T., Beck, S., and James, J., "Development and Performance of the Oxygen Sensor in the CSA-CP Aboard the International Space Station," SAE Technical Paper 2004-01-2337, 2004, doi:10.4271/2004-01-2337.

[5] Limero, T., Beck, S. W., & James, J. T. (2002). The Portable Monitor for Measuring Combustion Products Aboard the International Space Station (No. 2002-01-2298). SAE Technical Paper.

[6] Steiner, G., McHard, R., Reysa, R., and Granaham, J.; "Accuracy Assessment of the Major Constituent Analyzer", 2005-2893, SAE Technical paper, 2005.

[7] Reysa, R., Granahan, J., Steiner, G., Ransom, E., & Williams, D. E. (2004); "International Space Station (ISS) Major Constituent Analyzer (MCA) On-Orbit Performance" (No. 2004-01-2546). SAE Technical Paper.

[8] Reggie A. Spivey, William A Sheredy, and Ginger Flores; "An Overview of The Microgravity Science Glovebox (MSG) Facility, and the Gravity-Dependent Phenomena Research Performed in the MSG on the International Space Station (ISS)", 46th AIAA Aerospace Sciences Meeting and Exhibit, 7 - 10 January 2008, Reno, Nevada, AIAA-2008-812.

[9] Dotson, K. T., Sunderland, P. B., Yuan, Z. G., & Urban, D. L. (2011). Laminar smoke points of coflowing flames in microgravity. Fire Safety Journal, 46(8), 550-555.

[10] Mass Constituents data from ISS, data available online at https://mod2.jsc.nasa.gov/di/di52/constituentmonitor/

[11] JSC 20584; "Spacecraft Maximum Allowable Concentrations for Airborne Contaminants", 1999.

[12] Huggett, C. Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements, Fire Mater. 4, 61-65 (1980).