ICES-2022-005

Suborbital Testing of the OSCAR Trash-to-Gas System

Ray P. Pitts[1], David Rinderknecht[2], Dr. Joel A. Olson[3], Malay G. Shah[4], Jaime Toro Medina[5], and Dr. Annie J. Meier[6]
National Aeronautics and Space Administration, Kennedy Space Center, FL, 32899

With the sustained human exploration of nearby celestial bodies on the horizon, a renewed outlook on crew waste management must be realized. Current waste management strategies aboard the International Space Station become impractical as we venture beyond low Earth orbit. Furthermore, for future exploration missions, extracting resources from various waste streams becomes increasingly advantageous. One method of combatting the long-duration waste management problem is by thermally degrading solid and liquid crew waste items into a chemically inert, ventable gas stream, a process known as Trash-to-Gas. The Orbital Syngas/Commodity Augmentation Reactor (OSCAR) is the state-of-the-art Trash-to-Gas system which has been designed to explore microgravity Trash-to-Gas concepts for improved mass/volume reduction and resource recovery from waste. OSCAR is a subscale testbed design that supports the NASA Logistics Reduction project under the Advanced Exploration Systems Program and Space Technology Mission Directorate Flight Opportunities Program to determine the feasibility of Trash-to-Gas technology for future use on long duration space missions. OSCAR has flown on two suborbital flight demonstrations aboard Blue Origin's New Shepard launch vehicle. This paper presents a high-level comparative analysis of these microgravity test campaigns with Earth gravity laboratory experiments. Solid-to-gas conversion, gas production & composition, and reactor temperature & pressure are compared to highlight the operational factors and performance differences within the microgravity environment for future optimization.

Nomenclature

BPA	=	Brine Processor Assembly
CH_4	=	methane
CO	=	carbon monoxide
CO_2	=	carbon dioxide
DAC	=	data acquisition and controls
EPA	=	Environmental Protection Agency
FP	=	food packaging
g	=	gram
GC	=	gas chromatography
GC-MS	=	gas chromatography – mass spectrometry
GRC	=	Glenn Research Center
HFWS	=	High Fidelity Waste Simulant
IPC	=	Integrated Payload Controller
ISS	=	International Space Station
kPa	=	kilopascal
KSC	=	Kennedy Space Center
LEO	=	low earth orbit
μg	=	microgravity
MECO	=	main engine cut off
mmol	=	millimoles
N_2	=	nitrogen
NASA	=	National Aeronautics and Space Administration
O_2	=	oxygen

[1] Research Engineer, Exploration Systems and Development Office, KSC UB-E0.
[2] Chemical Engineer, Analytical Laboratories Branch, KSC NE-L3.
[3] SME 2: Sr. Analytical Chemist, Laboratory Support Services and Operations, Mail Stop: LASSO-008.
[4] Thermofluids Engineer, Advanced Engineering Development Branch, KSC NE-L6.
[5] Software Engineer, Testing and Design Branch, KSC NE-L1.
[6] KSC Point of Contact for In-situ Resource Utilization, Exploration Systems and Development Office, KSC UB-E0.

OSCAR	=	Orbital Syngas/Commodity Augmentation Reactor
OWS	=	OSCAR Waste Simulant
s	=	seconds
SPK	=	Software Payload Kit
ST	=	Smoldering Tank
Syngas	=	synthetic gas
T1	=	Gas Tank 1
T2	=	Gas Tank 2
T3	=	Gas Tank 3
TC	=	thermocouple
TtG	=	Trash-to-Gas
UPA	=	Urine Processor Assembly
wt%	=	weight percent
ZGF	=	Zero Gravity Facility

I. Introduction

Long duration space habitation poses various challenges that cannot be fully understood while in the comforts of low Earth orbit (LEO). One challenge that is further exacerbated during human spaceflight beyond LEO is waste management on board crewed spacecraft. Current waste management strategies aboard the International Space Station (ISS) consist of manually packaging all types of waste products into what is called a trash "football", placing these "footballs" into waste stowage bags and storing the waste stowage bags in a visiting logistics module to eventually be deorbited and burned upon re-entry in Earth's atmosphere.[1] As we travel deeper into space, such strategies are impractical for three reasons: they rely upon Earth's relatively dense atmosphere, they require the repeated deorbiting/destruction of supplementary logistics modules, and they dispose of valuable resources that can be reutilized to enhance mission sustainability and cost-efficiency.

Simply storing the waste items aboard the space habitat (the so-called 'stowage model') will not suffice either. During exploration missions, it is estimated that a crew of four will produce ~2122 kg/year of waste, including both metabolic and non-metabolic waste streams.[1] During a prospective 850-day Mars mission, this accumulates to several tons of waste being stored within the habitat, leading to a considerable decrease in crew habitable volume and requiring additional propellant for the spacecraft's necessary late-stage orbital maneuvers due to the presence of excess waste mass.[3] Thus, a waste volume and mass reduction strategy must be developed to enable future long duration crewed missions. One solution to this problem has been developed at NASA's Kennedy Space Center (KSC) and has since been termed Trash-to-Gas (TtG). TtG is the process of gasifying crew waste items via a thermal degradation process (combustion, pyrolysis, steam reforming, etc.) to produce gaseous products that can either be vented overboard or repurposed as a functional commodity. This method satisfies the necessary requirements of waste mass and volume reduction, has the ability to reuse resources from the available waste streams (water, oxygen, syngas), and mitigates potential concerns with orbital debris or planetary protection due to waste material disposal.

TtG is an ongoing effort since 2012, and several thermal degradation processes have been explored to better understand which methods are most applicable for the long duration microgravity environment. Previously studied thermal degradation processes include combustion, steam reforming, plasma gasification, pyrolysis, incineration, oxygen-enriched steam reforming, and torrefaction.[1,2] An up-to-date trade study was reported baselining the current performance metrics of the various thermal degradation processes, as was a follow-up study that investigated the effects of different TtG technologies on the overall propellant requirements for a crewed Mars mission.[1,3] The state-of-the-art TtG system is the Orbital Syngas/Commodity Augmentation Reactor (OSCAR). OSCAR uses combustion and has been developed at KSC since 2018. The OSCAR system is depicted in Figure 1. OSCAR has successfully demonstrated

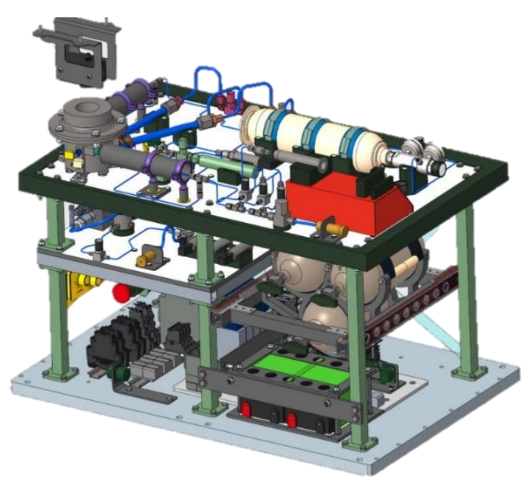


Figure 1. OSCAR System Design.

subscale TtG feasibility in microgravity via 2.2 second μg Drop Tower and 5 second μg Zero Gravity Facility (ZGF) testing at NASA Glenn Research Center (GRC), along with two 3-minute μg demonstrations aboard Blue Origin's New Shepard suborbital launch vehicle. The results and findings from the previous testing campaigns can be found in their respective publications.[4-7] OSCAR completed its second suborbital flight on August 26th, 2021; the results from this flight, comparing to the first suborbital flight and Earth gravity laboratory experiments, are the focal point of this paper.

Microgravity presents a unique environment for trash combustion processes that cannot be observed during ground tests on Earth.[8] Particularly, the lack of buoyancy and thus natural convection heat transfer, the ability for solid fuel materials to float freely within the reactor volume, and the differing boundary layer interactions should affect the combustion behavior during trash deconstruction in microgravity. Therefore, the principal question remains: will these environmental differences in microgravity significantly hinder overall combustion performance of various trash materials?

II. Methods & Design

OSCAR uses combustion to thermally degrade crew waste material of up to 10 grams.[4] To best approximate the waste composition that may be expected during future exploration missions, a variation of high-fidelity waste simulant (HFWS), called OSCAR waste simulant (OWS), was used during both suborbital flight demonstrations and associated laboratory testing. The waste items that comprise OWS are shown in Table 1. With the current application of the Urine Processor Assembly (UPA) and recent development of the Brine Processor Assembly (BPA) aboard the ISS, urine was not included as an OWS component, which is the major deviation from the original HFWS.[2] Waste components that amounted to less than 1 wt% of the total waste stream were not included in this study due to the relatively small sample size used for these suborbital flight experiments.

Table 1. OSCAR Waste Simulant Composition.

Waste Material	% of OWS (wt%)
Clothing	17.9%
Food Packaging (FP)	13.4%
FP Overwrap	13.4%
Cotton	9.5%
Tech Wipes	3.6%
Toilet Paper	3.6%
Nitrile Gloves	1.6%
Fecal Simulant	13.4%
Wet Wipes	10.8%
Food Simulant	10.6%
Toothpaste	1.2%
Shampoo	1.2%

A. System Design & Launch Operations

The OSCAR experimental design was configured to perform a set of combustion batch events using OWS during approximately three minutes of microgravity. Thus, several aspects of the experimental design were modified to satisfy the brief microgravity duration (pre-heat time, gasification time). To best capture the OSCAR test sequence, an overall process diagram of the OSCAR system is shown in Figure 2.

Prior to launch, samples of OWS were placed within the reactor, and within two pneumatic injection tubes. The pneumatic injection tubes were pressurized with air up to ~793 kPa. The reactor was initially set to ambient pressure with air. All gas colletion vessels, Gas Tanks 1-3 and the Smoldering Tank, were evacuated to less than 0.7 kPa pre-flight. An overview of the reactor settings used for the OSCAR suborbital flights and laboratory experiments is shown in Table 2.

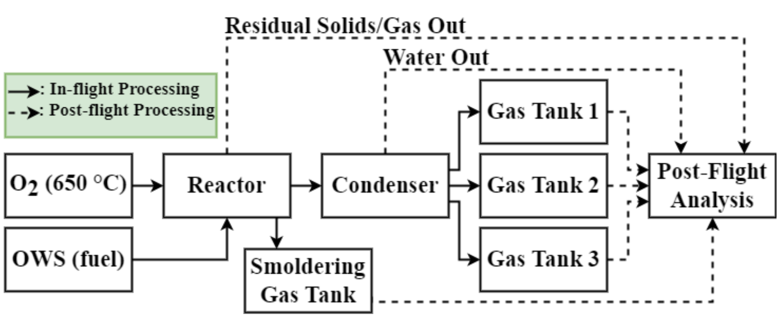


Figure 2. OSCAR Process Diagram.

Once liftoff was detected, two gas-lines were heated to a setpoint temperature to pre-heat the oxygen introduced to the reactor. Oxygen began flowing into the reactor after main engine cut off (MECO) was detected, up to the pressure setpoint of 308.2 kPa. As the payload entered the microgravity phase of the flight, three cartridge heaters within the reactor turned on, acting as ignition sources for the OWS fuel and intiating the gasification process of the first batch that was placed in the reactor pre-flight. Secondary and tertiary batches of OWS were pneumatically injected into the reactor in timed intervals to maintain OWS combustion throughout the entire three minutes of microgravity. The hot combustion products were forced downstream to a condenser, where the water was removed, and the dry gases were then transported into Tanks 1 – 3. After the microgravity phase ended, the reactor cartridge heaters were turned off, oxygen flow was halted, and the smoldering tank was opened to capture the gaseous products that were produced post-microgravity. Gases that remained in the reactor post-flight were also collected. After touchdown, all gases were then collected for subsequent analyses via Gas Chromatography (GC) and Gas Chromatography-Mass Spectrometry (GCMS).

For suborbital Flight 1, each of the three collection tanks were opened to capture the primary, secondary, and tertiary waste burns sequentially. The intent was to capture gases from the first, second, and third OWS burns individually. But with the complicated timing involved with the internal flow, this did not occur as expected. In addition, the resulting pressures in each gas tank were low, such that they required pressurization via gas dilution in order to capture gases effectively for analyses. To get a more representative product mixture for the second flight, the timings were changed to ensure apt gas collection for GC analysis to avoid the need for dilution post-flight.

Table 2. OSCAR Reactor Settings.

Parameter	Value
Reactor Pressure (kPa)	308.2
Reactor Volume (m^3)	8.9E-04
Max Reactor Temp. (°C)	800.0
O_2 flow rate (m^3/s)	5.0E-05

For suborbital Flight 2, Tank 1 (T1) was opened during the pre-microgravity phase of the flight. This captured the oxygen that flowed through the system prior to the gasification process during microgravity. T1 then closed and Tank 2 (T2) opened approximately 10 seconds after microgravity was detected; this 10 second offset was determined empirically during pre-flight laboratory tests based on the ignition time of OWS once the reactor cartridge heaters are enabled. The first OWS injection event occured approximately 57 seconds after T2 was opened. Midway through the microgravity phase, T2 was closed and Tank 3 (T3) was opened. The final OWS injection event occured approximately 27 seconds after T3 was opened and T3 remained open until the microgravity phase had ended. Post-microgravity, T3 closed and the Smoldering Tank (ST) was opened in order to capture any smoldering events that may have transpired within the reactor after the oxygen flow had halted. ST remained open for approximately 80 seconds before OSCAR was fully safed in preparation for capsule landing. Eight hours after launch, the OSCAR team received T1-T3. One day after launch, the OSCAR team received the rest of the OSCAR system, allowing for the collection of the reactor and smoldering gases and permitting mass measurements of key OSCAR components.

The operational differences between Flight 1 and Flight 2 are shown in Table 3. Due to the small batch amounts used for Flight 1, a ceramic cone was inserted into the reactor to reduce the reactor volume and help facilitate interactions between the fuel and ignition source (cartridge heaters). The larger batch amount used for Flight 2 did not necessitate the use of the ceramic cone and, thus, it was removed for Flight 2.

Table 3. Operational Differences Between Flight 1 and Flight 2.

Parameter	Flight 1	Flight 2
OWS cut size (mm)	5	5
Reactor Batch Mass (g)	4.5	8
Injection Tube Batch Mass (g)	1	1
T1 Open	Coast Start	MECO + 5 s
T1 Close	Trash Injection 1	Coast Start + 10 s
T2 Open	Trash Injection 1	Coast Start + 10 s
T2 Close	Trash Injection 2	T2 Open + 78 s
T3 Open	Trash Injection 2	T2 Close
T3 Close	Coast End	Coast End
Trash Injection 1	Coast Start + 56 s	T2 Open + 57 s
Trash Injection 2	Trash Injection 1 + 48 s	T3 Open + 27s
Injection 1 Success / Injection 2 Success (%)	100% / 0%	100% / 100%
O_2 Preheat Temperature (°C)	400	650

Ground testing was performed at KSC prior to the suborbital flight using Blue Origin's Software Payload Kit (SPK). The SPK simulates flight trigger events and warnings based on simulated signals representative of a real flight, and communicates that information to OSCAR through the Integrated Payload Controller (IPC). After the suborbital flight, data was collected and flight discrepancies were noted, such as premature and delayed trigger timing. Upon returning OSCAR to KSC, the team performed a triplicate of ground tests that mimicked the actual observed flight timings and conditions.

B. Analytical Methods

1. In-Flight Data Collection

OSCAR is equipped with a state-of-the-art data acquisition and controls (DAC) system from National Instruments. The system was designed to collect data from scientific experiments, monitor the conditions during operations, and provide manual and automated control for execution. During flight, the IPC broadcasts the event triggers of the flight as they occur. The OSCAR DAC used these triggers to execute the experiment in an automated manner. A flight sequence was pre-programmed on the OSCAR controller to execute this sequence as soon as the flight vehicle energized the OSCAR payload during the final countdown before liftoff. During flight, pressure, temperature, commands, and flight timestamps were recorded on the DAC system and retrieved at touchdown. Various pressure measurements were captured using stainless steel OMEGA™ pressure transducers (0-689.5 kPa). The reactor temperature was measured using an OMEGA™ multi-point thermocouple that captured the reactor temperature at four different locations along the axial direction of the reactor.

2. Mass Analysis

Conversion metrics were established via mass measurements of the trash and reactor components pre- and post-experiment. These components were then dried at 100°C for 24 hours before re-weighing. The dried masses were the values included in the solid-to-gas conversion calculations. Gas product masses were quantified by combining pressure, temperature, volume and gas composition data. The expected range of error from measurement for the total mass is +/- 0.07 g. This uncertainty does not account for operator sampling error.

3. Gas Production Analysis

All gas collections were performed by connecting the respective sources directly to evacuated Entech™ 1.0×10^{-4} m^3 gas sampling canisters. Compositions were analyzed with an Inficon Micro GC Fusion™ for bulk gases (CO_2, CO, CH_4, O_2, N_2) and an Agilent™ 6089N/5973 GCMS for trace gases. Additionally, samples were collected with evacuated 4.5×10^{-4} m^3 gas sampling canisters and later sent to the JSC toxicology lab for in-depth trace gas analysis (via Environmental Protection Agency (EPA) method TO15). These trace gas analyses are not reported in this paper but will be the focal point of a future publication.

Bulk gas quantitation is subject to a relative measurement uncertainty of < 2.5% when summing the uncertainty from the pressure transducer measurements and the standard deviation from GC calibration measurements. Unquantified error exists from temperature and pressure sensor location limitations.

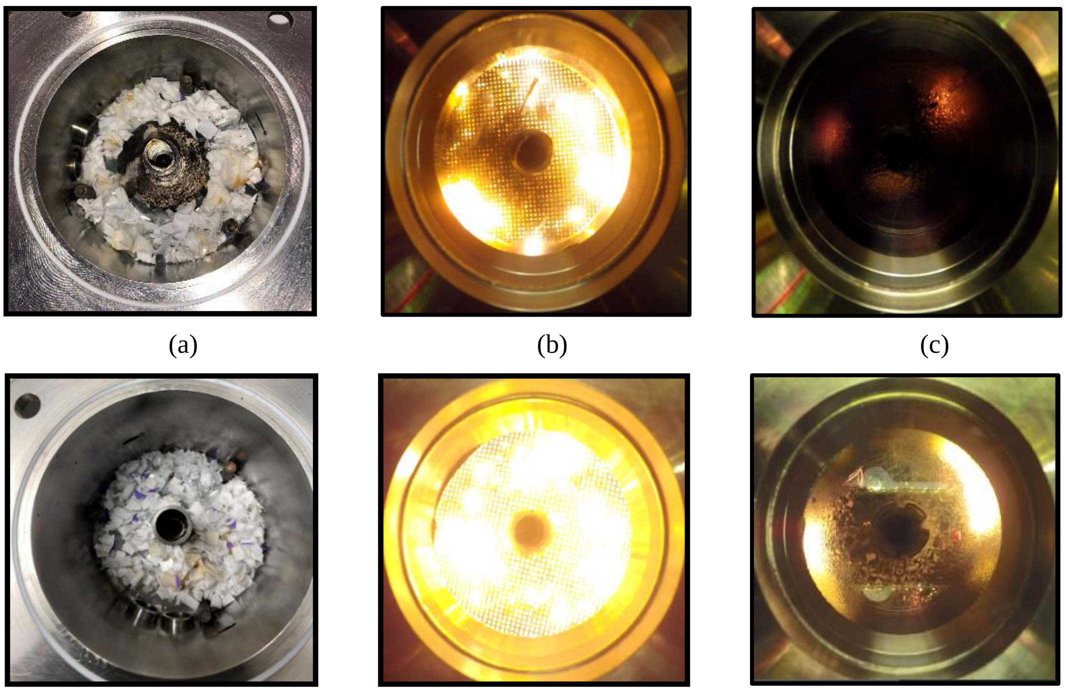
III. Results & Discussion

Both Flight 1 and Flight 2 successfully demonstrated Trash-to-Gas operations in the microgravity environment. During Flight 1, a few anomalies occurred which created an unidealized reactor environment during flight which hindered the quality of the flight data. Leveraging the lessons learned from Flight 1, the anomalies were overcome for Flight 2 producing a nominal flight sequence. Figure 3 shows still frames from the video data displaying the combustion activity pre-microgravity (Figure 3(a), (d)), the initial ignition event (Figure 3(b), (e)), and combustion midway through the microgravity phase of Flight 1 and Flight 2 (Figure 3(c), (f)). Post-flight ground tests mimicked the parameters that were observed during both the flight experiments. Due to the inherent difficulties with mimicking numerous flight anomalies during Flight 1 ground testing, Flight 2 data can be viewed as a more representative comparison of Trash-to-Gas performance between the flight and subsequent lab-based ground comparisons. The flight differences are listed below:

1. For Flight 1, only the first injection event transported the trash batch into the reactor; the second injection was unsuccessful (the trash was left in the injection tube). For Flight 2, both injection events

resulted in 100% trash injection. All ground tests observed incomplete injection in both injection tubes for each test. Thus, ≥80% injection success rate was deemed viable for ground testing.

2. A flat mesh was installed inside the reactor to contain all trash material near the cartridge heaters (ignition points). During Flight 2, the flat mesh was observed to shift upwards in the reactor volume (~16 mm above cartridge heaters toward the viewport), allowing the trash to move within the reactor more freely. For Flight 1 the flat mesh did not shift upwards during flight.
3. For Flight 1, a leak was observed in the oxygen tank lines. This leak caused flow decay in the oxygen input line, which led to decreased combustion as a result of reduced mixing and a probable oxygen deficiency in the final portion of the experiment. Flight 2 oxygen flow maintained nominal levels throughout the experimental duration.
4. Due to design limitations, reactor gases could not be collected for Flight 1. Flight 2 successfully captured the reactor gases.



(a) (b) (c)

(d) (e) (f)

Figure 3. Top view of the reactor. Trash material pre-Flight 1 (a), Flight 1 microgravity initial ignition (b), Flight 1 combustion events midway through microgravity phase (c). Trash material pre-Flight 2 (d), Flight 2 microgravity initial ignition (e), Flight 2 combustion events midway through microgravity phase (f).

A. Reactor Pressure & Temperature

Figure 4 shows the progression of the combustion process during Flight 2. The cartridge heaters were powered on immediately after the “Coast Start” signal (A). “Coast Start” marks the beginning of the microgravity phase, dictated by a Blue Origin on/off signal. On-board accelerometers were utilized to verify this Blue Origin microgravity signal (B). The initial ignition event was observed to occur approximately 14.4 seconds after cartridge heater power which was consistent with both pre- and post-flight ground tests. A large pressure spike was generated due to the sudden temperature increase associated with the ignition event (C); the reactor pressure spikes associated with the secondary and tertiary batch injections can also be seen in this figure (D, E). Corresponding temperature increases associated with these ignition events can be seen in the yellow/orange plot (second from bottom in Figure 4) showing the TC2 temperature values.

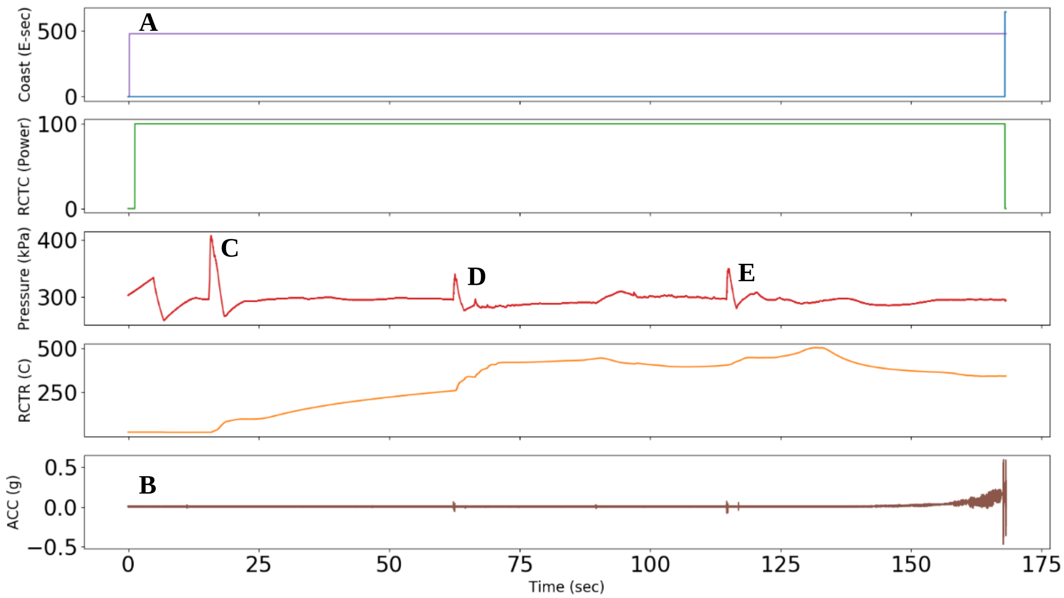


Figure 4. OSCAR Flight 2 Test Progression showing the coast signal (top), cartridge heater power (second from top), pressure (middle), temperature (second from bottom), and acceleration (bottom).

Microgravity reactor pressure spikes due to the initial ignition event were observed to be of lower magnitude than any of the ground tests, as shown in Table 4. Flights 1 and 2 are single measurements from their respective suborbital flight campaigns. Lab Flight 1 and Lab Flight 2 values are an average of three ground tests performed at KSC; error values in this table represent the standard deviation of the test triplicate. Ground tests are characterized by larger pressure spikes and more rapid flame propagation compared to both microgravity experiments. The Flight 2 pressure spike was observed to be higher than Flight 1, likely due to the suboptimal reactor environment as a result of the previously reported O_2 leak anomaly. Additionally, Flight 1 used a lower initial batch amount of 4.5 g of OWS, compared to 8 g of OWS used in Flight 2. This decreased batch amount for Flight 1 was also incorporated into Lab Flight 1 tests. This batch difference, along with the unideal reactor conditions used in Lab Flight 1, both attribute to the difference in pressure spikes between Lab Flight 1 and Lab Flight 2. Due to the dependent relationship of reactor pressure and temperature, this is also understood when analyzing the temperature measurements within the reactor profile between varying gravity environments.

Table 4. Initial Reactor Pressure Spike in Microgravity vs. Earth Gravity.

Experiment	Pressure Spike (kPa)
Flight 1	291.0
Flight 2	406.8
Lab Flight 1	324.3 ± 25.6
Lab Flight 2	501.9 ± 15.9

Due to the unidealized reactor conditions during Flight 1 and changes in the experimental design, Flight 1 and 2 temperature profiles could not be appropriately directly compared. Nonetheless, Flight 2 temperature data provides key insight into the temperature differences between flight and ground tests, as shown in Figure 5. The dual oxygen ports injected O_2 into the system at the midpoint of the reactor. This zone received a constant feed of O_2 enabling the trash to react exothermically. Soon after ignition, temperatures increased due to combustion flame production. Hot gases circulated clockwise around the midpoint of the reactor, caused by forced convective mixing via the dual O_2 inlet flow. The pneumatic trash injection events also aid in further mixing of the oxygen and trash material (fuel). Figure 5 shows the axial average temperature gradient measured by the 4-point thermocouple from the time of initial ignition to termination of combustion. The overall Flight 2 reactor thermal profile was observed to be lower with respect to average and peak temperatures when compared to post-flight ground tests (Figure 5). For both microgravity and Earth gravity experiments, the top and bottom of the reactor maintained a lower temperature profile during the sustained combustion, likely due to the localized nature of the trash combustion events in the center (microgravity) or bottom (Earth gravity) of the reactor volume, and due to the lack of buoyancy. During ground testing, although the trash was located at the bottom of the reactor due to the gravitational force, buoyancy allowed the hot gases, and subsequent flame propagation, to travel upwards within the reactor, heating TC3 to higher temperatures than was observed during Flight 2. TC2 was observed to have a slightly higher temperature during Flight 2 than in the ground tests. In microgravity, the video recording revealed that the sustained combustion events occurred preferentially at the oxygen inlets, which behaved similary to a torch (Figure 3(f)). The flow proceeds to exit the center outlet tube towards the top of the reactor. These "torches" explain part of the thermal profile difference observed between lab and microgravity near TC2, which is the only thermocouple with a higher average temperature in microgravity. These "torches" also highlight the presence of volatile combustibles in the reactor during combustion (CO, CH_4, etc.).

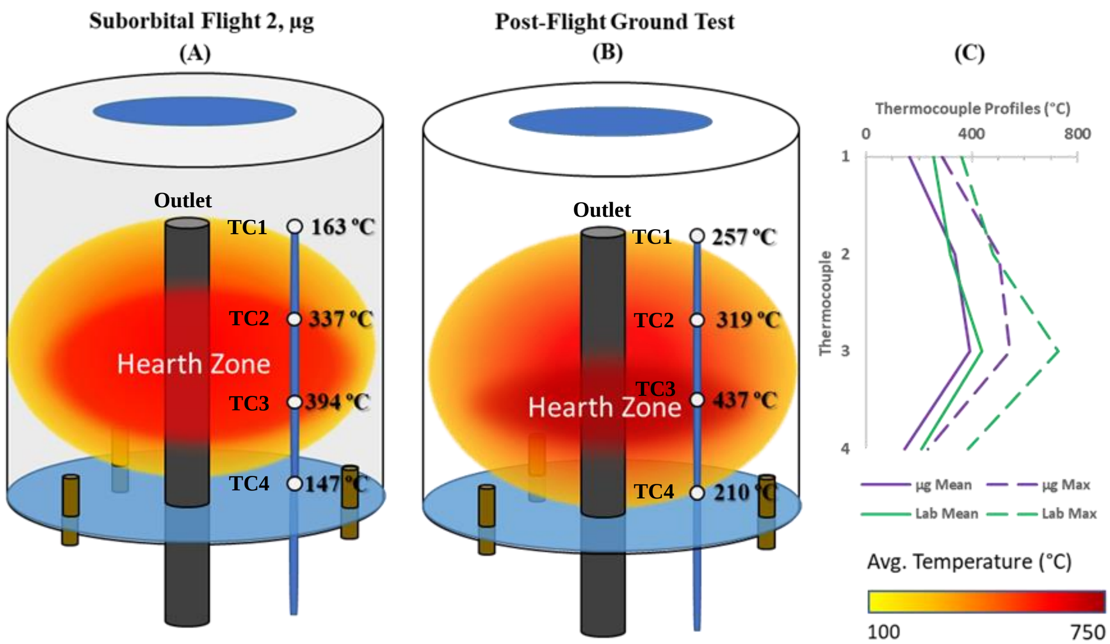


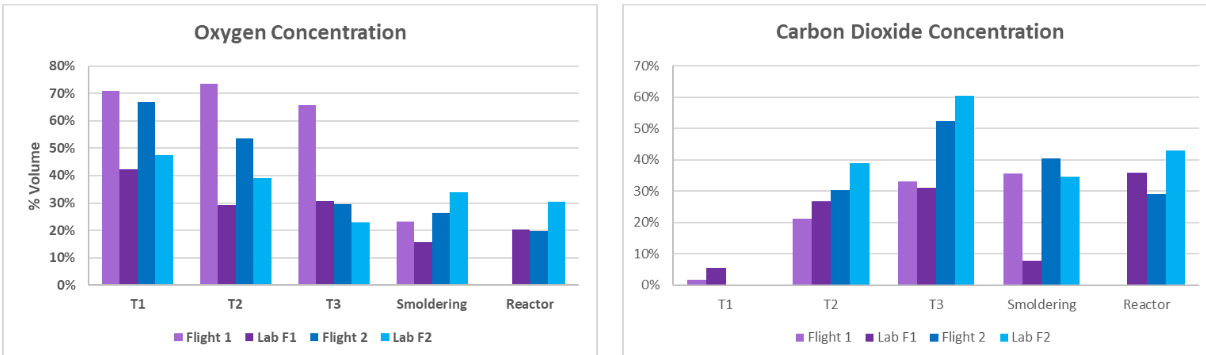
Figure 5. Reactor Thermal Profile - Flight 2 (A), ground tests (B), and comparison of temperature profiles between Flight 2 and ground tests (C).

With the lack of buoyancy in microgravity, heat transport from the flame was largely reliant on the forced convective mixing supplied by the circular oxygen flow. The lack of buoyancy in microgravity is likely a contributing cause for the difference in thermal gradients observed between TC2 and TC1. Indeed, laboratory experiments exhibited a smaller and more linear average thermal gradient (20% / 60 °C drop) than the flight did (50% / 175 °C drop). A smaller thermal gradient results from the more efficient heat transfer. Nonetheless, both microgravity and Earth gravity experiments were observed to have similar thermal profiles. It can be concluded that the reactor circulation design promoted the mixing of gases in microgravity, centralized around the mid-section zone of the reactor, but that, the contribution from buoyancy was not rendered completely insignificant. Flight 1 data exhibited the same thermal gradient trends seen during Flight 2.

This thermal data should be interpreted with caution, as the increased dispersion of trash materials in microgravity, due to the floating nature of trash items, along with the flat mesh shifting upwards during flight 2, makes it difficult to conclusively compare the thermal profiles between microgravity and Earth gravity experiments; the combustion events in microgravity, and thus heat generation, may not be located at the same proximity to the thermocouples as they are during ground tests on Earth.

B. Gas Production & Composition

Gas analysis is complementary to pressure and temperature data in observing the reactor dynamics. Pressure and temperature data showed larger pressure spikes in lab testing accompanied by much faster temperature increases upon ignition. Oxygen consumption indicated the same effect. At the beginning of the flight, the reactor was loaded with air at ambient pressure. Prior to ignition, the reactor pressure was primed to ~308.2 kPa with pure oxygen. The expected oxygen composition at ignition was approximately 75%. During combustion, gas was collected in sequential collection vessels (i.e., in T2 and T3); the composition of each individual vessel represents the average composition during the period of collection. T2 opened immediately prior to ignition, followed by collection in T3. As seen in



(a) (b)

Figure 6. Reactor output concentrations for oxygen (a) and carbon dioxide (b). Flight 1 data is included for comparison albeit no reactor gas was collected for the dataset. For Flight 1, Tank 1 did collect some combustion products by design.

Figure 6, the average oxygen concentration for T2 was 54% in Flight 2 versus 39% in the analogous lab experiments. This difference was also observed in T3 where the Flight 2 average concentration was 30% while the lab runs approached 23%. The decrease in oxygen concentration in the lab runs was then reversed in the final sample collected from the reactor (as fuel was depleted and oxygen consumption fell below the oxygen input), ending around 30% oxygen. The higher combustion activity in the lab runs consumed oxygen at a higher rate. The Flight 2 oxygen concentrations continued to decrease to an end point of ~20%.

During Flight 1, the oxygen leak induced flow decay in the reactor, reducing mixing. This is expected to have a higher impact in microgravity where there is no buoyant heat transport. Flight data did exhibit higher oxygen concentrations than in the lab within all collection tanks due to the delayed/lower combustion activity. However, both Flight 1 and the corresponding lab simulations displaed a decrease in oxygen concentration through the experiment as opposed to the experiments that were performed at the nominal oxygen flow, which showed a decrease followed by an increase in oxygen concentration as combustion activity slowed down and was outpaced by oxygen input.

Carbon dioxide concentrations are presented in Figure 6(b). Carbon dioxide production suggests the same dynamics as temperature, pressure and oxygen consumption. Lab experiments exhibited a much larger CO_2 output in T2, with the flights catching up in T3 and the reactor (note that reactor gas was not collected for Flight 1). It does appear that the main difference in conversion is temporally located at the early combustion stage of the experiment. Indeed, for T3, the flight produced 71.5 mmol of synthetic gas (syngas) versus 74.6 mmol in the lab (4.3% higher in lab). This is in contrast to T2 in which the flight produced 51.2 mmol of syngas versus 62.5 mmol for lab experiments (22% higher in lab). Syngas is the term used to describe the fuel gas mixture derived from solid fuel (trash) via the gasification process; in OSCAR, syngas primarily consists of CO_2 and CO. The total amount of syngas produced is presented in Figure 7. These findings suggest that, early in the combustion reaction, the microgravity environment led to a decreased combustion efficiency. While the flight produced a similar quantity of combustion products in the second half of the experiment, it also experienced higher oxygen concentrations, suggesting a diminished effiency during this period.

The dynamics were slightly different for Flight 1. The lab experiments yielded 1.9, 11.4 and 12.8 mmol of syngas in T1, T2 and T3, respectively, while Flight 1 produced 1.1, 8.4, and 16.2 mmol, respectively, outpacing the syngas production rate in the lab in T3. Since reactor gases were not collected for Flight 1, total gas production analysis was not attainable. Similar to Flight 2, gas production for Flight 1 started slower than in the lab but caught up and, contrary to Flight 2, surpassed lab production. This difference is likely linked to the fact that the trash load in Flight 2 was roughly double that of Flight 1. In this respect, the rate of combustion in microgravity appears to exhibit slight differences in sensitivity to trash crowding the reactor.

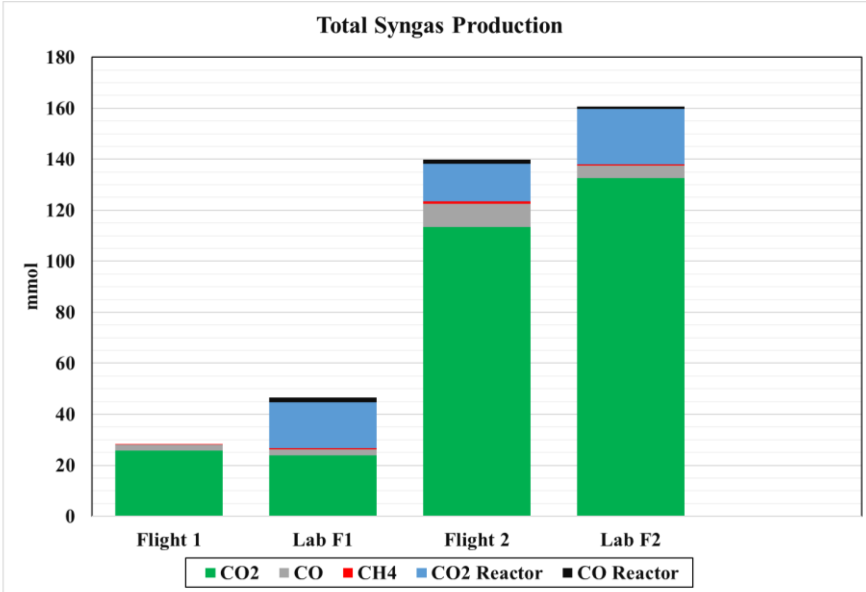


Figure 7. Total Syngas Production of Flight and Ground Tests.

The solid-to-gas conversion, carbon conversion, and CO_2/CO ratio for Flight 1, Flight 2, and their respective lab experiments are shown in Table 5. For Flight 1, the reactor contents were open to the environment and dried in the time between reactor disassembly by the launch provider and team access for mass measurements. For Flight 2 and respective ground tests, all pertinent OSCAR components were sealed from the environment and weighed immediately after gaining access to the OSCAR system post-experiment.

Flight 1 suffered from an oxygen line leak which engendered oxygen depletion and flow decay. In addition, the trash batch size was smaller. Flight 2 successfully rectified these matters. A similar CO_2/CO ratio was observed between the two flights**.** Mass analysis indicated the same results as the gas analysis: slightly lower combustion efficiency in microgravity overall for Flight 2. Both solid-to-gas and carbon conversion suffer from respective limitations. Solid-to-gas conversion is subject to measurement error and humidity effects. Carbon conversion is limited by feedstock variation and limited confidence in the heterogenous feedstock carbon content. As such, they are complimentary. The lack of reactor gas collection for Flight 1 prohibits a full comparison of carbon conversion and gas production. Error values in Table 5 strictly represent instrumental uncertainty unless otherwise indicated.

Table 5. Solid-to-Gas and Carbon Conversion.

	Solid-to-Gas Conversion (%)	**Carbon Conversion (%)**	**CO_2/CO**
Flight 1	28.5 ± 1.3%	13.9 ± 0.2%	11.0 ± 0.4
Lab 1	44.6 ± 8.3%*	13.8 ± 2.0%**	11.0 ± 1.9**
Flight 2	55.7 ± 1.0%	52.9 ± 1.0%	12.0 ± 0.4
Lab 2	61.8 ± 3.3%*	58.9 ± 2.6%*	26.1 ± 2.6*

*Uncertainty is the standard deviation for the lab data set
**Uncertainty is the standard deviation for the lab data set excluding reactor gas (not collected on Flight 1)

It is inherently difficult to compare combustion performance due to multiple confounding factors, perhaps chief among them, are the small compositional and moisture differences in the trash mixture with slight variations in cut size. This is further complicated by trash injection during the course of the experiment. Variables such as temperature, reaction speed, and completeness of combustion are affected. Flight 2 is considered higher quality data since constraints were put in place to limit experimental variability that occurred for Flight 1 and associated lab tests. Flight 2 data exhibits a solid-to-gas conversion that is slightly lower in microgravity within the allotted time scale. In addition, within the confines of the OSCAR reactor design, lower CO_2/CO ratios were observed in microgravity.

Nonetheless, these results highlight the overall success of achieving similar conversion performance in the microgravity environment compared to analogous experiments in Earth gravity.

For Flight 1, it was previously reported that the carbon conversion was not in disagreement with the distribution of corresponding laboratory measurements, and that the mass measurement system had issues rendering the results unreliable. The astute reader may notice revised numbers from the Flight 1 paper, however, this did not alter conclusion, which was that there was no observed statistically significant degradation in conversion performance. For Flight 2, statistical results are mixed. Indeed, a single sample *t*-test indicates that the difference in carbon conversion between the flight and lab triplicate was large enough to be considered statistically significant ($t = 4.45$, significance = 0.05, 2 degrees of freedom). However, mass conversion was still within 2 standard deviations from laboratory testing ($t = 3.21$, significance = 0.05, 2 degrees of freedom). This mixed result highlights the fact that, if there is a decreased performance in microgravity, it is not different enough to statistically characterize this decrease without a larger microgravity sample set.

V. Conclusion

For the second suborbital flight of OSCAR, multiple improvements were made as a result of observations and lessons learned from Flight 1, including hardware and process design. The system performed as expected, and a second data point in microgravity was collected which further instills confidence in Trash-to-Gas performance in the microgravity environment. It is confirmed through these two flights that gravity has a slight, but not overwhelmingly substantial, impact on Trash-to-Gas processing in its current design. The gravity-influenced aspects are mainly observed through the temperature profile of the reactor hearth zone, heat transfer, gas composition, and flame propagation. The suborbital flight microgravity duration was approximately three minutes, a timeframe for which complete conversion is not achievable for the chosen batch size and reactor volume; longer duration ground experiments have achieved greater than 92% solid-to-gas conversion. The increased batch size in the short microgravity duration was employed purposefully to demonstrate the operations of the system, reduce relative uncertainty and provide fuel margin under a variety of possible failure modes. The overall solid-to-gas conversion from this timed experiment was approximately 62% in gravity and 56% in microgravity. Trash solid-to-gas and carbon conversion is higher in gravity, rather than microgravity, under this current design. The lower conversion in microgravity was expected, as buoyancy and trash localization are shown to play large roles within the combustion process. To further bridge the operational gaps between microgravity and Earth gravity, future reactor designs are suggested to incorporate forced flow oxidizer ports opposite of the gas outlet to best mimic buoyant heat transfer. Additionally, localizing all trash materials near heat sources, either by decreasing reactor volume or increasing heater surface area, may help mitigate the combustion implications that arise due to the free floating nature of particles in microgravity (material ignition and flame propagation). Furthermore, the suborbital timing constraints did not allow for the appropriate design parameters for highly efficient microgravity operation; rather than having cartridge heaters act as the sole ignition sources for the trash items in the reactor, maintaining a temperature threshold throughout the reactor volume is preferred, enabling complete combustion regardless of trash item location. The OSCAR subscale suborbital flight demonstrations have completed a key milestone in the development of Trash-to-Gas technologies for use on future long-duration crewed missions. Full-scale Trash-to-Gas system development is the next great leap for Trash-to-Gas mission infusion.

Acknowledgments

The OSCAR team would like to thank the NASA Space Technology Mission Directorate Flight Opportunities Program and the NASA Exploration Systems Development Mission Directorate Advanced Exploration Systems Logistics Reduction Program for the continued funding and support of Trash-to-Gas technologies. Additional acknowledgments to other OSCAR team members, past and present, including Gino Carro, Cam Stewart, Emily Forrestor, Jake Hochstadt, Evan Bell, Jon Gleeson, Claire Pedersen, Mirielle Kruger, Morgan Benson, Tom Cauvel, and Dr. Paul Hintze.

References

[1]Olson, J., Rinderknecht, D., Essumang, D., Kruger, M., Golman, C., Norvell, A., and Meier, A. "A Comparison of Potential Trash-to-Gas Waste Processing Systems for Long-Term Crewed Spaceflight." *International Conference on Environmental Systems* 2021.

[2]Anthony, S. M., and Hintze, P. E. "Trash-to-Gas: Determining the Ideal Technology for Converting Space Trash into Useful Products." *International Conference on Environmental Systems*, Vol. 2012, p. 12.

[3]Olson, J. A., Chai, P., Rinderknecht, D., and Meier, A. J. A Comparison of Propellant Requirements for Crewed Mars Missions Incorporating Different Waste Processing Technologies. In *ASCEND 2021*, American Institute of Aeronautics and Astronautics.

[4]Meier, A. J., Rinderknecht, D., Olson, J., Shah, M. G., Medina, J. A. T., Pitts, R. P., Carro, R. V., Gleeson, J. R., Hochstadt, J., Bell, E. A., Forrester, E. A., Kruger, M., and Essumang, D. "Pioneering the Approach to Understand a Trash-to-Gas Experiment in a Microgravity Environment." *Gravitational and Space Research*, Vol. 9, No. 1, 2020, pp. 68–85.

[5]Toro Medina, J. A., Meier, A. J., Shah, M., and Rinderknecht, D. "Waste Conversion to Usable Gases for Long Duration Space Missions." In *ASCEND 2020*, American Institute of Aeronautics and Astronautics, 2020.

[6]Shah, M., Meier, A., and Toro Medina, J. "Microgravity Experimentation of Long Duration Space Mission Waste Conversion." *International Conference on Environmental Systems,* 2019.

[7]Meier, A., Shah, M., Toro Medina, J., Rinderknecht, D., and Pitts, R. "Space Mission Waste Conversion Experiments at the Zero Gravity Facility." *International Conference on Environmental Systems*, 2020.

[8]Olson, S.L., "Mechanisms of Microgravity Flame Spread Over a Thin Solid Fuel: Oxygen and Opposed Flow Effects.", *Combustion Science and Technolog*y, 1991, *76*, 233.