TRASH-TO-GAS: CONVERTING SPACE TRASH INTO USEFUL PRODUCTS

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NASA's Logistical Reduction and Repurposing (LRR) project is a collaborative effort in which NASA is determined to reduce total logistical mass through reduction, reuse and recycling of various wastes and components of long duration space missions and habitats. LRR is focusing on four distinct advanced areas of study: Advanced Clothing System, Logistics-to-Living, Heat Melt Compactor and Trash to Supply Gas (TtSG). The objective of TtSG is to develop technologies that convert material waste, human waste and food waste into high-value products. High-value products include life support oxygen and water, rocket fuels, raw material production feedstocks, and other energy sources. There are multiple pathways for converting waste to products involving single or multi-step processes. This paper discusses thermal oxidation methods of converting waste to methane. Different wastes, including food, food packaging, Maximum Absorbent Garments (MAGs), human waste simulants, and cotton washcloths have been evaluated in a thermal degradation reactor under conditions promoting pyrolysis, gasification or incineration. The goal was to evaluate the degradation processes at varying temperatures and ramp cycles and to maximize production of desirable products and minimize high molecular weight hydrocarbon (tar) production. Catalytic cracking was also evaluated to minimize tar production. The quantities of CO_2, CO, CH_4, and H_2O were measured under the different thermal degradation conditions. The conversion efficiencies of these products were used to determine the best methods for producing desired products.

Nomenclature

Al	=	Aluminum
ACS	=	Advanced clothing system
AES	=	Advanced Exploration Systems
atm	=	Atmosphere, standard
CH_4	=	Methane
CO	=	Carbon monoxide
CO_2	=	Carbon dioxide
FPS	=	Food Packaging Simulant
FTIR	=	Fourier transform infrared spectrometer
GC/MS	=	Gas chromatography-mass spectrometer
HMC	=	heat melt compactor
HFWS	=	High fidelity waste simulant
ISS	=	International Space Station
ISRU	=	In-situ resource utilization
KSC	=	Kennedy Space Center
LRR	=	Logistics Reduction and Repurposing
LEO	=	Low Earth Orbit
LFWS	=	Low fidelity waste simulant
LTL	=	logistics-to-living
MAG	=	Maximum absorbency garment
MFU	=	MAGs, fecal and urine waste simulant
MFWS	=	Medium fidelity waste simulant

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N_2 = Nitrogen
NASA = National Aeronautics and Space Administration
O_2 = Oxygen
PE = Polyethylene
PET = Polyethylene terephthalate
slm = standard liters per minute
TtSG = Trash to Supply Gas

I. Introduction

WASTE treatment methods used on past Space Shuttle missions and current International Space Station (ISS) missions involve mission crew members storing waste materials until return vehicles either bring the material back to earth or burn it during atmosphere reentry. With the retirement of the Space Shuttle program and NASA's plans for long duration deep space missions beyond low earth orbit (LEO), return missions to earth will become less frequent, increasing the volume of trash stored on ISS and atmospheric burns of waste becoming more common. As NASA moves towards deep space missions outside of LEO, the focus of space travel must also shift to developing advanced exploration systems and in-situ resource utilization (ISRU) systems. ISRU is part of NASA's Human Exploration Destination System Roadmap with a purpose of developing technologies that enable the capability of self-sufficiency at locations beyond LEO and that eliminate the requirement to launch large amounts of mass for consumables and other items.[1] During long duration space missions and space travel, large amounts of human biological food and other material wastes are produced. The stored waste can present sanitation issues and occupies space that could otherwise be used for mission activity. Trash processing into consumables will provide useful consumables and reduce waste accumulation during long transit time, and provide a trash management technique while at the destination.[1] In addition, humanity undertaking deep space travel must keep in mind planetary protection efforts and preserve the natural habitat of celestial bodies as much as possible. If microbes and other wastes are released into space environments from human spaceflight, there is a possibility of rediscovering life from human waste. The LRR project views waste as a resource from which useful products can be derived.

The Trash to Supply Gas (TtSG) effort, part of the LRR project, supports the Advanced Exploration Systems (AES) program through pioneering innovative "reduce, reuse and recycle" approaches of future deep space missions. The main objectives of TtSG is to develop technologies that recycle material waste, human waste and food waste into high-value products for long duration space missions and habitats. High-value products include life support oxygen and water, rocket fuels, feedstocks for material production, and other energy sources. When these products are produced in situ, the mass of the Earth departure stage is reduced, which allows for more cargo capability during earth's launch or reduces cost of resources required to bring on a deep space mission. TtSG technologies will minimize the volume of waste that has to be stored and completely stabilize the waste.

TtSG is currently focused on the production of methane and involves multiple technologies being developed at different NASA centers.[2] This paper will discuss KSC's thermal degradation reactor which investigated a series of space waste simulants and various temperature cycles and gas feed mixtures to understand their thermal processing behaviors. The combination of system parameters to maximize the production of carbon dioxide (CO_2) would be determined for future downstream implementation into a Sabatier reactor for conversion of CO_2 into methane (CH_4) and water (H_2O). CH_4 is a useful fuel for propellants and alternative energy while water is valuable for environmental control and life support systems. The Sabatier reaction is displayed below. The thermal degradation reactor and Sabatier reactor are not currently connected. KSC is currently testing catalysts and gas separation techniques prior to integrating the two reactors.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

II. Characterization of Waste

Efforts were made to standardize waste simulants used for the TtSG task. The standardized waste simulants introduced three incrementing levels of processing challenges: low, medium and high fidelity waste simulants. As each level is studied, understanding and overcoming limitations assists in progressing the waste treatment technology development. The use of standardized waste simulants ensures that accurate comparisons can be made between each test run in the reactor as well as different waste technologies developed at other NASA centers. Waste simulants for the TtSG study were identified from waste characterization records of historical ISS and Space Shuttle missions.[3] an internal LRR NASA study took data from the historic mission studies and modeled the amount of

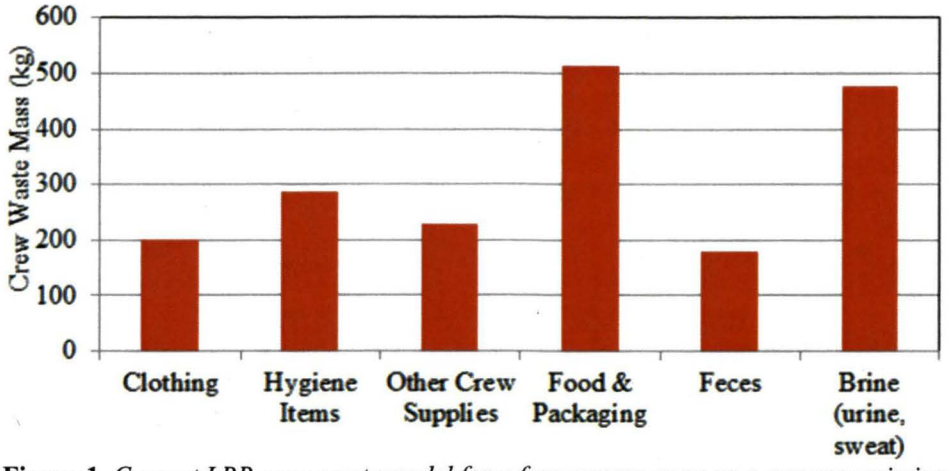

Figure 1. *Current LRR crew waste model for a four-person crew on a one year mission*

waste generated from a four person crew on a one year space exploration mission. Figure 1 displays the major waste sources, such as clothing, hygiene items, crew supply, food and food packaging, feces and brine, generated during one year. These waste simulants may change in the future based on new waste models or mission requirements.

KSC investigated the composition of the food packaging, which revealed that the food packaging was comprised of aluminum (Al), polyethylene (PE), and nylon and polyethylene terephthalate (PET). Eliminating brine and other crew supplies from this study, food packaging comprises over 40% of the waste by mass. Since PE consisted of more than half of food packaging mass, low fidelity waste simulant (LFWS) contained only PE for preliminary work with the reactor system. LFWS was used to understand the thermal degradation system before moving on to the more realistic and rigorous waste simulants. Only a short investigation was spent on the PE waste simulant, while more time was spent on the medium fidelity waste simulant (MFWS) and high fidelity waste simulant (HFWS) behavior. MFWS consisted of MAGs, FPS, and cotton towels. HFWS consisted of MFWS, fecal, urine and food waste simulant. When utilizing the trash reactor system in space, it is not intended for detailed trash separation prior to processing the waste. Trash simulant was loaded into the reactor in its natural mixed state to provide a realistic approach of processing the waste. MFWS accounts for approximately 50% total dry mass of waste produced in space, while the HFWS accounts for over 65% mass of waste generated. The percent by mass breakdown of the high fidelity, food and fecal waste simulant recipes are listed in Table 1. The waste simulants were cut into smaller segments before being placed into the reactor. The MAG, cotton washcloth and aluminum foil were cut into 1 inch squares and food simulant was mixed in a blender. The PE and nylon beads were approximately 0.0625 inches in diameter.

Table 1. *High fidelity waste simulant recipe by mass weight percent.*

COMPONENT	MASS %
HFWS	
Cotton Towel	17%
Aluminum Foil	5%
FPS (PE, PET, Nylon)	19%
MFU (MAGs, Fecal, Urine)	40%
Food	19%
FOOD SIMULANT	
Juice	41%
Dried Apricot	11%
Tortilla	21%
Hot Dog	27%
FECAL SIMULANT	
Cellulose	6%
Polyethylene glycol (PEG)	3%
Peanut Oil	11%
Miso	17%
Potassium chloride (KCl)	2%
Calcium chloride (CaCl2)	1%
Water	60%

Table 2. *Water Content of Waste Simulant*

CONTENT	DRY MASS %	ASH MASS %
COTTON	93.7%	0.0%
MAG	92.4%	11.8%
FPS	99.6%	31.3%
HFWS	58.4%	9.5%
MFU	29.5%	4.3%

The water and ash content was determined for each of the waste simulants. The simulants were dried in crucibles at 110°C for 3 days. The dry samples were then heated to 575°C for 16 hours and the ash content was determined. The results of the water content of each waste simulant are displayed in Table 2. Ash content was highest in the MAG and FPS. The fecal, food and urine simulant contained over 50% water, while the cotton, MAG and FPS contained over 90% dry mass. The dry mass was converted into carbon based products in the TtSG thermal degradation system. Water was collected in the condenser portion of the system and its weight recorded.

III. Experimental Set Up

The thermal degradation reactor consisted of an Inconel tube reactor with a 1.5 inch internal diameter with an internal Watlow multi-cell tube heater. The waste simulant was pre-loaded into the reactor bed, which surrounded the tube heater. The heated zone of the reactor was approximately 9 inches tall with the tube heater at 8 inches tall. The void space of the reactor bed allowed 0.28L of trash to surround a tube heater. This heated zone processed 10 grams of waste simulant per test.

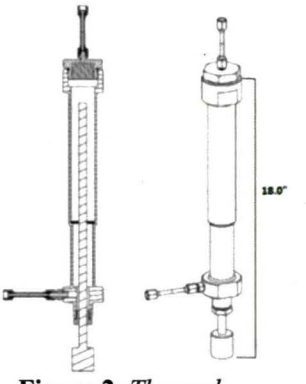

Figure 2. *Thermal Degradation Reactor*

Either air, nitrogen or a mixture of the two was fed into the bottom of the reactor while the reactor was being heated. Products leaving the top of the reactor traveled through a condenser, packed with steel beads and cooled with external thermal electric coolers (TECs) to chill the hot effluent reactor stream. A filter column, packed with glass wool, was placed downstream of the condenser to filter tar and collect other remaining solids of the stream prior to entering analysis instrumentation. The stream was then split and sent to a Fourier transform infrared spectrometer (FTIR) or a gas chromatograph-mass spectrometer (GC/MS) for analysis. Temperature and pressure readings were controlled and acquired from integrated thermocouples and pressure transducers to Labview software which also recorded experimental data.

The FTIR was calibrated for quantifying CO_2, CO and CH_4 production and also identified C_2H_4 and long chain hydrocarbons for a comparative analysis. The GC/MS was able to identify the amount of oxygen in the exit stream. Both FTIR and GC/MS were able to qualitatively identify many hydrocarbons produced in the reaction. Heavy tars were collected in the condenser and filter, but were not subjected to analysis.

A large test matrix with variables of inlet flow rate, inlet gas composition, reactor temperature ramp rate, reactor temperature limit, waste simulant material and waste simulant mass was performed. The test matrix is shown in Table 3. These efforts allowed for testing of multiple parameters to understand how different waste simulants behaved at different thermal cycles in order to choose the best conditions to maximize the amount of CO_2 production.

Table 3. *Test Matrix*

CASE NUMBER	FLOW		T CONDTIONS		MATERIAL		CATALYST	
	RATE (SLM)	GAS	RAMP [°C/MIN]	HOLD T [°C]	WASTE SIMULANT	MASS [g]	MASS [g]	Type
1	5	Air	10	500	HFWS	10	-	-
2	5	Air	Full (~100)	500	HFWS	10	-	-
3	5	Air	10	100, 500	HFWS	10	-	-
4	5	Air	Full (~100)	500	HFWS	10	18	Dolomag
5	5	Air	10	500	Cotton Washcloth	10	-	-
6	2.5 & 2.5	Air & Nitrogen	10	500	Cotton Washcloth	10	-	-
7	2.5 & 2.5	Air & Nitrogen	10	500	FPS	10	-	-
8	5	Air	10	500	FPS	10	-	-
9	5	Air	10	500	FPS	10	-	-
10	5	Air	10	500	MFU	10	-	-
11	5	Air	10	500	MAG	10	-	-
12	2.5 and 2.5	Air & Nitrogen	10	500	MAG	10	-	-

IV. Results and Discussion

Each case in the test matrix was performed in the thermal degradation reactor. The goal was to maximize the production of CO_2 for downstream conversion to CH_4 and liquid H_2O. The various combinations propagated many thermal degradation processes including pyrolysis, incineration and gasification.

A. Minor Products

As expected, the major products of the reactions included CO and CO_2. Minor products included CH_4, H_2O, C_2H_4, tar, and ash. Unconverted aluminum foil remained in the reactor after each experimental run. A list of

Table 4. *Trace byproducts and their classifications.*

CLASS NAME	PROPERTY	REPRESENTATIVE COMPOUNDS
GC-Undetectable	Very heavy tars	
ALKENE	Containing at least one carbon-to-carbon double bond	Acetylene, Allene, 1-Butene, 1-Butene-3-yne, Ethylene, Propene, 2-Methylpropene
ALKANE	Consist only of hydrogen and carbon atoms and are bonded exclusively by single bonds	Ethane, Propane
ALKYNE	Hydrocarbons that have a triple bond between two carbon atoms	Propyne, Ethyne
ALDEHYDE	R-CHO, consists of a carbonyl center (a carbon double bonded to oxygen) bonded to hydrogen and an R group	Acetaldehyde, 2 propenal,
CYCLOALKANE	One or more rings of carbon atoms	Methylenecyclopropane
CYCLIC ETHER	An oxygen atom connected to two alkyl or aryl groups — of general formula R–O–R'	Ethylene Oxide
DIENE	Contains two carbon double bonds.	1,3-Butadiene
KETONE	A carbonyl group (C=O) bonded to two other carbon atoms	Acetone

byproducts identified in most runs is shown in Table 4. The effect of these small hydrocarbons on the overall trash to methane process is unclear. If trace amounts of these compounds are acceptable in a methane propellant, then they would pose no problem as long as they did not affect the Sabatier process. If either of these cases is a problem, they will need to be completely combusted or separated from the product stream.

Heavy tars were collected in the condenser and filter column. The tars were not analyzed, but they were present in all runs. Figure 3 shows a picture of the glass wool that has been discolored by tar. Tar and hydrocarbon byproducts may seriously limit the use of such technologies in closed systems of human spaceflight. Important efforts of tar and byproduct removal are important for the future capacity of converting trash into energy since a closed system in a space vehicle or habitat would not allow for any type of polluting mechanism with human life present. Current tar removal methods include modifying and controlling system conditions in order to achieve the desired composition of the product gas therefore eliminating tar byroduct.[4] If perturbing the system to minimize tar production does not work, external measures such as scrubbers, catalytic cracking and other chemical conversion methods can be tested. The unreacted hydrocarbons will be reduced in future work through a modified second reactor manufactured at KSC as well as investigation of catalysis, which will also assist in cracking of long chain hydrocarbons.

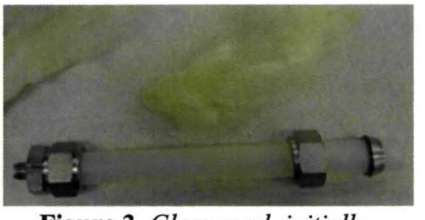

Figure 3. *Glass wool, initially white, turned yellow from tar capture in the filter.*

Ash was also a minor product in the experimental runs, with approximately 0.85 grams left over from a 10 gram HFWS run. Some of the losses are not accounted for due to losses during transfer to weigh the amount. This accounts for roughly 8.5% ash accumulation from the trash, which matches closely with the measured ash percentage shown in Table 2.

B. Variable Waste Simulant Experimentation

It is important to describe the overall trends of the waste behavior that is presented in the FTIR and GC/MS analysis. The most commonly run test of the HFWS will be described here and the results of CO_2, CO and CH_4 are given in the data summaries. Air was fed to the reactor, which held 10 grams of pre-loaded simulant and was heated at a full ramp rate (approximately 100°C per minute) to 500°C. When the reactor core temperature reached 500°C, the external reactor wall temperature was approximately 300°C with the wall temperature still climbing over 400°C during the reaction time, nearly reaching the internal core heater temperature. Figure 4 displays the relationships described between the reactor core heater and the external wall temperature. Internal reactor temperature maintained a steady temperature rate due to the insulation installed externally on the reactor. Once the reactor core reached 500°C, CO_2, CO and CH_4 compounds peaked in production rate. The production rates drastically reduced after 12 to 15 minutes.

The GC/MS detected a reduction in oxygen content from 21% to 11% for approximately 8 minutes during the CO_2 peak production time. CO_2 continued production for approximately 5 to 7 more minutes after the O_2 levels returned to 21%. The decrease in oxygen content from the GC/MS is displayed in Figure 5.

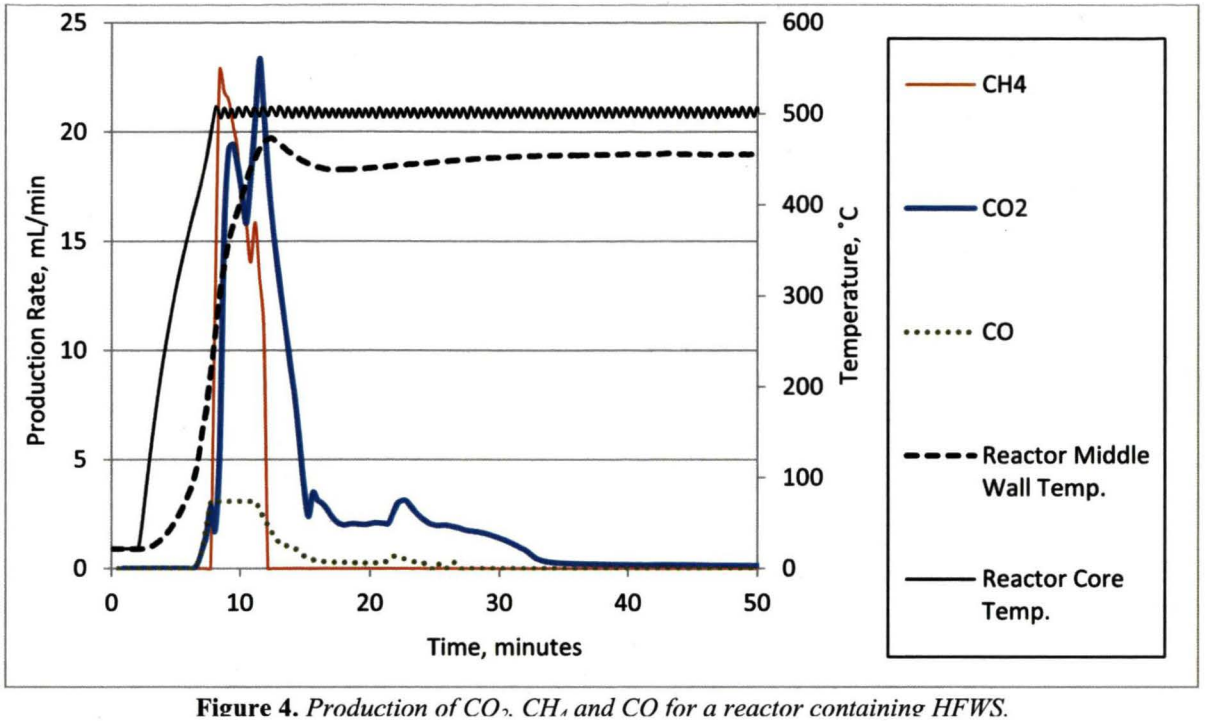

Figure 4. *Production of CO_2, CH_4 and CO for a reactor containing HFWS.*

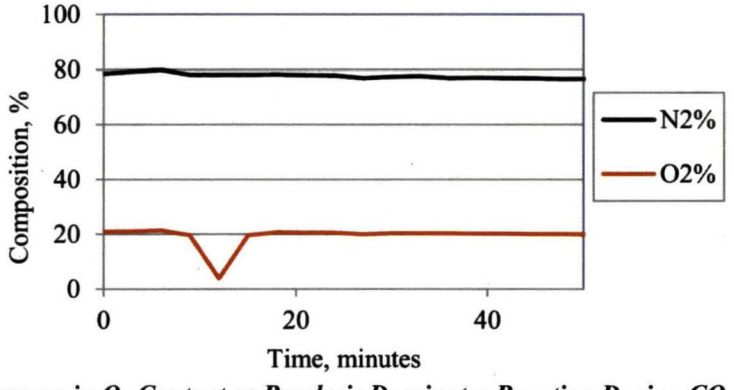

Figure 5. ***Decrease in O_2 Content as Pyrolysis Dominates Reaction During CO_2 Production***

Each of the components making up the MFWS was tested as separate components to understand how the simulants behaved during thermal degradation before being combined into the HFWS. Figure 6 displays the production of CO, CO_2 and CH_4 from several waste simulants of MFWS including cotton washcloths, FPS, MFU and MAGs.

The waste simulants produced over 6 grams of CO_2 during the 10 to 15 minute production peak. The CO_2 production from FPS with an air and nitrogen mixture is fairly low compared to the FPS with air. This is most likely due to the reduced oxygen content as nitrogen is introduced, favoring pyrolysis. The polymers may not have had enough oxygen to interact with, producing lower amounts of CO_2, and more heavy tars. MFU simulant produced significantly less CO_2 compared to the other MFWS which was due to the reduced amount of dry mass available for conversion. Only alkenes, alkanes and ketones were present in the byproducts for the MFU simulant as well. The longer chain byproducts were not as predominant in the MFU since PE, PET and Nylon were not present. MAGs contain some polymeric compounds like PE and polypropylene but mainly consist of pulp as fluff, which are typically small fibrous pieces of wood.[5] Cotton washcloth is mainly composed of cellulose with the formula $(C_6H_{10}O_5)_n$, which, in the right thermal conditions produced similar amounts of CO_2 and CO in comparison to the FPS.

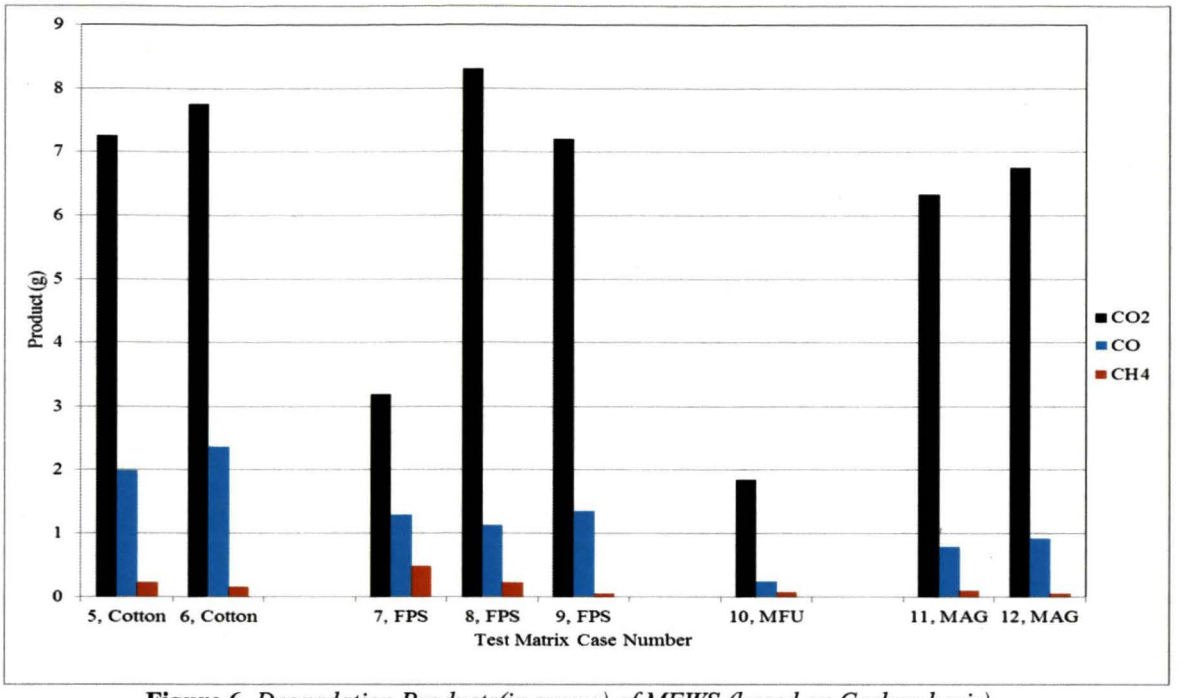

Figure 6. *Degradation Products(in grams) of MFWS (based on Carbon basis)*

HFWS results are displayed in Figure 7. When food and fecal matter were introduced into the HFWS system, lower averages of CO_2 were produced. HFWS had a CO_2 production range of 4.4 to 5.5 grams during the approximate 15 minutes of mean residence time in the reactor, while the MFWS had a range of 6.2 to 8.3 grams of CO_2 with air fed systems. This was most likely a result of the high water content within the food, fecal and urine, decreasing the overall average dry mass to be converted into the desired product rather than condensed out of the system.

C. Variable Gas Feed Experimentation

Air at 5 slm, nitrogen (N_2) at 5 slm and a mixture of air and N_2 at 2.5 slm each were fed to the reactor to observe behavior differences in CO_2 production for different waste simulants. Pyrolysis dominated the system as pure nitrogen was fed to the reactor. Pyrolysis experiments were run with 5 slm of N_2 at a 10°C per minute ramp and held at 500°C with 10 grams of PE and repeated for 10 grams of MFWS. Both the PE and MFWS run with N_2 produced less CO_2, CO and CH_4 compared to air or mixed gas experimental runs. Pyrolysis conditions caused many experimental issues including clogging and unreacted products and were eliminated early on in the testing phase.

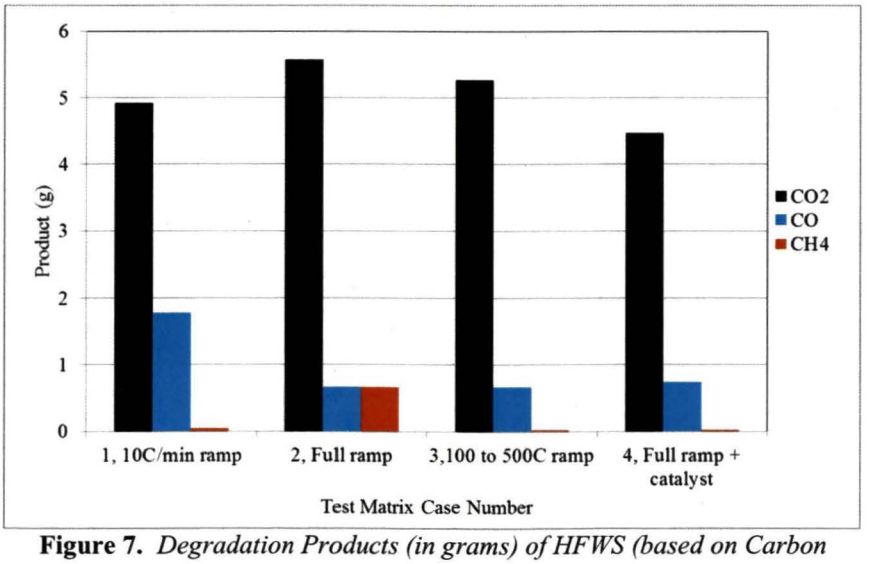

Figure 7. *Degradation Products (in grams) of HFWS (based on Carbon*

For cotton and MAG simulants, the amounts of CO_2 and CO were similar in air fed and air/nitrogen systems. The FPS produces twice as much CO_2 in air than in the air/nitrogen fed mixture. Since there was no advantage to using the air and nitrogen mixture, pure air feeds were the focus for HFWS.

D. Catalyst Experimentation

A dolomitic limestone catalyst, dolomag, was produced in a quarry from National Lime and Stone Company and shipped to KSC via Pioneer Astronautics. The dolomag was introduced into the HFWS to see if byproducts and tar production would be reduced and production of CO_2 increased. Dolomag is mainly comprised of calcium carbonate. It was pre-loaded into the top of the reactor heated zone on top of the waste simulant. The dolomag catalyst did not support the same level of CO_2 production compared to other HFWS testing as displayed in Figure 7. The dolomag did eliminate 2-propenal and allene byproducts from those listed in Table 5 of the GC/MS detection. The catalyst also collected black tar as displayed in Figure 8.

E. Variable Heat Rate Experimentation

Varying temperature heat cycles were studied to see if it affected the production of CO_2. Three different heat cycles were chosen for the HFWS:

1. 10°C per minute ramp to 500°C
2. Full ramp, approximately 100°C/min to 500°C
3. Partial ramp: 10°C per minute ramp to 100°C, hold for 30 minutes, 10°C per minute ramp to 500°C

The production of CO_2, CO and CH_4 are displayed in Figure 7 at the varying heat cycles. The highest production of CO_2 occurred during a full ramp rate. Based on these results, future tests will heat the waste at maximum rate to the desired operating temperature. This is important for future implementation into a space system since the lowest possible power requirements are necessary as resources of power supply are limited in deep space travel. The maximum ramp cycle was the optimal selection when considering minimization of the power requirements for this test while retaining the efficiency of CO_2 production.

F. Production Rates

The total production rates were calculated from the reactor data of the HFWS at the conditions of Label 2 in the Test Matrix. These production rates are based off of a 15 minute mean reaction time producing 0.3667 grams per minute of CO_2, displayed in Table 5. This corresponds to processing approximately 1 kilogram of waste per day, or roughly 20 percent of the waste that is produced by a four person crew in one year. The production rates in the table are extended to show if the reactor ran continuously during periods of maximum CO_2 production. These production rates were scaled up to processing 200 grams of trash to predict rates for the second generation TtSG reactor that is ten times large in volume. The current reactor is 0.28L and can hold up to 20 grams of trash, producing approximately 192 kilograms per year of CO_2 on a continuously run system. The CO_2 from this reactor fed to a downstream Sabatier reactor would theoretically produce 70.13 kilograms per year of the desired product, CH_4. When the system is scaled up, it should be able to process all waste and produce between 800 and 1,500 kg of CH_4 per year, depending on the quantity of waste generated.

According to NASA's Exploration Systems Architecture Study estimates, approximately 4,000 kg per year of O_2/CH_4 (mixture ratio of 3.6:1 by mass) propellant is needed for an ascent stage of a Lunar Exploration Mission. [6] This requires approximately 870 kilograms of CH_4. Therefore, once the trash is converted to CO_2 and fed to a downstream Sabatier reactor for CH_4 production, scaled up production of this system should produce enough CH_4 to fuel a lunar ascent vehicle.

PRODUCTS	AIR FEED (SLM)	THERMAL DEGRADATION REACTOR (~10g trash)	LARGE SCALE REACTOR ESTIMATES (~200g trash)
		kg/yr	kg/yr
CO_2	5	192.74	3,854.75
CO	5	23.39	467.78
THEORETICAL CH_4	5	70.13	1,402.60

Table 5. *Production Rates of First Generation TtSG Reactor*

V. Conclusion

There are many benefits from a trash processing system for deep space travel or habitats on other planets. Such a system reduces waste volume, and generates energy and life support commodities for deep space exploration systems and architectures. The TtSG system has many approaches for commodity production including integrated applications of ISRU for lunar or Mars missions, alternative energy systems (i.e. fuel cells), fuel for propulsion systems, CO_2 for plant life support, ash production for activated carbon systems and water and oxygen for human life support. If certain commodities are produced during a space mission, this reduces the total logistical up mass that is needed to be sent from earth. This first generation TtSG reactor has successfully characterized reactor conditions for processing various waste simulants. The optimal HFWS reactor parameter was a full temperature ramp rate to 500°C. These conditions could produce approximately 192 kilograms per year of CO_2, if operating continuously, while reducing the trash mass by 20%. Estimates of the Sabatier reactor to convert CO_2 into CH_4 yield a theoretical CH_4 production rate of 70 kilograms per year. Scaling up by a factor of five from the current waste processing rate of 1 kg/day, would process all waste generated by a crew of four and generate between 800 and 1,500 kg of CH_4 per year, depending on the quantity and composition of the waste. This is enough to fuel a lunar ascent stage vehicle, assuming the oxygen is generated by another ISRU process.

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