Gas Evolution from Torrefaction Processing of Human Solid Wastes

Joseph E. Cosgrove[1], Marek A. Wójtowicz[2], and Michael A. Serio,[3]
Advanced Fuel Research, Inc., 87 Church Street, East Hartford, CT 06108-3720 USA

and

Jeffrey M. Lee[4]
NASA Ames Research Center, Moffett Field, CA 94035-1000 USA

A Torrefaction Processing Unit (TPU) can be used to sterilize human solid waste (and related spacecraft solid wastes), produce a stable and relatively odor-free solid product that can be more easily stored or recycled, and can also be used to simultaneously recover moisture. This TPU is designed to be compatible with the Universal Waste Management System (UWMS), now under development by NASA and Collins Aerospace. A stand-alone TPU could be used to treat the waste canister from the UWMS, thus allowing the waste canister to be reused and significantly reducing the number of canisters required on board for a long duration mission. Besides water vapor, the major gas product from torrefaction is carbon dioxide, while carbon monoxide, hydrogen sulfide, methane, and carbonyl sulfide are minor gaseous products. For untreated material, many of these same gases are also produced from biological processes. This paper addresses the gas species evolutions from both untreated and treated human solid waste and the implications for storage of these materials.

Nomenclature

AFR = Advanced Fuel Research, Inc.
CH_4 = Methane
CO = Carbon Monoxide
CO_2 = Carbon Dioxide
COS = Carbonyl Sulfide
ESM = Equivalent System Mass
FTIR = Fourier Transform Infrared
H_2S = Hydrogen Sulfide
HMC = Heat Melt Compactor
ISRU = In-Situ Resource Utilization
LPM = Liters per Minute
MCT = Mercury-Cadmium-Telluride
MGA = Multi-Gas Analyzer
MSWS = Metabolic Solid Waste Storage
N_2 = Nitrogen
NASA = National Aeronautics and Space Administration
PTFE = Teflon™
SMAC = Spacecraft Maximum Allowable Concentration
TC = Thermocouple
TCPS = Trash Compaction and Processing System
TPU = Torrefaction Processing Unit
UWMS = Universal Waste Management System

[1] Laboratory Manager, Advanced Fuel Research, Inc. (AFR), 87 Church Street, East Hartford, CT 06108.
[2] Vice President, Clean Energy & Carbon Materials, AFR, 87 Church Street, East Hartford, CT 06108.
[3] President, Advanced Fuel Research, Inc. AFR, 87 Church Street, East Hartford, CT 06108.
[4] System Analyst, Bioengineering Branch, MS N239-15, NASA Ames Research Center, Moffett Field, CA 94035.

I. Introduction

A. The Problem and Technical Approach

New treatment technology is needed to collect, stabilize, recover useful materials, and store human solid waste and other spacecraft solid wastes for long duration missions. The motivations include volume reduction, crew safety, comfort and resource requirements, along with planetary protection.[1-5] The current paper addresses a torrefaction (mild pyrolysis) processing system that can be used to sterilize human solid waste and related solid biomass wastes (food, paper, wipes, and cotton clothing) and produce a stable char residue that can be more easily stored or recycled, while simultaneously recovering all of the moisture and producing small amounts of other gases. Torrefaction is usually defined as thermal treatment done in the absence of air.[6] However, since the temperature is lower (usually <300 °C), some air can be present without having much effect. Previous NASA sponsored work[7-9] demonstrated that torrefaction processing was effective for a fecal simulant using bench scale experiments, with both microwave and conventional heating. In subsequent work, the process was operated at full scale for realistic samples (canine, human).[10,11] The objective of the current study was to examine gas species produced from the Torrefaction Processing Unit (TPU) and the contribution of biological processes.

B. Potential Advantages versus Current Solid Waste Management Technology

As discussed by Linne *et al.*,[12] the need for waste processing varies greatly, depending on the mission scenario, and the choices include rejection, reuse, or recycle. At a minimum, reducing the volume of waste will increase the amount of habitable space and the goal is also to increase crew comfort and safety. There has been a lot of NASA supported work (both internal and external) on solid waste management. These studies include evaluating such technologies as catalytic wet oxidation, incineration/gasification, ozone oxidation, pyrolysis, and steam reforming,[13] demonstration of a plasma assisted gasification process,[14] and further improvements of that process.[15] Volume reduction, sterilization, and water recovery from waste, along with the repurposing of waste in radiation protection tiles, such as those produced in the Heat Melt Compactor (HMC), have been emphasized in the most recent work.[3-5] Since human solid waste is a relatively small percentage of the solid waste generated on board a spacecraft, most of these processes have been designed around other types of solid waste (plastic, paper, food, etc.).

C. Potential Benefits for NASA

The use of torrefaction processing would make it technically feasible to process human solid waste and related solid waste streams in space, which will benefit long term space travel such as an extended Lunar stay or a mission to Mars. As discussed in previous papers,[7-11] the proposed torrefaction approach is beneficial to NASA in allowing for volume reduction, solid waste sterilization and stabilization, and water recovery for near term missions. In the case of longer term missions, more severe (pyrolysis) processing in the same or similar equipment would allow for enhanced water and CO_2 production, production of fuel gases (CH_4, CO, and H_2) and multi-purpose carbon, along with In-Situ Resource Utilization (ISRU). The torrefaction processing system is also complementary to the HMC and other types of Trash Compaction and Processing System (TCPS) concepts, and could also be designed to be compatible with the Universal Waste Management System (UWMS),[16] now under development by NASA and Collins Aerospace. The potential integration of the TPU with other life support technologies was discussed previously.[11] A recent paper compared the Equivalent System Mass (ESM) for Metabolic Solid Waste Storage (MSWS) with processing in the TPU for various mission scenarios.[17]

II. Experimental

A. TPU Design and Operation

Figure 1 depicts a schematic of the prototype full-scale TPU. The operation of the TPU and its major components, including the canister and lid, the heater and controller, bottom (heat bridge) plate, top heating plate, heating jacket, a thermocouple (TC) insertion probe, the condensing and filtering equipment, and the gas sensor array for CO_2, CO, and H_2S, using sensing elements from Sensor Electronic Corporation (SEC), have been described previously.[10,11] Some additional improvements have recently been made.[18,19] These include enhancement of the particle filtration system, addition of an insulated collar, use of a longer liner bag, and reinforcement of the support structure. The TCs were located in the heating jacket (~wall), top plate, center probe, and the bottom (heat bridge) plate.

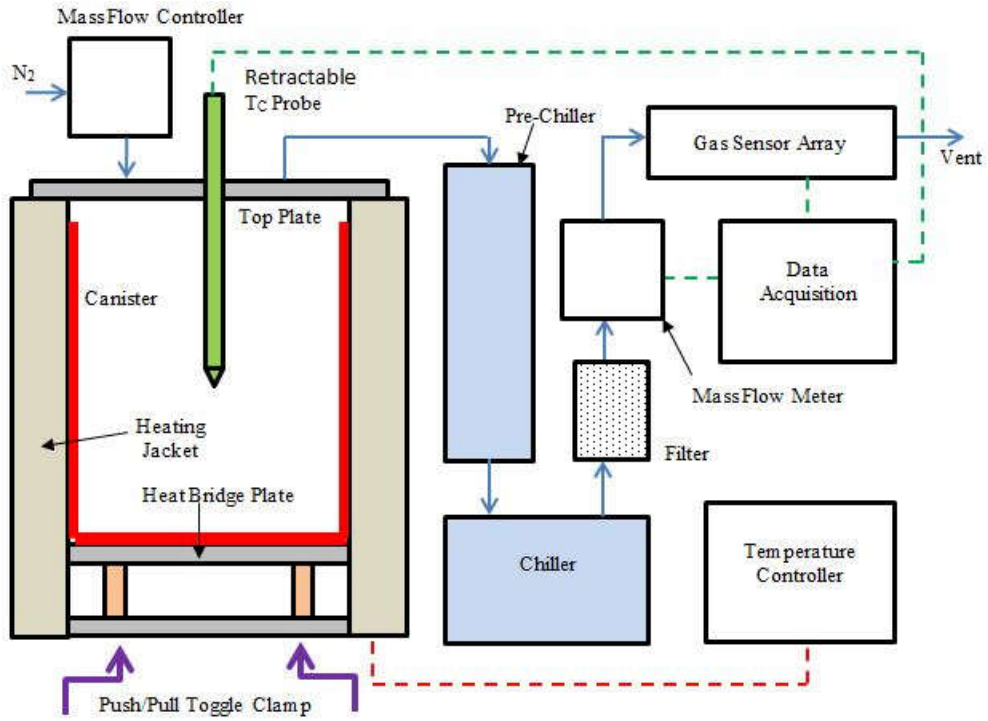

Figure 1. Schematic of the full-scale prototype TPU.[11,18]

B. Gas Analysis Measurements

For gas analysis, most runs included an FTIR gas analyzer, the On-line Technologies, Inc. Model 2010 Multi-Gas Analyzer (MGA), located downstream of the TPU gas sensor array, which only measures three gases (CO_2, CO, and H_2S). The MGA sample compartment is a heated multi-pass cell, with an effective pathlength of 5 m and a resolution of 0.5 cm^{-1}. It employs a liquid nitrogen-cooled mercury-cadmium-telluride (MCT) detector for measurements in the 600-6000 cm^{-1} region. The liquid nitrogen hold time for the detector is ~ 10-12 hours, but it was possible to acquire continuous spectra by maintaining the fill level of the detector throughout the ~ 36 hour run periods. All of the gas yield data reported in this paper were determined by the FTIR MGA, except for H_2S and the CO_2 yields for Run 327.

C. TPU Experimental Procedures

A total of 13 TPU experiments involving human solid waste (10) and canine solid waste (3) were done.[18,19] For the first 12 experiments, the individual sample bags were fabricated from a 66 cm wide roll of porous polyester supported PTFE (5-micron, 3-5 mil thickness) that was purchased from Sterlitech Corporation (Kent, WA). The bags were cut into 17.8 cm x 66 cm sheets, folded over and sewn along the sides by a local seamstress. The resulting bag dimensions were ~ 10.2 cm diameter by 33 cm tall with seamless bottoms. Each torrefaction run was performed with 20 sample bags. Each bag contained 150 g of sample, 1 latex glove, a strip of medical gauze, 1 Tempo® dry wipe, 2 Huggies® wet wipes and 1 Tech® wipe. The total initial mass, including the liner bag (~29 g) was ~ 3850 g. This is a nominal value since it was impractical, for sanitary reasons, to weigh the wet wipes. Consequently, there may be variations in their moisture content. In the last run (#340), sample bags supplied by Materials Modification, Inc. (Fairfax, VA) made of a proprietary material were used. These bags were fabricated to match the same dimensions, but were trimmed because of their greater wall thickness. A summary of all the TPU experiments is included in Table 1. The operating conditions were similar, a 1 LPM nitrogen gas flow, a wall setpoint temperature of ~190 to 225 ° C, and a sample target endpoint temperature of 150 to 200 ° C at the center of the canister.

III. Results and Discussion

A. TPU Prototype Experiments

Figure 2 displays the temperature profiles, after heating begins, for the center probe, bottom plate, top plate, and gas traces for several non-condensable species from Run #329. All gas traces shown were measured by FTIR, except for H_2S. The center reaches the endpoint temperature in ~34 hours with an energy usage of 7.01 kWh. After shutdown,

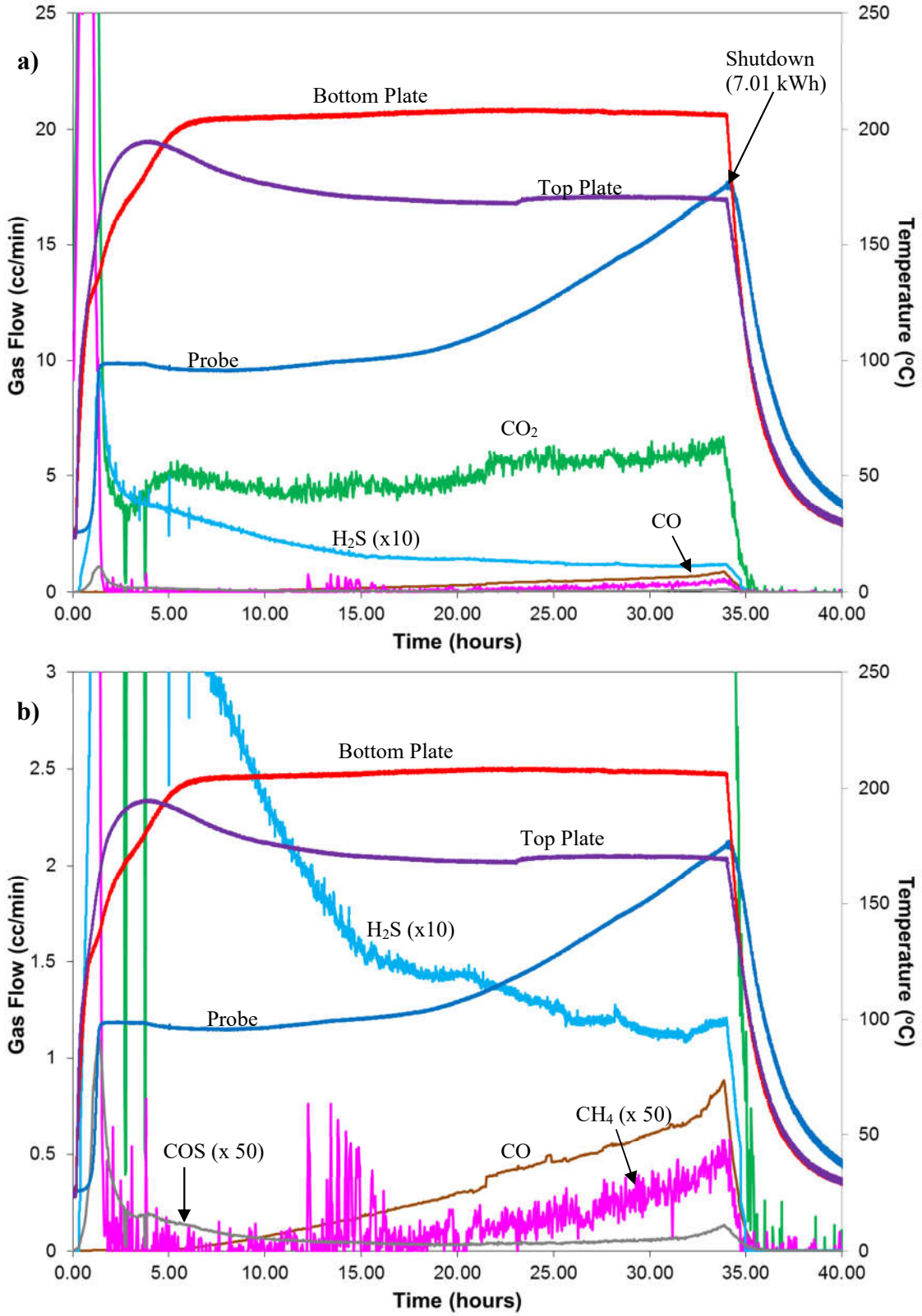

Figure 2. (a) Temperature and gas profiles recorded during a full-scale TPU test with human solid waste for Run # 329; (b) Plot is zoomed in at lower gas flows to highlight the trace gas profiles. *The wall setpoint temperature was ~205 °C and the target endpoint at the center was 175 °C.*

the jacket heater was immediately opened, and the sample probe temperature cooled to 50 ° C in ~ 5 hours. This processing time and energy usage was typical for most of the experiments, as can be seen in Table 1. For each run, the peak power was 1.2 kW.[17]

Table 1. Summary of process parameters and product yields for TPU experiments.

Run #	Fecal Sample Type	Wall Setpt. T(°C)	Target/ Actual Endpt. T (°C)	Heat Period[1] (hours)	Energy Usage[1] (kWh)	Char Yield (g)	Liquid Yield[2] (g)	Non-condensable Gas Yields (g)					Odor[6]
								CH_4[3]	CO[3]	CO_2	COS[3]	H_2S[4]	
325[5]	Canine	225	200/212	40.23	8.87	1268	2436.5						FC
326[5]	Human	225	200/216	35.72	8.31	1153	2405.8						FC
327[5]	Human	225	200/215	32.79	7.75					44.92[4]		1.391	FC
328	Human	225	200/200	32.66	7.61	1149	2493.1	0.023	2.204	32.40[3]	0.012	0.593	FC
329	Human	205	175/175	33.99	7.01	1198.9	2499.1	0.035	0.675	25.08[3]	0.010	0.584	FC
330	Human	205	150/150	36.17	7.42	1262.7	2534.2	0.064	0.461	30.51[3]	0.012	0.552	VL
331	Human	205	150/150	35.93	7.69	1249.8	2645.8	0.003	0.564	25.88[3]	0.011	0.510	VL
332	Canine	205	175/191	43.07	8.41	1363	2421.1	0.005	0.893	40.33[3]	0.017	0.543	FC
333	Human	205	175/175	41.28	8.35	1270.5	2535.9	0.049	0.933	30.973	0.016	0.520	FVL
334	Canine	225	175/175	36	8.35	1328.6	2421.3	0.011	1.101	49.29[3]	0.014	0.474	FC
338	Human	225	200/200	39.82	9.41	1229.4	2252.3						FC
339	Human	225	200/200	35.53	8.64	1183.4	2520.2						FC
340	Human	190	165/165	38.8	7.55	1268.8	2543.4	0.038	0.56	28.06	N/A	0.565	FC

1. Measured at target endpoint for center probe temperature.
2. Includes gas-phase H_2O measured by FTIR (runs 328-333).
3. Measured by FTIR.
4. Measured by TPU electrochemical sensor.
5. Phase II experiment
6. FC = Faint Char; VL = Vomit-Like; FVL = Faint Vomit-Like (subjective determination by 1 to 3 individuals)

Several experiments were done to examine the effects of the wall setpoint temperature (205 °C to 225 °C) and centerline target endpoint temperature (150 °C to 200 °C) on processing time, energy consumption, and odor (see note 6 in Table 1) of the solid residue. In general, a wall temperature of 205 °C and a centerline temperature of 175 °C was typical based on this set of 13 TPU experiments with human and canine solid waste. In this case, run #329 represents what were the nominal operating conditions for the current prototype TPU, based on this limited set of runs.[18,19]

B. Gas Analysis Results

The data for individual yields for the non-condensable gases are also summarized in Table 1. An obvious effect of lowering the torrefaction processing temperature (average of wall and centerline) was the reduction in CO yields, which were much lower for runs # 330, # 331, and # 340, when compared to run #328. The total yields for CO_2 are summarized for the FTIR determined values for runs # 328 to #334 and # 340 and from the TPU sensor for run # 327. As discussed previously,[18,19] the TPU sensor measurements of CO_2 are usually about 20% lower than the FTIR measurements. For this reason, it is particularly interesting that the CO_2 yield for run # 327 was even higher than # 328, given that the operating conditions were similar. These differences can be caused by variations in solid waste sample composition and holding time, along with seasonal fluctuations in the ambient laboratory temperature. The H_2S yield is also much higher in the earlier run, which is also a gas that can be formed during storage due to biological processes, along with CH_4.[20] All three gases (CO_2, H_2S, CH_4) have a spike early in each TPU run, as shown in Figure 2 for run #329, which can be attributed to this variable biological component. This is also true of COS, and to a much lesser extent in the case of CO. For example, the yields for CH_4 for runs # 328 and #329, shown in Table 1, may be somewhat misleading, suggesting that more CH_4 was generated at the lower processing temperature. Besides the setpoint temperature, there was one other difference between these two experiments. For run # 328, the canister was processed immediately after filling the last bagged samples and loading into the TPU reactor. For run # 329, however, the canister was loaded into the TPU, but the torrefaction processing did not start until the following day, nearly 24 hours later. It can be seen from Figure 3 that a large amount of the CH_4 is measured during the first ~ two hours of each run. For run # 329, a strong spike is observed prior to the start of heating. After the 2-hour point, much more CH_4 appears to be generated in the higher temperature run. The above results are consistent with the hypothesis that the human solid waste undergoes biological degradation during storage (e.g., fermentation), which could explain the early release of both CO_2 and CH_4. The formation of both CO and H_2S (in smaller amounts) has also been reported under these conditions for biomass materials.[20]

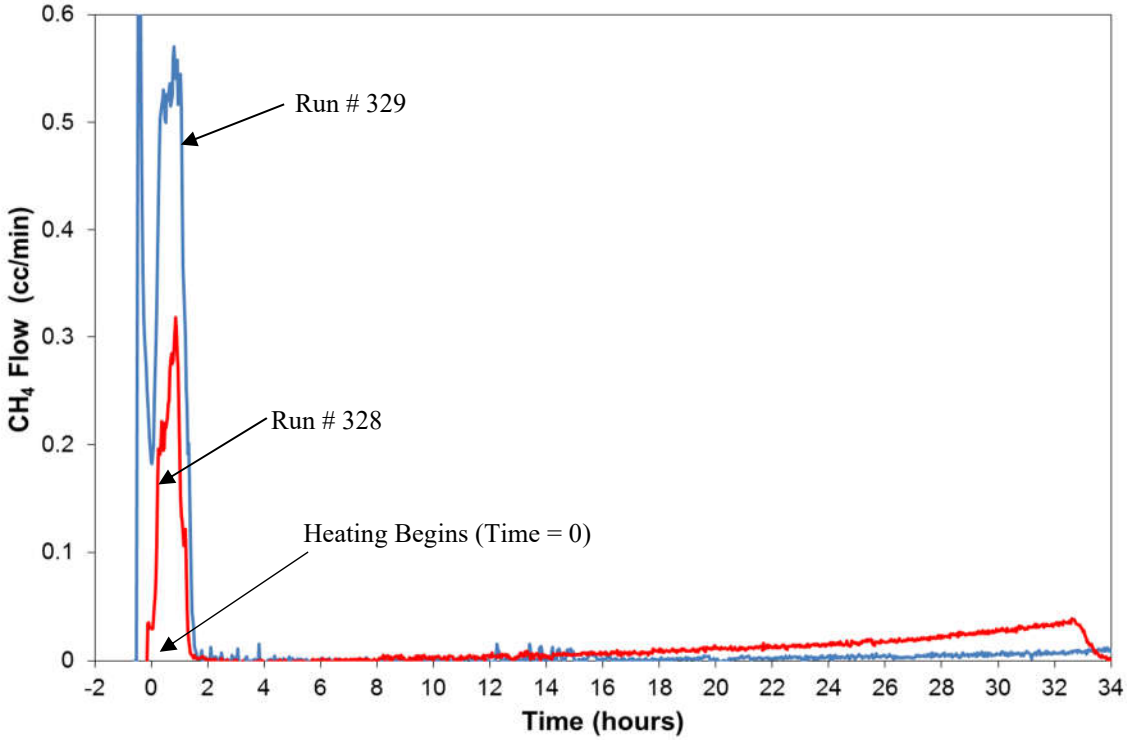

Figure 3. Comparison of CH_4 profiles for run # 328 (red) and run # 329 (blue).

Table 2 summarizes the TPU runs with human solid waste for which there was available data for CH_4, CO, CO_2, COS, and H_2S yields, either from the FTIR MGA (CH_4, CO, CO_2, COS) or the TPU electrochemical sensor, in the case of H_2S. These are tabulated from highest effective temperature to lowest, where the effective temperature was crudely defined as the average of the wall and centerline temperature. Based on this limited set of results, it appears that the yields of CO, CO_2, and H_2S are correlated with temperature, especially above 200 °C. The yields of COS and CH_4 are very small and appear to be less correlated with torrefaction temperature in this range (172 to 212 °C). However, as discussed above, all of these gas yield data are also influenced by biological processes, which can be affected by ambient conditions, container loading time, and sample variations. The importance of biological contributions was tested by excluding gas evolutions in the first 2 hours from the total, which are given in parentheses in Table 2. It was found that CH_4> CO_2~COS>H_2S>CO, regarding the importance of these contributions.

Table 2. Torrefaction Gas Yields as a Function of Temperature from Human Solid Waste

Run #	Effective Temperature[3] (°C)	CH_4[1]	CO[1]	CO_2	COS[1]	H_2S[2]
327	220			44.9[2] (37.5)		1.39 (1.31)
328	212	0.022 (0.013)	2.20 (2.20)	32.4[1] (29.2)	0.012 (0.011)	0.59 (0.54)
329	190	0.035 (0.003)	0.67 (0.67)	25.1[1] (17.3)	0.010 (0.007)	0.58 (0.51)
333	190	0.049 (0.008)	0.93 (0.93)	31.0[1] (23.8)	0.016 (0.013)	0.52 (0.48)
330	177	0.064 (0.009)	0.46 (0.46)	30.5[1] (20.4)	0.011 (0.009)	0.55 (0.49)
331	177	0.003 (0.003)	0.56 (0.56)	25.9[1] (18.9)	0.011 (0.009)	0.51 (0.46)
340	177	0.038 (0.006)	0.56 (0.56)	28.1[1] (18.1)	N/A	0.56 (0.50)

1. Measured by FTIR spectrometer
2. Measured by TPU electrochemical sensor
3. Average of wall and centerline temperature

N/A = not available

C. Gas Analysis Results for Untreated Samples

As discussed above, in previous torrefaction runs involving human solid waste, the presence of CO was observed prior to the start of the heating cycle, although in much smaller amounts that CO_2. This was also true in the case of canine solid waste.[10,11] This prompted a study of the CO evolution from human solid waste that is stored at room temperature for extended periods, either in advance of torrefaction processing or for the end purpose of storage in canisters in the presence of activated carbon. CO is toxic at relatively low concentrations and is also not efficiently captured with standard sorbents, such as activated carbon. For these reasons, it is believed this supplemental study will provide useful data to NASA for the safe storage of un-processed human solid waste on long term missions.

A standard porous polyester/PTFE (Sterlitech) bag was filled with a 210 g sample of human solid waste. The bag also included the usual dry waste products employed for full-scale torrefaction experiments (1 latex glove, 1 Tempo wipe, 1 Tech wipe, gauze strip and 2 Huggies wet wipes). The bag was then loaded into a 1.6 L reaction canister, a sub-scale reactor used in previous work, and sealed. The canister, shown in Figure 4, included several feedthroughs for gas entry and withdrawal, as well as temperature and pressure/vacuum measurements. A pair of ball valves were added so that it could be sealed between gas measurements, as described below. The canister was stored in a laboratory hood where there was no climate control. Due to the time of year (mid-summer 2020), the daytime temperatures could reach in the high 80s ^oF (~30 °C) in this area.

Figure 4. Reaction canister used for stored human solid waste gas evolution testing.

As discussed above in section II B, gas analysis was performed with an FTIR Analyzer (On-Line Technologies, Inc. Model 2010 MGA). After an initial period of ~ 48 hours, the canister was coupled to the MGA. It was then purged with nitrogen (flow rate of 0.5 LPM) with the MGA measuring the composition of the effluent gas at 1-minute intervals. After about 25 minutes, the nitrogen purge was shut off. At this point, the concentrations of all non-condensable gases being monitored were below the detection limit of the instrument, based in the signal/noise ratio. The canister was then removed from the measurement system, flushed with dry air (bottled) for another 20 minutes, and then sealed. Figure 5 shows the flow rates for CO and CO_2 measured as the canister was being purged.

Figure 6 displays the infrared absorbance spectrum measured at a point where all non-condensable gases were at their peak levels, including CO for which the concentration was determined to be about 24 ppm. As shown in the top plot, the spectrum absorbance features are dominated by CO_2 and H_2O, which were present in levels of about 24% and 3% (by volume), respectively. The high spectral resolution of the MGA enables trace species such as CO to be identified and quantified. For illustration purposes, these interferences can be removed by subtraction to highlight trace species such as CO. The bottom plot shows a “cleaner” spectrum after removing the CO_2 and H_2O contributions, using scaled calibration spectra for each of these gas interferences.

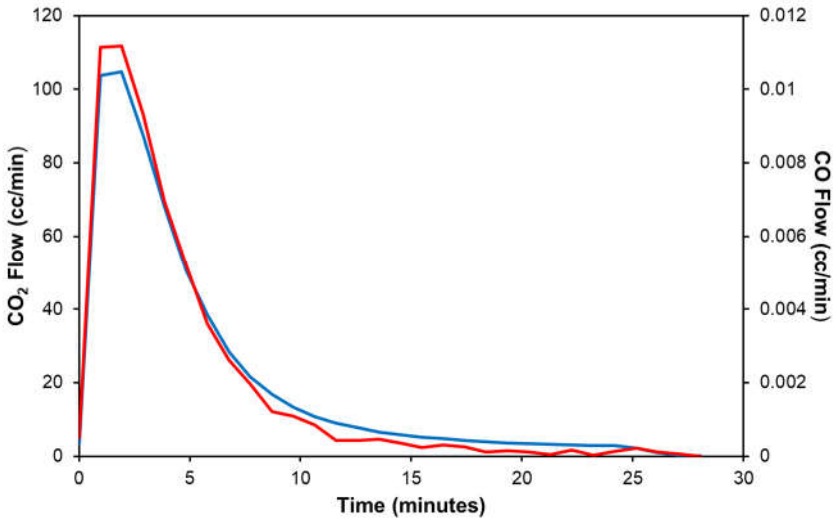

Figure 5. CO (red) and CO_2 (blue) flows measured after the initial 48 hour storage period at room temperature, for 210 g of human solid waste. *The total yields for CO and CO_2 were 0.57 cc and 598 cc, respectively.*

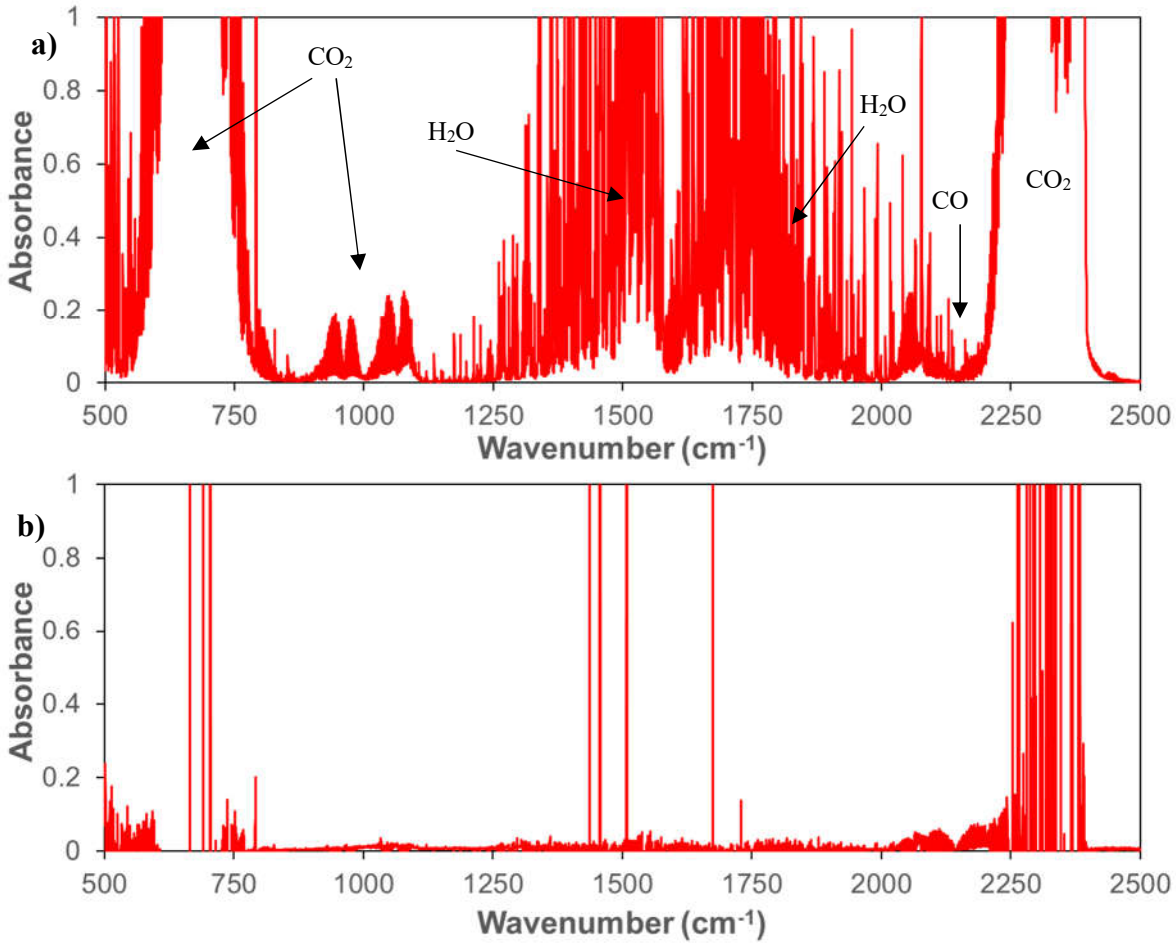

Figure 6. Infrared absorbance spectrum obtained for human solid waste decomposition gas after a storage period of ~ 48 hours: (a) shows the uncorrected data, dominated by CO_2 and H_2O features; (b) shows the data with CO_2 and H_2O interferences removed and the CO band in the region between 2000 and 2300 cm^{-1} is more apparent. *An expanded view of the CO band appears in Figure 7.*

Figure 7 shows two plots of the corrected spectrum from Figure 6, but zoomed in on the CO band region. The top plot displays the canister effluent sample by itself and the bottom plot includes a calibration spectrum (measured with the same instrument) of 30 ppm CO in nitrogen. The presence of CO is unmistakable as we observe a very good match in the overall CO band shape and excellent overlays of the individual CO lines.

In subsequent measurements, monitoring of the canister gas production was done over a period of nearly 7 weeks. The initial two measurements were collected at 2- and 4-day intervals, while all subsequent measurements were recorded at 2-week intervals. Data for the time-averaged and cumulative generation for CO and CO_2 are shown in separate plots in Figure 8. Note that the CO and CO_2 data are normalized on a per kg basis and the two gases are plotted on different scales. With these data, it is anticipated that the concentrations of these species in a confined storage area, with little or no ventilation, can be estimated for a given time period.

For example, if one assumes a maximum CO generation rate of 1 cc/kg stored human solid waste (see Figure 8 cumulative totals) and have a total of 100 canisters (with 3 kg human solid waste per canister) in a room of 800 ft^3 (~22.7 m^3), the accumulated CO concentration would be ~ 13.5 ppm, which is below the 15 ppm Spacecraft Maximum Allowable Concentration (SMAC) level.[21] This assumes no mitigation or ventilation, and of course would be higher in a smaller compartment.

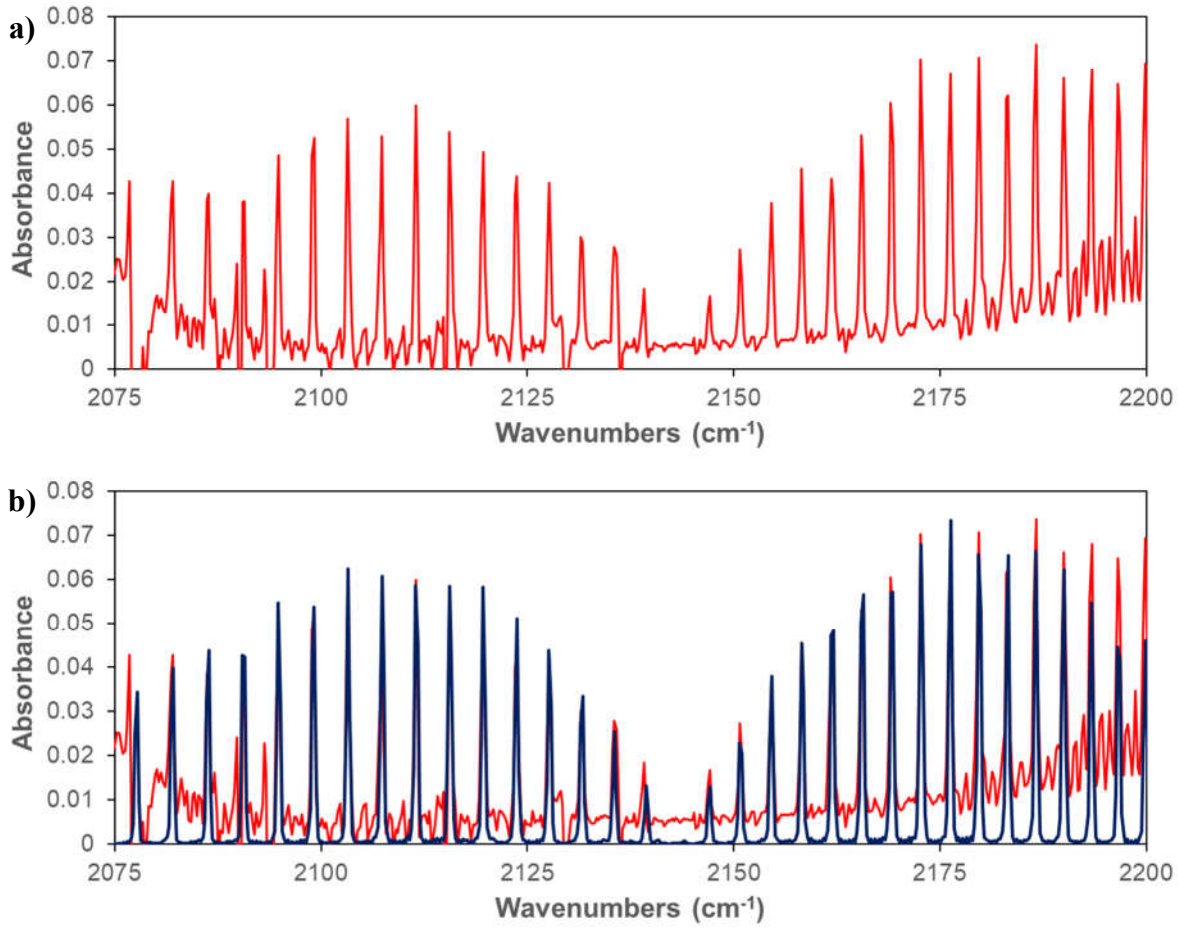

Figure 7. Infrared absorbance spectrum measured for human solid waste decomposition gas (red) after a storage period of ~ 48 hours: (a) spectrum is the same corrected data shown in Figure 6b but zoomed in on the CO band region; (b) plot shows the measurement overlayed with a 30 ppm CO calibration spectrum (blue).

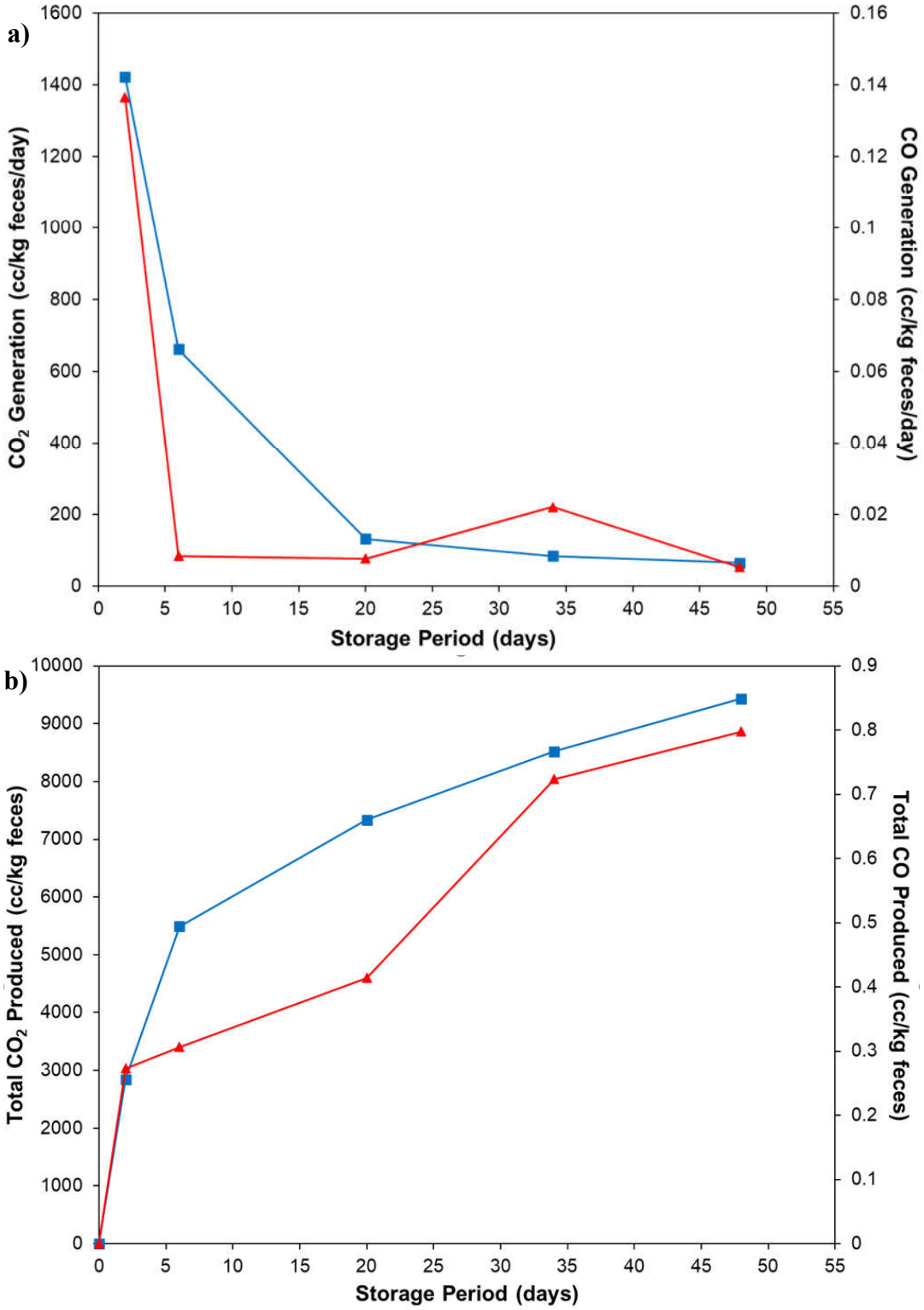

Figure 8. Gas generation rate (top) and cumulative totals (bottom) for CO (red) and CO_2 (blue) measured during the decomposition of human solid waste over a period of several weeks.

IV. Conclusion

The overall objective of this project was to design, construct, test, and deliver to NASA a prototype full-scale Torrefaction Processing Unit (TPU) that is compatible with the Universal Waste Management System (UWMS) and other Advanced Life Support Technologies. This full-scale TPU prototype was used to conduct 13 experiments on human and canine solid waste, with monitoring of off gases (CO_2, CO, H_2S, CH_4, COS) and collection of condensed liquids (mostly water). The final torrefaction centerline probe temperature was varied from 150°C to 200°C and it was found that variations in the gas product yields were modest below 200°C and were influenced in most cases by biological processes in storage. This conclusion was based on spikes in gas evolutions prior to active torrefaction processing. This phenomenon was further examined by doing experiments with untreated human solid waste samples over a period of weeks, which tracked evolutions of CO_2 and CO. While much larger amounts of CO_2 were generated than CO, these biological processes will likely contribute to background CO levels in a spacecraft in the case of stored, untreated human solid waste samples.

Acknowledgments

The support of this work by NASA under contracts NNX15CJ46P, NNX16CA06C and 80NSSC19C0051 is gratefully acknowledged. The authors also wish to acknowledge helpful discussions with Mr. James Broyan and Mr. Michael Ewert of the NASA Johnson Space Center, and Prof. Eric Suuberg of Brown University. In addition, the authors wish to thank Dr. Kris Rangan of Materials Modification, Inc. for supplying sample bags.

References

[1] Metcalf, J., Peterson, L, Carrasquillo, R., and Bagdigian, R., "National Aeronautics and Space Administration (NASA) Environmental Control and Life Support (ECLS) Integrated Roadmap Development," *42nd International Conference on Environmental Systems,* AIAA 2012-3444, 2012.

[2] Carrasquillo, R., and Anderson, M., "Environmental Control and Life Support (ECLS) Hardware Commonality for Exploration Vehicles," *42nd International Conference on Environmental Systems,* AIAA 2012-3623, 2012.

[3] Goodliff, K. E. Stromgren, C., Dickert, Z., Ewert., M. K., Hill, J. and Moore, C., "Logistics Need for Future Human Exploration Beyond Low Earth Orbit," *AIAA Space Forum,* AIAA 2017-5122, 2017.

[4] Broyan, J. L, Ewert, M. K., McKinley, M., Fink, P., Badger, J., and Lee, J., "Development Status of Logistics Reduction Technologies for Exploration Missions," *International Conference on Environmental Systems,* ICES 2020-416, 2020.

[5] Anderson, M. S., Macatangay, A. V., McKinley, M. K. Sargusingh, M. J., Shaw, L.A., Perry, J. L, Schneider, W. F., Toomarian, N., Gatens, R. L., "NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2018 to 2019 Overview," *49th International Conference on Environmental Systems,* ICES-2019-297, 2019.

[6] Wannapeera, J. Fungtammasan, B., and Worasuwannarak, N., "Effects of Temperature and Holding Time During Torrefaction on the Pyrolysis Behaviors of Woody Biomass," *Journal of Analytical and Applied Pyrolysis*, 92, 99-105, 2011.

[7] Serio, M. A., Cosgrove, J. E., and Wójtowicz, M. A., "Torrefaction Processing of Human Fecal Waste," Final Report under Contract No. NNX13CA54P, November 2013.

[8] Serio, M. A., Cosgrove, J. E., Wójtowicz, M. A., Lee, L., Kanapathipilai, W., and Fisher, J., "Torrefaction Processing of Spacecraft Solid Waste," *44th International Conf. on Environmental Systems,* ICES-2014-211, Tucson, AZ, July 13-17, 2014.

[9] Serio, M. A., Cosgrove, J. E., Wójtowicz, M. A., Lee, J., Wignarajah, K., and Fisher, J., "Space Applications of Torrefaction Processing," *45th International Conference on Environmental Systems*, ICES-2015-291, Bellevue, WA, July 12-16, 2015.

[10] Serio, M.A., Cosgrove, J.E., and Wójtowicz, M.A., "Torrefaction Processing for Human Solid Waste Management," NASA Final Report, Contract NNX16CA06C, March 12, 2019.

[11] Serio, M.A., Cosgrove, J.E., Wójtowicz, M.A., Stapleton, T.J., and Lee, J.M., "Operational Data for a Full Scale Prototype Torrefaction Processing Unit (TPU) for Spacecraft," *49th International Conf. on Environmental Systems*, ICES-2019-291, Boston, MA July 7-11, 2019.

[12] Linne,, D. L, Palaszewski, B. A., Gokoglu, S., Gallo, C. A., Balasubramaniam, R., Hegde, U. G., "Waste Management Options for Long_Duration Space Missions: When to Reject, Reuse, or Recycle," *7th Symposium on Space Resource Utilization*, AIAA, National Harbor, MD, 2014.

[13] Anthony, S. M., and Hintze, P. E., "Trash-to-Gas: Determining the Ideal Technology for Converting Space Trash into Useful Products," *44th International Conference on Environmental Systems,* ICES-2014-016, 2014.

[14] Meier, A., Shah, M., Engeling, K., and Quinn, K., "Demonstration of Plasma Assisted Waste Conversion to Gas," *49th International Conference on Environmental Systems,* ICES-2019-128, 2019.

[15] Engeling, K. W., and Meier, A. J. "Utilizing a CO_2 Carrier Gas in a Plasma Assisted Waste Conversion Test Cell for Space Applications," *International Conference on Environmental Systems,* ICES-2020-230, 2020.

[16] Stapleton, T. J., Baccus, S., and Broyan, J. L., Jr., "Development of a Universal Waste Management System," *43rd International Conference on Environmental Systems*, AIAA 2013-3400, Vail, CO, July 14-18, 2013.

[17] Wójtowicz, M.A., Cosgrove, J.E., Serio, M.A., and Lee, J., "An Equivalent System Mass (ESM) Analysis for the Universal Waste Management System (UWMS) with and without the Torrefaction Processing Unit (TPU)," *International Conference on Environmental Systems*, ICES-2020-560*,* 2020.

[18] Serio, M.A., Cosgrove, J.E., Wójtowicz, M.A., and Lee, J.M., "Optimization of a Spacecraft Torrefaction Processing Unit (TPU) for Human Metabolic Waste, *International Conference on Environmental Systems*, ICES-2020-507.

[19] Serio, M.A., Cosgrove, J.E., Wójtowicz, M.A., "Torrefaction Processing for Human Solid Waste Management," Final Report, Contract No. NNX16CA06C, December 12, 2020.

[20] Arrhenius, K., Johansson, U., "Characterization of contaminants in biogas before and after upgrading to vehicle gas," Report SGC 246 – English translation, September 2012.

[21] Spacecraft Maximum Allowable Concentrations for Airborne Contaminants, Revision A, JSC 20584, April 2020.