Investigating Waste Preparation Methods for Trash-to-Gas Technologies

Malay G. Shah[1], Ray P. Pitts[2], Morgan A. Benson[3]
National Aeronautics and Space Administration, Kennedy Space Center, FL, 32899

and

Jonathan R. Gleeson[4]
The Bionetics Corporation, Kennedy Space Center, FL, 32899

Trash-to-Gas technologies show promise in addressing the need for a proper waste management system onboard a long-duration space mission. However, there is a clear need to better understand how the initial waste preparation can affect the overall conversion efficiency. Factors such as the waste size, moisture content, and packing density can have significant impacts on the reactor performance. This paper will focus on the effects of various pre-processing steps on the overall solid-to-gas conversion on the state of the art Trash-to-Gas system developed at NASA Kennedy Space Center. These results will help inform future Trash-to-Gas technologies on what types of supporting subsystems will be necessary to operate effectively for exploration missions.

Nomenclature

HMC	=	Heat Melt Compactor
MPV	=	Mass, Power, and Volume
OSCAR	=	Orbital Syngas Commodity Augmentation Reactor
OWS	=	OSCAR Waste Simulant
TCPS	=	Trash Compaction and Processing System
TtG	=	Trash to Gas

I. Introduction

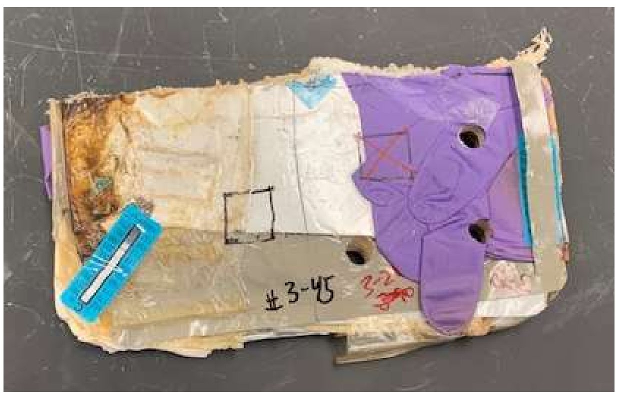
Trash-to-Gas (TtG) technologies aim at reducing the overall onboard crew waste mass and volume for long-duration exploration missions in space. The idea is to use a thermal degradation process to convert the solid waste into gas which can either be repurposed to generate resources or safely vented as would be necessary for a Mars transit mission. Crew waste generated over the course of a mission ranges from a variety of materials including metal-lined plastic food packaging, food waste, clothing, nitrile gloves, and feces. A robust design is necessary to handle such a complicated waste stream, and there is a need for greater understanding in the types of pre-processing that would be beneficial to such a reactor design. The primary methods of pre-processing for this paper have been selected based on a trade study which characterized various mechanisms on categories such as complexity, mass, throughput, maintainability, and predicted ability to enhance solid-to-gas conversion through combustion; the methods selected were shredding, pre-drying, and compaction of the waste.

The current state of the art TtG technology is the Orbital Syngas Commodity Augmentation Reactor (OSCAR) which has successfully demonstrated subscale solid-to-gas conversion of crew waste using combustion in microgravity[1,2]. OSCAR used a representative mixed waste stream called OSCAR Waste Simulant (OWS). For the microgravity test campaign, the waste was pre-processed only to aide in the pneumatic injection of trash and to provide

[1] Thermofluids Engineer, Advanced Engineering Development Branch, KSC NE-L6.
[2] Research Engineer, Exploration Systems and Development Office, KSC UB-E0.
[3] Pathways Intern, Exploration Systems and Development Office, KSC UB-E0.
[4] Aerospace Engineer, KSC-LASSO-6720.

consistency in the overall size of the mixture components. The waste components were cut into approximately 5mm pieces and not pre-dried.

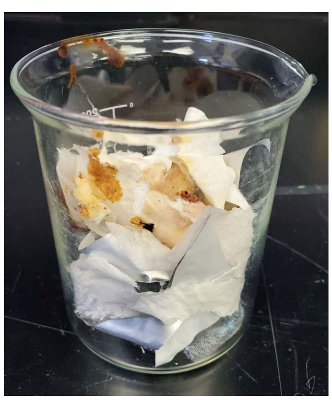
For drying and compacting waste for space applications, the state of the art system is the Heat Melt Compactor (HMC), or Trash Compactor and Processing System (TCPS) as it is currently known. This technology is capable of extracting in excess of 90% of moisture from crew waste and compacting waste to solid pucks[3]. Tiles generated from HMC were tested in OSCAR as a single piece as well as after being shredded; the tiles were shredded using a Filamaker Mini XXL shredder to investigate if the order of operations between compaction and shredding had a noticeable impact on the solid-to-gas conversion performance. These HMC tiles were also used to investigate how compatible this pre-processing technology is with current TtG efforts underway at NASA Kennedy Space Center. While waste materials used in HMC were not identical to the ones uses in OWS, they are sufficiently similar for comparison from a solid-to-gas conversion perspective as the HMC materials would not behave in a drastically different manner from OWS under combustion. Pucks made from OWS were also tested in the OSCAR reactor which provided a more representative comparison with other tests; these pucks were not shredded post-compaction. The approximate compaction density for the HMC pucks is 465 $kg \cdot m^{-3}$ and for the manually compacted OWS it was approximately 190 $kg \cdot m^{-3}$. The HMC tiles and the manually compacted pucks can be seen in Figure 1 and Figure 2 below. See Table 2 in the Appendix for a comparison of the composition of HMC and OWS materials. Because of the non-uniform distribution of the waste in the HMC tiles, the reduced sized pieces using in OSCAR could potentially have and inconsistent mixture (i.e. one piece may have more fabric or more glove material than another). This was unavoidable due to the limitations in the size of the OSCAR reactor.



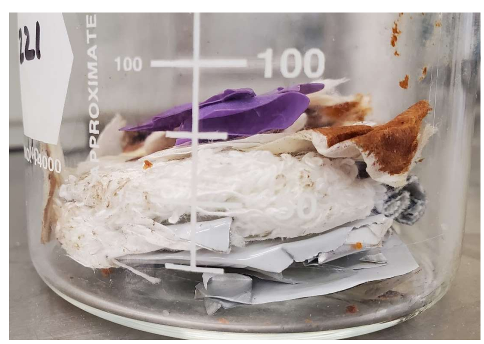
(a)

(b)

Figure 1. HMC tile in the a) original form and b) reduced size for OSCAR operations.



(a)



(b)

Figure 2. Large OWS material in the a) loose form and b) compacted.

II. Experimental Method

Several experiments were conducted while varying the following parameters: trash size, moisture content, compaction, and reactor pressure. Each of these tests were done in triplicate using approximately 8 grams of OWS with the exception of the compacted OWS waste for which only a single test was conducted; additional tests were completed using ~20 gram pucks generated from high-liquid HMC tiles. All of the tests involving compacted waste were pre-dried. A summary of the tests conducted can be seen in Table 1.

Table 1. Test matrix.

Parameter	Sub-parameter	Waste
Size	5 mm	OWS
	10 mm	OWS
	Large	OWS
Moisture	Pre-Dried	OWS
	Not Pre-Dried	OWS
Compaction	Whole	OWS
	Whole	HMC Puck
	Shredded	HMC Puck
Pressure	Large Pre-Dried 0.1 MPa	OWS
	Large Pre-Dried 0.3 MPa	OWS

The mixture as it was placed inside the reactor can be seen in the Appendix for various trash sizes and compacted waste. For the tests involving the compacted material, the waste was placed between two of the three cartridge heaters and directly next to the multi-point thermocouple to get an axial temperature profile during combustion.

Each test involved combusting the waste in a pure oxygen environment for durations exceeding 10 minutes. The internal volume of the OSCAR reactor is approximately 0.5 L. Oxygen flow was fixed at 3 SLPM and the reactor was operated at ambient pressure for all listed OWS tests. The HMC tests and one additional set of Large Pre-dried OWS tests were conducted at 0.31 MPa (30 psig) for gas analysis (unrelated to this effort). The overall order of the experimental process is as follows:

1. Pre-weighed waste is loaded into the reactor prior to the test.
2. At the beginning of the test, two pre-heat lines heat up to a set temperature of 650ºC.
3. Once heaters reach set temperature, oxygen flow begins at 3 SLPM.
4. The cartridge heaters turn on once pressure stabilizes in reactor.
    a. These cartridge heaters heat up trash within the reactor to initiate ignition of the waste.
5. Combustion is sustained following initial ignition.
6. The test ends once all temperature sensors within the are all below 200ºC.
    a. Video data was also used to verify combustion has ceased.
7. Remaining waste mass is collected for solid-to-gas conversion calculation.

A. Trash Size

Exploring the size of the waste is important to understand what kind of requirements a future full-scale TtG system would entail. If it were necessary to reduce the size of the waste material via a shredder for example, then the mass, power, volume, and complexity of the system increases with the inclusion of a shredder and motor. The trash size parameters here were tested in order to explore the resulting effects on the overall solid-to-gas conversion and to gain some knowledge on what those future requirements should cover. There are other issues that may arise when utilizing a shredder that must be addressed, such as the excessive dust generation which was found when running various OWS materials through a Filamaker Mini XXL shredder.

The individual components of the OWS were manually cut into pieces of varying sizes using scissors. The 5mm size is equivalent to the ones used on the suborbital flights and have microgravity data. The size listed as Large in Table 1 indicates that each of the waste components making up OWS were made of a single piece that still follows the overall mixture ratio (e.g. with clothing being ~17% of the OWS mixture, a single piece of clothing with a mass of 1.36 gm was used in the test, likewise for all other components). All of the solid components with the exception of cotton were thin sheets of material. Cotton tended to fray and clump up as it was cut and mixed with the other waste. The HMC shredded triplicate was shredded using the Filamaker Mini XXL shredder and an image can be seen in Figure 8 in the Appendix.

B. Moisture Content

Water can be recovered effectively simply by heating up the trash, which has a moisture content of about 24.3% in the case of OWS. By removing this water before the combustion process is initiated, less energy is required within the reactor to pull this water out and quenching can be avoided if any excessively wet waste is introduced into the reactor (i.e. the water could end the combustion process prematurely by rapidly cooling the reactor). Having dry waste is also a benefit for reducing the possibility of clogging a receptacle or feed mechanism on a full scale system. For the tests conducted, waste was either assembled into the reactor as-is, or pre-dried for at least 12 hours in an oven at 100ºC. The largest piece size was used for these tests.

C. Compaction

Densifying the waste through compaction allows more waste to be processed while keeping the reactor volume constant, or reduce the required volume of the reactor to process a fixed waste mass. However, compacted solid fuels may also inhibit oxygen/fuel interactions and can make it difficult to process wet waste materials. The OWS compaction tes ts involved using pre-dried Large OWS mixture size and compacting it in a manual press (Greenerd Model No. 3C) to pucks with a diameter of ~5 cm and thickness of ~2 cm. The HMC tiles were cut into a single puck small enough to fit inside of the OSCAR reactor and resulted in masses of ~20 grams.

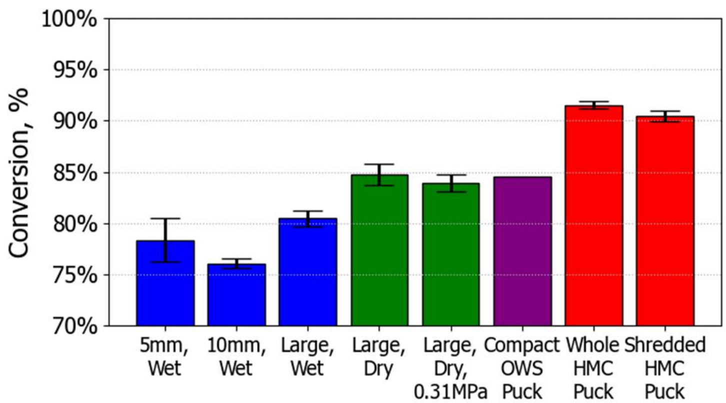


Figure 3. Solid-to-gas conversion percentage for each test.

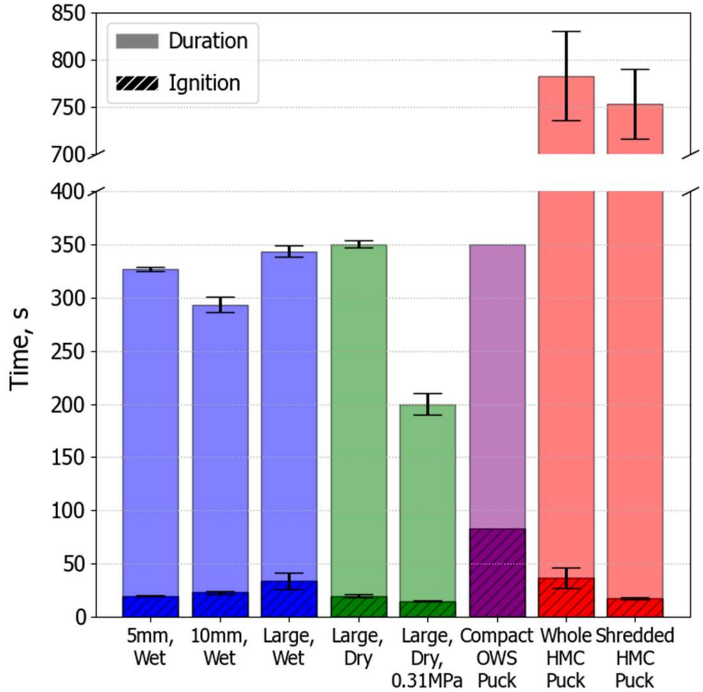


Figure 4. Approximate ignition time and duration of combustion for each test.

D. Pressure

Pressure plays a large role in the combustion reaction kinetics and can determine how much soot and ash is formed as a result. The OSCAR system was designed to combust waste at a reactor pressure of 0.31 MPa for approximately three minutes. For some of these long duration tests, the experiments were run using a modified procedure to keep the reactor at ambient pressure. Later tests allowed long duration combustion at the nominal pressure of 0.31 MPa for much longer than originally intended and are included with results in this paper.

III. Results

The conversion percentage is a ratio of the leftover solid mass to the initial dry mass of the waste. The overall solid-to-gas conversion performance can be seen in Figure 3. Smaller waste size did not have a significant impact on the solid-to-gas conversion performance of the reactor and in fact, smaller waste size tended to have slightly less efficiency in conversion than larger pieces for this set of subscale tests in OSCAR. On average, the solid-to-gas conversion for tests involving wet waste was 78.4% for 5mm, 76.1% for 10mm, and 80.5% for Large pieces. The solid ash remnants in the reactor largely consists of carbon, aluminum, hydrogen, and oxygen. Larger pieces tended to be much easier to clean out of the reactor after combustion was complete. For the smaller pieces, the layers of plastic in the food packaging were more in contact with the reactor core and thus had more difficulty burning away and tended to adhere to the bottom steel surface. Drying the waste also was observed to increase the solid-to-gas conversion. The solid-to-gas conversion of the compacted OWS case was very similar to the conversion from the Large Dry OWS cases, possibly indicating that the compaction level was not sufficient to draw a conclusion from these tests. However, the HMC tiles achieved a much larger conversion than any OWS case, perhaps due to the differences in the material composition. The level of compaction for HMC tiles may also lead to being a denser fuel even after being shredded.

Ignition times for all waste were fairly consistent with a couple of exceptions on some of the larger material tests where it became important how the waste was oriented within the reactor core. There are three cartridge heaters spaced out evenly within the reactor core; if there is a significant amount of space between the waste and the heaters, the ignition time can increase dramatically; this can also be affected by what type of material is in contact with the heater as the various materials have differing ignition times[1]. This was most apparent for the Large tests and the Whole HMC and Compact OWS Puck tests. Approximate ignition times along with the overall test duration are shown in Figure 4. Wet waste generally ignited around 21 seconds after power was sent to the cartridge heaters with the exception of one Large Wet test where ignition occurred 60 seconds after the cartridges were enabled; this could also be attributed to the space between the waste and the cartridge heaters as mentioned previously. Large Dry OWS waste also ignited at around 20 seconds on average for the ambient pressure case, but that ignition time decreased to an average of about 15 seconds for the case at elevated pressure. For the compacted waste, the Compact OWS Puck test showed ignition after 83 seconds and Whole HMC Pucks ignited at 20 seconds with one test having ignition at 71 seconds. The Large Dry OWS test also completed combustion much more quickly at the elevated pressure compared to the ambient pressure cases. Also as expected, the additional mass in the HMC Puck cases required more time to fully process.

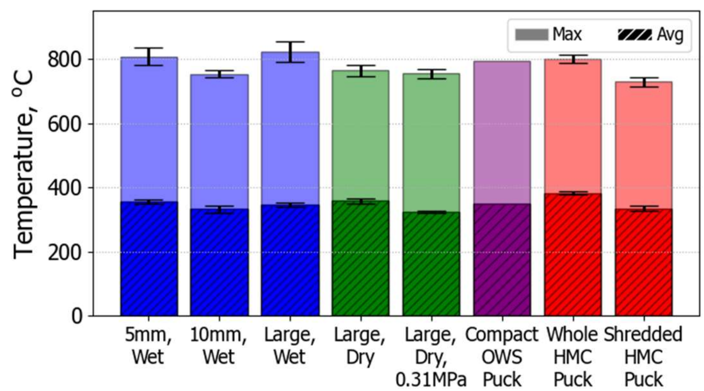


Figure 5. Average and maximum temperatures.

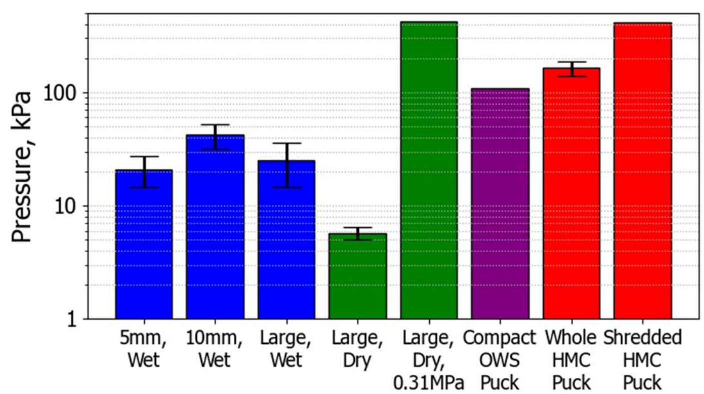


Figure 6. Average spikes from ignition events.

The average and maximum temperatures of the seven thermocouples within the reactor can be seen in Figure 5. Across the variety of tests and despite the difference in material between OWS and HMC, the averages and peaks appeared to be fairly consistent at about 350ºC and 780ºC, respectively.

Pressure spikes associated with initial ignition events is shown in Figure 6. The pressures shown are the difference between the nominal operating pressure for that test and the maximum pressure resulting from the ignition. Note, for the Large Dry OWS case at elevated pressure and the Shredded HMC Puck case, the pressure exceeded the relief device on the system temporarily and thus the spike is limited to the value shown in the plot (i.e. it could have been higher but the value was truncated).

During the combustion process, the pucks generated a single large sustained flame and had an larger pressure spike from the ignition event compared to shredded/cut materials. Following the initial ignition of the shredded waste, the flames tended to drift and sustain on the more densely packed areas of the waste in the reactor through time. This can be observed in Figure 7 in the Appendix which show some examples of the fire within the reactor partway through a test.

Based on these results, the highest OSCAR solid-to-gas conversion of >91% was observed using waste that was pre-dried and compacted to 465 kg·m^{-3} (i.e. HMC tiles). Drying OWS gave an increase of approximately 3% above the average for Large Wet waste tests, although manually compacting this Large Dry OWS did not have a noticeable effect on increasing this further.

IV. Conclusion

Any future large scale Trash-to-Gas technology will have to accommodate certain mass, power, and volume (MPV) requirements. Simplification in the pre-processing system can have large benefits regarding those constraints. Results from these tests indicate that the additional MPV from having a shredder and motor would not provide significant benefits in solid-to-gas conversion, while adding design complexity. Dry and compacted waste on the other hand has the potential to yield much higher conversions as was seen from the HMC tile tests. However, this would need to be further validated in a full scale demonstration as differences in compacted versus shredded waste material may not be fully realized at the relatively small throughput of the OSCAR system. Factors such as the additional MPV required for subsystem components to support pre-drying the waste should be compared to simply utilizing the heat from combustion to drive moisture away (which may increase processing time and/or reduce conversion efficiency) should also be investigated. This efficiency will also have an effect on the remaining amount of ash which must be cleaned out of the reactor and will therefore drive how often maintenance intervals are required.

The Trash-to-Gas efforts at KSC will continue to be developed with the primary goal of scaling up experiments as the team explores how these features could be implemented on a full-scale system. Depending on where this technology will be used, whether it is aboard a Mars Transit vehicle or on the Lunar surface, the constraints associated with each mission will dictate what kind of trade-offs are acceptable when it comes to the reactor efficiency in reducing the overall mass of trash onboard the spacecraft or habitat. Having gravity-independent systems would be necessary for a microgravity implementation, although further studies need to be done on how to effectively use these preparation technologies in such an environment.

Appendix

Table 2. Material composition for HMC and OWS.

HMC	
General Category	**Percent Composition (wt%)**
Cloth	33.9
Wet Wipes	2.8
Dry Wipes	4.1
Personal Hygiene	5.1
Paper	2.7
Duct Tape	0.6
Velcro	0.7
Food Packaging & Storage	41.3
Sweat Solids	2.5
Food	6.3

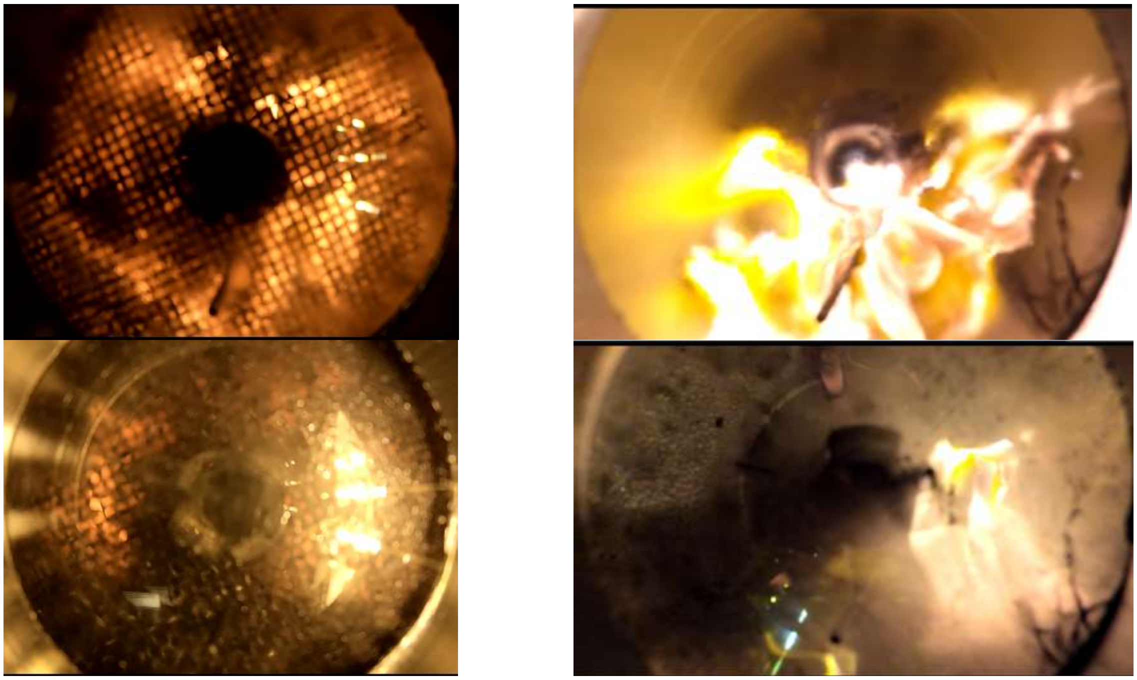
OSCAR waste simulant (OWS)	
Waste Material	**Percent Composition (wt%)**
Clothing – cotton T-shirt	17.9
Cotton cloth	9.5
Wet Wipes	10.8
Tech (dry) Wipes	3.6
Toilet Paper	3.6
Toothpaste	1.2
Shampoo	1.2
Nitrile Gloves	1.6
Food Packaging (FP) - White	13.3
FP - Clear	13.3
Fecal Simulant	13.4
Food Simulant	10.6
Note: Overall OWS composition contains approximately 4.7% incombustible materials, primarily from metals in the food packaging.	

(a) (b) (c)

Figure 5. Waste of size (a) 5mm, (b) 10mm, and (c) Large in the reactor before and after burns (top and bottom, respectively).

(a) (b) (c)

Figure 6. Compacted waste (a) Compact OWS Puck, (b) Whole HMC Tile, and (c) Shredded HMC Tile in the reactor before and after burns (top and bottom, respectively).



(a) (b)

Figure 7. Example of fire within OSCAR reactor partway through the combustion process, (a) 5mm Wet OWS and (b) Whole HMC Puck shortly after ignition and about a minute into the combustion process (top and bottom, respectively).

(a) (b)

Figure 8. (a) Filamaker Mini XXL shredder and (b) an example of a shredded HMC puck.

Acknowledgments

The authors would like to acknowledge Justine Richardson at NASA Ames Research Center for providing the HMC tiles in support of this effort. Additional acknowledgments to the NASA KSC Center Innovation Fund (CIF) program for funding this research.

References

[1]Meier, A. J., Shah, M. G., and Medina, J. T., "Microgravity Experimentation of Long Duration Space Mission Waste Conversion," *49th International Conference on Environmental Systems*, 2019.

[2]Meier, A. J., et al. "Pioneering the Approach to Understand a Trash-to-Gas Experiment in a Microgravity Environment." *Gravitational and Space Research*, Vol. 9.1, 2021, pp. 68-85.

[3]Mesa, J. R., Spexarth, G., Guinn, J., Morrison, T., and Strange, J., "The Trash Compactor and Processing System Development,", *50th International Conference on Environmental Systems*, 2021.