Optimization of a Spacecraft Torrefaction Processing Unit (TPU) for Human Metabolic Waste

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This paper describes work on the further development and testing of a full-scale prototype Torrefaction Processing Unit (TPU), which can be used to sterilize human solid waste to produce a stable and relatively odor-free solid product that can be more easily stored or recycled, and which 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. 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. Several improvements were made to the TPU to address back pressure, heat losses, gas sensor measurement errors, and liner bag dimensions. The current paper also includes additional experiments to examine variations in the torrefaction external heater temperature (200 to 225°C), sample endpoint temperature (150 to 200°C) and pressure (partial vacuum to 1 atm) on the torrefaction time, energy consumption, solid product odor, solid product bacterial contamination, and liquid composition. The data include processing time, the solid, liquid and gaseous product yields, and the total energy consumption. The overall goal is to reduce the Equivalent System Mass (ESM) and improve the ease and safety of operation for the TPU.

Nomenclature

ALS = Advanced Life Support
AFR = Advanced Fuel Research, Inc.
CA = Collins Aerospace
DOC = Dissolved Organic Carbon
ESM = Equivalent System Mass
FTIR = Fourier Transform Infrared
HMC = Heat Melt Compactor
IR = Infrared
ISRU = In-Situ Resource Utilization
kWh = Kilowatt-hour
LPM = Liters per Minute
MCT = Mercury-Cadnium-Telluride
OD = Outside Diameter
OLT = On-Line Technologies, Inc.
OMPCV = Orion Multi-Purpose Crew Vehicle
PMWC = Plastic Melt Waste Compactor

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PTFE = Teflon™
RTC = Raytheon Technolgies Company
SEC = Sensor Electronics Corp.
SBIR = Small Business Innovation Research
TC = Thermocouple
TOC = Total Organic Carbon
TPU = Torrefaction Processing Unit
UWMS = Universal Waste Management System
WMS = Waste Management System

I. Introduction

A. The Problem and Technical Approach

New waste management technology is needed to collect, stabilize, recover useful materials, and store human fecal waste and other spacecraft solid wastes for long duration missions. The motivations include 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 feces and related cellulosic 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. As in the case of pyrolysis, 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 optimize the full scale Torrefaction Processing Unit (TPU).

B. Potential Advantages versus Current Solid Waste Management Technology

As discussed by Fisher et al.,[12] the need for waste processing varies greatly, depending on the mission scenario. The near term needs are for the Orion Multi-Purpose Crew Vehicle (OMPCV), which will provide crewed missions to low Earth orbit and beyond. The intermediate term needs are for waste management technologies that could support missions to the moon and, eventually, the establishment of a habitat on the moon. The longer term missions would be to establish a long-term base on the moon and ultimately to go to Mars. There has been a lot of NASA supported work (both internal and external) on Waste Management Systems (WMS). These include testing of a Plastic Melt Waste Compactor (PMWC),[13] use of microwaves to stabilize waste and recover water,[14] and evaluating water recovery using a microwave freeze drying unit, a microwave powered ambient dryer, and a recirculating hot air dryer.[15] This represents a shift in emphasis away from fully regenerative technologies, such as incineration and supercritical water oxidation, which received a lot of attention in the 1990s.[12] All the above approaches have their advantages, but also disadvantages which have prevented adoption of any single method. For example, incineration utilizes a valuable resource, oxygen, and produces undesirable byproducts, such as oxides of sulfur and nitrogen. In addition, incineration will immediately convert all of the waste carbon to CO_2, which will require venting excess CO_2.

C. Potential Benefits for NASA

The use of torrefaction processing would make it technically feasible to process human fecal 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 Plastic Waste Melt Compactor[13] and other types of Heat Melt Compactors (HMCs) and could also be designed to be compatible with the Universal Waste Management System (UWMS)[16], now under development by NASA and Collins Aerospace (CA), a Raytheon Technologies Company (RTC). The potential integration of the TPU with other Advanced Life Support (ALS) technologies was discussed previously[11].

II. Experimental

A. TPU Design and Operation

Figure 1 depicts a schematic of the prototype full-scale TPU. The operation and dimensions 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, have been described previously[10,11]. Some additional improvements are described below.

B. TPU Improvements

1. Particle Filtration – A filter (Headline Filters model 137G) was originally employed for removal of particles, oil aerosols, etc. It uses a Pyrex bowl to allow visual inspection of the filter. The filter element is a disposable type that is rated for 99.99% removal of particles down to 0.1 micron. It measures approximately 3.18 cm OD x 6.35 cm length and is expected to be replaced every run. Note that in the schematic shown in Figure 1, the filter is located after the chiller. This is somewhat arbitrary, as it can also be positioned between the pre-chiller and the chiller. Its primary purpose is to prevent particulate and oil contamination on the gas sensors, so it just needs to be upstream of the sensor array.

In the initial testing[10,11], TPU runs were plagued by disruptions in the gas analysis measurements. These disruptions were attributed to the particle filter that became saturated with condensate, causing the canister to pressurize and leak. In order to prevent this problem, the filter housing was replaced by a larger volume unit (~ 3 times larger) and the filter medium was changed from a particulate filter to a coalescing filter. The advantage of the coalescing filter is that it is designed to drain off captured liquids, while still also providing particle removal from the gas.

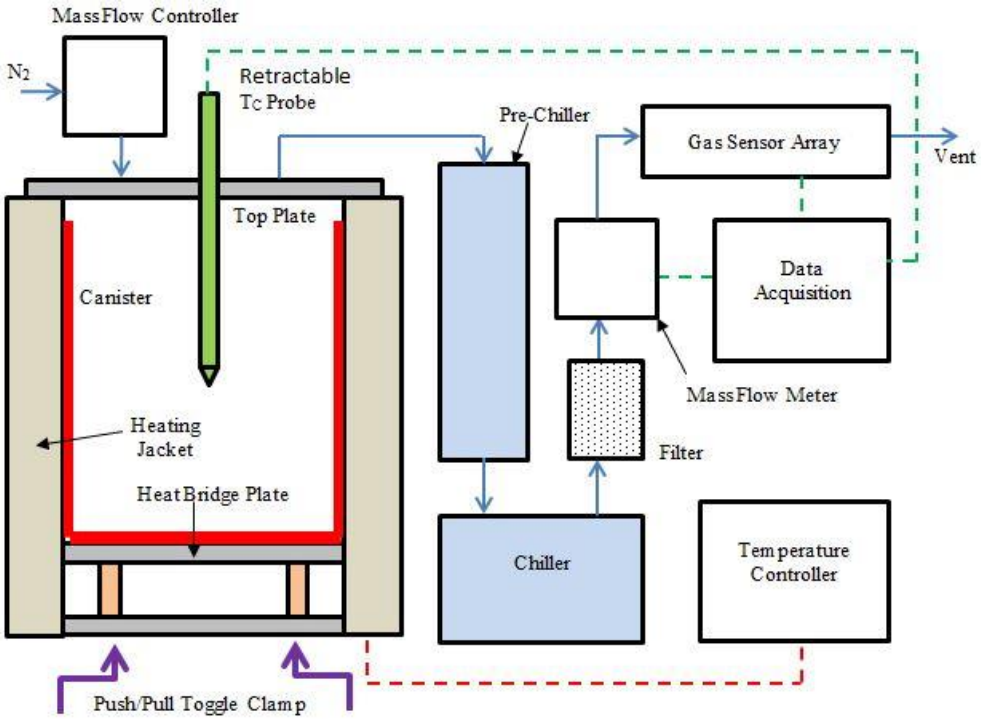

Figure 1. Schematic of the components of the full-scale prototype TPU.

2. Insulated Collar – A custom insulated collar/jacket was obtained to replace the ceramic wool section that had been used to reduce heat loss from the top metal flange area of the canister. The jacket is a split design, and includes a Velcro flap and buckled strap, similar to the heater jacket. It also includes a loop on the backside for attaching to the frame that supports the heater jacket. The insulation is 2.5 cm thick fiberglass.

III. Results and Discussion

A. Testing of the TPU Prototype

1. TPU Experiments – A total of 9 additional TPU experiments involving human feces (7) and canine feces (2) were done. As with the previous runs[10,11], 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. 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. As before, each bag contains 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. A summary of all of the TPU runs performed to date is included in Table 1. Each run included a 1 LPM nitrogen carrier flow.

For gas analysis, some runs (#328-#334 in Table 1) included the addition of an On-Line Technologies (OLT) Multi-Gas® 2030 FTIR gas analyzer, located downstream of the TPU gas sensor array. The analyzer sampling 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.

Run # 328 was basically a repeat of the first two full-scale human feces experiments (#326, #327) that were previously reported[10,11]. The operating conditions were the same, using a heater jacket setpoint temperature of ~225°C and a sample target endpoint temperature of 200°C at the center of the canister. The only change to the experimental configuration was the upgraded coalescing filter, described above, and the addition of the FTIR gas analyzer.

Figure 2 displays the temperature profiles, after heating begins, for the probe, bottom hot plate, top plate and the gas traces for several non-condensable species fro Run #328. All gas traces shown were FTIR measured, except for H_2S. The center reaches the endpoint temperature in ~33 hours with an energy usage of 7.61 kWh. After shutdown, the jacket heater was immediately opened and the sample probe temperature cooled to 50°C in just over 5 hours. The processing time and energy usage were very similar to previous runs under the same nominal conditions[10,11].

For run # 329, the setpoint temperature and target endpoint temperature were reduced to 205°C and 175°C, respectively. The resulting temperature and gas evolution profiles are shown in Figure 3. In this case, the endpoint was reached in ~34 hours with an energy usage of 7.01 kWh. After opening the jacket heater, the center cooled down to 50°C in about 4.5 hours.

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

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. Previous Study (see Reference 11).
6. FC = Faint Char; VL = Vomit-Like; FVL = Faint Vomit-Like

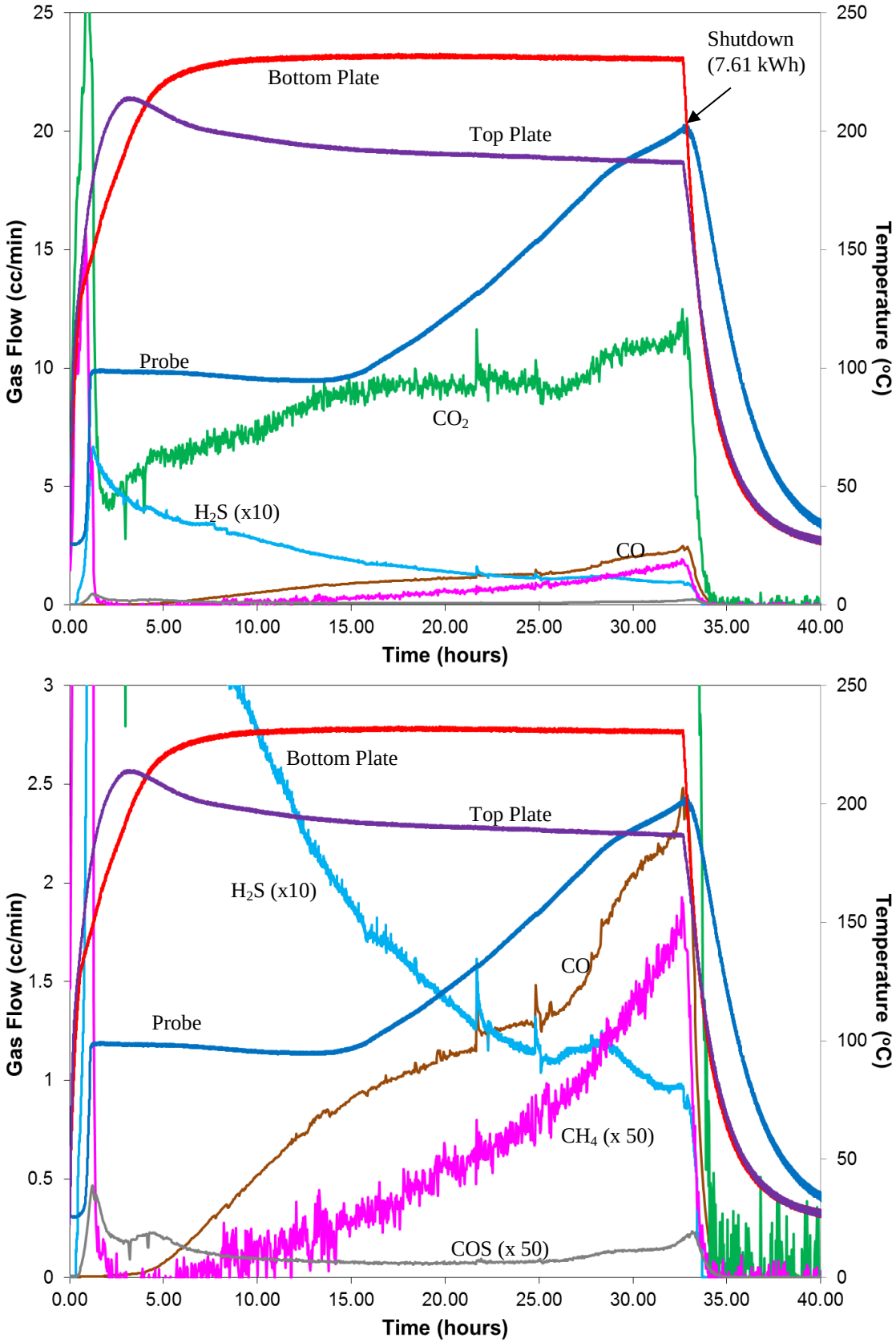

Figure 2. Temperature and gas profiles recorded during a full-scale TPU test with human feces (Run # 328). The setpoint temperature was ~225°C and the endpoint at the center was 200°C. The bottom plot is zoomed in at lower gas flows to highlight the trace gas profiles.

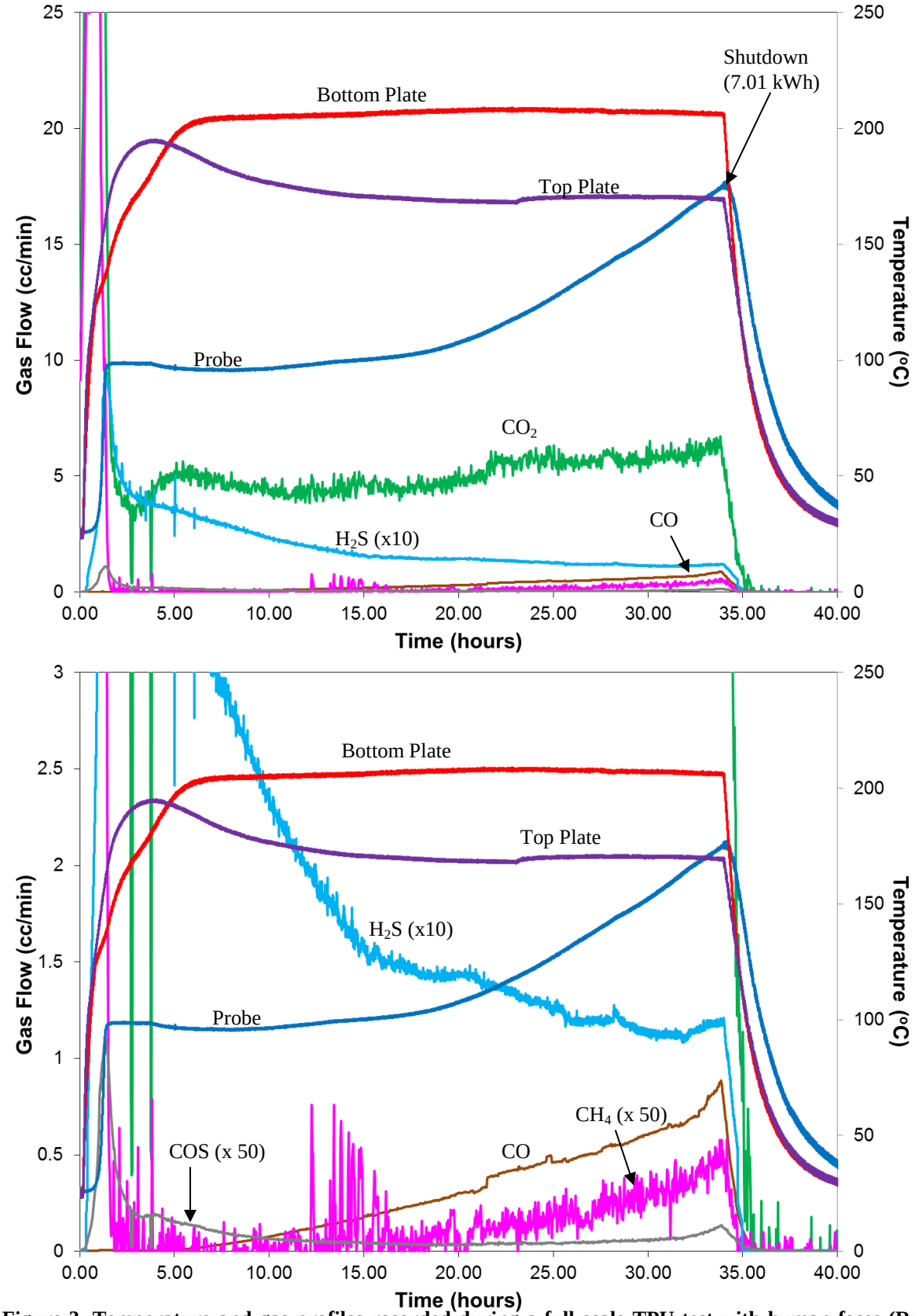

Figure 3. Temperature and gas profiles recorded during a full-scale TPU test with human feces (Run # 329). The setpoint temperature was ~205°C and the endpoint at the center was 175°C. The bottom plot is zoomed in at lower gas flows to highlight the trace gas profiles.

Data from both runs, including the individual yields for the non-condensable gases, are summarized in Table 1, along with data from the previous work (#325-#327)[10,11]. An obvious benefit to lowering the processing temperature is the reduction in CO, which is about 3 times lower for run # 329. The total yields for CO_2 are summarized for the FTIR determined values for runs #328 to #334 and the TPU sensor for run #327. As discussed in the next section, the TPU sensor measurements of CO_2 are usually about 20-25% lower than the FTIR measurements. For this reason, it is particularly interesting that the CO_2 yield for run # 327 is even higher than # 328, given that the operating conditions were the same. One possible explanation is that a significant portion of the CO_2 may be dissolved in the moisture in the feces, the extent of which is dependent on the storage temperature (and time). Run # 327 was conducted in early March 2019, when storage temperatures were much lower than for run # 328, which occurred in July 2019. 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. All three gases (CO_2, H_2S, CH_4) have a spike early in each TPU run, as shown in Figures 2 and 3, which can be attributed to this variable biological component. 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 processing did not start until the following day, nearly 24 hours later. It can be seen from Figure 4 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 fecal matter 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[17].

A total of 7 additional TPU experiments involving both human and canine feces were conducted with an emphasis on examining the effects on product yields, energy consumption, char odor, etc. of lowering the processing temperature down to 175 or 150°C at the center of the canister. One additional change that was implemented was the use of a longer liner bag so that it could be sealed or tied off after processing. This is described below.

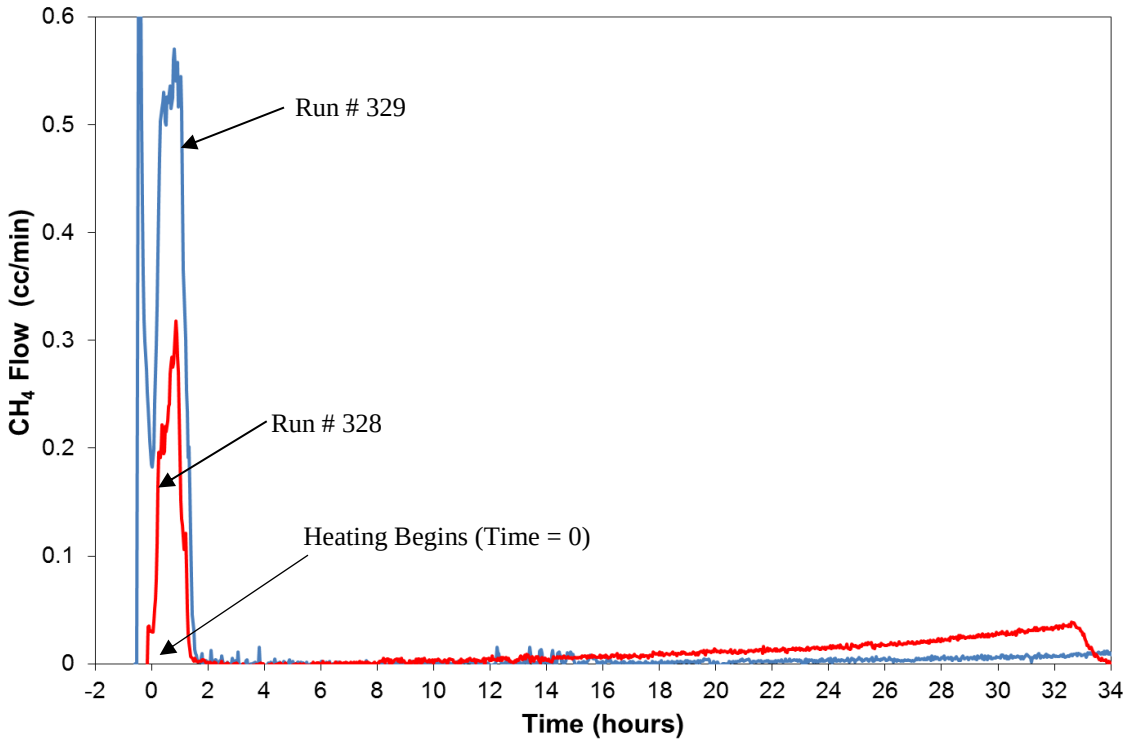

Figure 4. Comparison of CH_4 profiles for run # 328 (red) and run # 329 (blue).

Table 1 provides the detailed results in terms of the product yields and the experimental parameters for these additional runs. The table also includes a description of the resulting char odor, which of course should be considered a subjective result. In general, the odor of the solid residue was much more noticeable for the lowest temperature (150°C) runs. The gas analyses for most of these experiments continued to include the FTIR measurements (CH_4, CO, CO_2, COS), in addition to the TPU sensor data for H_2S and selected results for CO_2. All gas traces shown are FTIR measured, except for H_2S. It does seem clear from Figures 2 and 3 and Table 1 that the final temperature has a strong effect on the yields of CO. This may also be true for CO_2, H_2S and CH_4, but the results are somewhat obscured by the contribution of the biological component, as discussed above.

Based on a total of 12 full scale TPU runs performed, it can be seen that the TPU is able to process fecal samples in 48 hours or less, assuming a typical cooling period of 4-5 hours. There also seems to be a fair degree of variation in the processing time and energy usage for a given set of conditions, which may be in part due to seasonal effects. The TPU system is currently located in a laboratory hood which imparts a strong draft on the reactor. In addition, because the room is so heavily ventilated, its temperature is not well-controlled and tends to track the outside temperature.

It should be noted that Runs #338 and #339 (human feces) used wall setpoint and center endpoint temperatures of 225°C and 200°C, respectively, similar to the earliest TPU runs. However, the heating system for these two most recent runs was temporarily modified by adding separate temperature controllers to the bottom and top plate heaters. The setpoints at the bottom and top were 225°C and 200°C (limited by the O-ring seal), respectively. Using the additional controllers shortens the ramp-up time for the bottom and top zones, but given the relatively long typical heating cycle of 30-40 hours, it did not appear that the additional complexity was offset by any benefits (energy or time savings).

2. *Liner Bags* – As discussed above, longer liner bags were employed in the most recent runs, in order to enable the char to be tied off after processing. The new bags are the same Teflon material (modified PTFE) with the same width (30.5 cm) and thickness (60 micron) but the length is nearly double (63.5 cm). Prior to being installed into the canister, the excess bag is easily rolled over to the desired length. Each of the bags is tied off with a cable tie. The bags are actually longer than needed and probably could be trimmed down, if required (see also Section E).

3. *Particle Filter* – In previous work, clogging issues with the particle filter created interruptions with the gas analysis measurements. This problem appeared to be resolved by replacing the original filter with a larger volume, coalescing-style unit, as described above. However, filter clogging was a problem again in the two most recent TPU runs (#338, #339). The culprit is believed to be an oil or oils that are evolved at later stages of the process and which are not effectively removed by the pre-chiller or chiller. Using different filter locations was explored, upstream versus downstream of the chiller, but the problem persisted. At this point it is believed that the best solution may be to increase the filter capacity yet again. Since the filter supplier (United Filtration Systems) does not offer a larger volume filter, two options are being considered in the future: 1) install a second, identical filter in a parallel configuration with the current unit, or 2) obtain a larger filter from a different supplier.

B. Gas Sensor Studies

1. *Cross-Sensitivity*– In previous work[10,11], there was a concern that the electrochemical (CO and H_2S) sensors had been "poisoned" by some reactant in the gas stream. The CO sensor appeared to still be working, but it was noted that its background signal was somewhat unstable. For the early full-scale TPU runs (#325, #326), the H_2S sensor was rendered completely unresponsive and it was also believed that this occurred during the first full-scale run, which involved simulant samples. Note that prior to that, the H_2S sensor had only been used for sub-scale canine feces experiments and no evidence of contamination had been observed. The H_2S sensing element was eventually replaced and it was possible to record data during the last several TPU runs (Run #327 - #334) [10,11]. However, based on the relatively high levels of H_2S that were measured, it was thought to be necessary to further investigate any potential cross-sensitivities with other species that might be present.

Using an OLT Multi-Gas 2030® FTIR analyzer, several gas species were identified (in concentrations > 100 ppm) in the gas product stream including CO_2, H_2O, CO, CH_4, CH_3OH (methanol) and CH_3CHO (acetaldehyde). Of these gases, the manufacturer supplied cross-sensitivity data for CO_2, CO and CH_4. Based on these data, the H_2S sensor is not expected to produce any response to CO_2 or CH_4, and only a small response to CO (0.002ppm/ppm CO).

To evaluate any cross-sensitivity to methanol or acetaldehyde, the sensor array was tested using a simple test apparatus. A few drops of liquid were added to a reservoir, where a carrier gas was introduced into the headspace. After the target concentration was reached, as determined by the FTIR analyzer, the gas stream was switched from the bypass position to the sensor arrays. The setup did not provide a stable concentration flow, but was sufficient for this purpose.

The H_2S sensor, which has a range of 0-500 ppm, showed no response to either methanol and acetaldehyde. On the other hand, the CO sensor showed strong cross-sensitivity to both gases. Based on these results, it was believed that the CO sensor was not working properly and previous results[10,11] regarding this sensor should be regarded with caution and no results from this sensor are included in Table 1.

*2. Assessment of TPU Gas Sensor Performanc*e – It was noted above that the infrared-based TPU CO_2 gas sensor measures somewhat lower levels than the FTIR analyzer. In addition, it was found that the electrochemical CO sensor measurements did not agree with the FTIR analyzer, as discussed below.

CO_2 Sensor – Table 2 compares the FTIR and TPU sensor measured yields for the torrefaction experiments that included both types of measurements. In general, the CO_2 yields measured by the TPU sensor are 20-25% lower than the FTIR measurements. Measurements were performed of two different CO_2 calibration bottles in order to further assess the accuracies of the FTIR and TPU sensors at a low (0-1%) and high (5-10%) ranges of CO_2. The low range measurements were acquired using a 0.985% (nitrogen balance) calibration source from Cal Gas Direct and the higher range measurements were acquired using a 9.914% (nitrogen balance) calibration source from Airgas. The gases were further diluted using high purity nitrogen controlled by a mass flow controller.

In both the low and high range cases, the response of the TPU sensor was actually closer to the calibration gas concentration, except at the very lowest concentrations where the TPU sensor is near its detection limit. It appears that the FTIR analyzer calibration has drifted, so these discrepancies will require further investigation.

Table 2. Comparison of FTIR and TPU measured CO_2 yields.

Run #	CO_2 Yield (g)	
	FTIR	TPU Sensor
328	32.40	24.52
329	25.08	22.79
330	30.51	23.05
331	25.88	20.06
332	40.33	30.75
333	30.97	22.19

CO Sensor – As discussed above, it was observed that the CO sensor exhibited high cross-sensitivity to other gases such as methanol and acetaldehyde. Through subsequent discussions with the sensor supplier, Sensor Electronics Corp. (SEC)), it was learned that the CO electrochemical sensor requires a minimum 5% oxygen atmosphere to operate properly. For this reason, in Runs 331-333, the ~ 1 LPM nitrogen dilution gas (introduced downstream of the reactor) was changed to air, to maintain ~ 10% oxygen in the sensor array. However, this did not appear to improve the CO sensor response, compared to the FTIR measurements. The sensor showed some response to CO near the end of the run, but it also appeared to respond to other species throughout the run. At this stage, it is believed that the sensor was poisoned during the initial experiments and a replacement sensor will be installed.

C. Condensate Analyses

Selected liquid condensate samples that were generated in the previous work[10,11] and in the current study with canine feces and human feces were sent to Huffman Laboratories (Golden, CO) for analysis for Dissolved Organic Carbon (DOC) and Total Organic Carbon (TOC). The results are shown in Table 3, along with results for subscale experiments using simulant and canine feces at various temperatures, all normalized to a 70% moisture content for the TOC in the last column. The TOC and DOC results for these full scale experiments were generally consistent with the subscale results, although it should be noted that all of the subscale results were for canine feces. In general, the TOC and DOC amounts increased with increasing processing temperature, as expected, although certain results, like for Run #326, appear anomalous.

D. Bioactivity Testing

Char bioactivity was tested for samples from four different runs, including a run from the previous work[10,11]. Char samples were applied to two agar plates for each run, at the center ~ 3.8 cm region of each plate, and then incubated at 32°C (90°F) for 44 hours. The agar plates were commercial Lysogeny Broth plates provided by EZ BioResearch LLC. Observations of mold growth in the contaminated region indicated a positive result for bioactivity. Control samples of bottled water and miso were also tested (one plate each). The results are summarized in Table 4 and indicated the TPU processing eliminates any bioactivity that can be measured by this test. As noted in Table 4, there was some mold growth for one of the plates from Run #327, but it was outside the region of the plate that was intentionally contaminated.

Table 3. Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC) for liquid condensates from several torrefaction experiments.

Run #	Sample Size (g)	Sample/Moisture Content(%)/Atmosphere* Flow Rate (LPM)	Max. Temp. (°C)	Center Temp. (°C)	Total Org. Carbon (mg/L)	Dissolved Org. Carbon (mg/L)	Normalized[1] Total Org. Carbon (wt.%)
204	105	C. Feces/70%/ N2, 1.0	250	226	11,000	10,800	1.10
205	99	C. Feces/70%/N2, 1.0	225	203	8840	8690	0.88
206	99	C. Feces/70%/N2, 1.0	200	164	8150	7990	0.82
207	100	C. Feces/70%/Air, 0.5-1.0	225	223	9730	9410	0.97
208	100	C. Feces/70%/Air, 0.5	200	196	6650	6540	0.66
209	100	C. Feces/70%/Air, 0.5-1.0	175	158	8350	8120	0.83
325	3000	C. Feces/75%/N2, 1.0	225	200	9010	7090	0.96
326	3000	H. Feces/73%/N2, 1.0	225	200	9660	8430	1.01
328	3000	H.Feces/73%/N2,1.0	225	200	13,800	13,000	1.41
329	3000	H.Feces/73%/N2,1.0	205	175	11,500	10,900	1.20
330	3000	H.Feces/73%/N2,1.0	205	150	10,300	9,780	1.08
331	3000	H.Feces/73%/N2,1.0	205	150	9,730	9,490	1.02

** Carrier Gas, LPM*

1. Normalized to 70% moisture content

Table 4. Summary of agar plate test results. A positive result indicates bioactivity.

Run #	Sample Type	Sample Age (days)	Actual Endpt. T (^{o}C)	Test Results	
				Agar Plate #1	Agar Plate #2
327	Torrefied Char (human)	201	215	?[1]	Negative
328	Torrefied Char (human)	67	200	Negative	Negative
329	Torrefied Char (human)	53	175	Negative	Negative
330	Torrefied Char (human)	6	150	Negative	Negative
Control	Miso	NA	NA	Positive	NA
Control	Water	NA	NA	Negative	NA

Some mold growth observed at the edge of the agar plate (outside of the intentionally contaminated region).

E. Vacuum Processing

Previous work using sub-scale reactors suggested that vacuum torrefaction of homogeneous biosamples (simulant, canine feces) that do not contain any additional waste materials such as paper, gloves, wipes etc., may be advantageous in terms of time and energy usage[10]. On the other hand, vacuum processing of pre-soaked cotton rolls, appeared to have a somewhat opposite effect, at least in terms of processing time[10]. It has therefore been of interest to investigate the effect of vacuum on the full-scale TPU system and the more representative heterogeneous samples that are being processed.

The previous sub-scale experiments generally lasted 8-10 hours and therefore allowed for constant supervision. With the much larger samples that are currently being studied, however, the TPU is generally left unattended for several hours at a time, over the course of its ~ 35-40 hour heat cycle. Consequently, it was necessary to run some preliminary experiments using more innocuous samples, consisting of 2 rolled up white terrycloth bath towels (~ 1100 g) soaked with 2000 g of water. This would allow for experiments to be curtailed, where necessary, and be

able to safely handle under-processed samples. The primary objective was to demonstrate that the vacuum pump could operate continuously over a 40 hour period, and that the condensers operate properly to avoid contaminating/flooding the vacuum pump. In addition, the system geometry must assure that the sample is not exposed to air if the pump fails, as this could potentially result in thermal runaway under certain conditions. Note that it is assumed that for actual space operation, vacuum would be achieved through venting, minimizing concerns over mechanical failure. Two vacuum test configurations were evaluated for this purpose using small towels that were soaked with water and then compared to ambient pressure tests with the same material.

With this additional data, it was unclear whether vacuum-aided processing over the full duration of a heating cycle will offer any time or energy savings for processing bagged fecal samples in the TPU system. However, future work will investigate a hybrid or two-stage approach, for example, where vacuum is initially utilized to accelerate early water removal and then the system is returned to ambient pressure in the second stage of the process. An acceptable pump geometry has been established and it should be possible to transition to fecal samples.

F. Compaction

Prior to torrefaction, the unprocessed material (bags, feces,, gloves, wipes, etc.) and liner completely fills the canister (with some effort required). After processing, approximately 20% volume reduction is typically observed. At this stage, the charred remains are hard and rigid and the bagged contents are able to support a 160 lb person without collapsing. A first-attempt compaction experiment was performed to demonstrate that the processed char volume can be further reduced with the aid of a makeshift mechanical press, using a Bridgeport milling machine. As shown in Figure 5, a 17.8 cm diameter x 1.3 cm thick aluminum disk with a 1.3 cm diameter steel shaft was installed in the chuck of the milling machine. A char bag (torrefied to a center temperature of 200°C) was placed inside the reaction canister and then positioned on the Bridgeport milling table directly under the press. The table was then raised until it was compacted to ~ 1/3 of its original height. Upon removal from the canister, the initial hardness and rigidity appears to be gone and the bag has a cushion-like feel. Consequently, there is some "springback", resulting in an uncompressed volume ~ 50% of the original (pre-processed) volume (see Figure 5).

Figure 5. (Left) Photo of the apparatus used for mechanical compaction. (Right) Photo comparing (right to left) a compacted char bag versus an uncompacted char bag and the reactor canister.

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 (ALS) technologies. This full-scale TPU prototype was used to conduct 9 additional experiments on human and canine feces, with monitoring of off gases (CO_2, CO, H_2S) and collection of condensed liquids (mostly water). The total power, heating time, cooling requirements, and water recovery were established for

these full-scale experiments, and some volume reduction (~ 20 %) along with significant odor reduction was observed. The final torrefaction sample probe temperature was varied from 150°C to 200°C and it was found that variations in the total run time and energy consumption were modest and seemed to be affected as much by variations in the ambient temperature. In all cases, the total time (heating + cooling) was less than 48 hours. The odor of the solid residue was much more noticeable at the lowest temperature (150°C). The yields of certain gas products like CO were noticeably lower at 150°C than 200°C and this may have also been true for CO_2, CH_4, and H_2S, but these gas yields were also affected dramatically by biological processes during storage. Some preliminary work was done to configure the system for vauum operation, study post processing compaction, and analyze the liquid and solid products..

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