Trash to Gas (TtG) Simulant Analysis

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Space exploration in outer earth's orbit is a long-term commitment, where the reuse of discarded materials is a critical component for its success. The Logistics Reduction and Repurposing (LRR) project under the NASA Advanced Exploration System Program is a project focused on technologies that reduce the amount of consumables that are needed to be sent into space, repurpose items sent to space, or convert wastes to commodities. In particular, Trash to Gas (TtG), part of the LRR project, is a novel space technology capable of converting raw elements from combustible waste including food waste and packaging, paper, wipes and towels, nitrile gloves, fecal matter, urine brine, maximum absorbency garments, and other organic wastes from human space exploration into useful gases. Trash to gas will ultimately reduce mission cost by producing a portion of important consumables in situ. This paper will discuss results of waste processing by steam reforming. Steam reforming is a thermochemical process developed as part of TtG, where waste is heated in the presence of oxygen and steam to produce carbon dioxide, carbon monoxide, hydrogen, methane and water. The aim of this experiment is to investigate the processing of different waste simulants and their gaseous products. This will lay a foundation for understating and optimizing the production of useful gases for propulsion and recovery of water for life support.

Nomenclature

TtG = Trash to gas
LRR = Logistics Reduction and Repurposing
CH4 = Methane
CO = Carbon monoxide
CO2 = Carbon dioxide
GC/MS = Gas chromatography-mass spectrometer
H2 = Hydrogen
HFWS = High fidelity waste simulant
ISS = International Space Station
NASA = National Aeronautics and Space Administration

I. Introduction

The steam methane reformer is widely used in industry to make hydrogen. In previous years, the United States has had a production capacity of approximately 11 million tonnes of hydrogen. 95% of the generated hydrogen was being utilized predominantly for petroleum refining and the production of industrial commodities such as ammonia[1]. Conventionally, hydrogen production is performed in multi-tubular-fixed-bed reactors in the presence of a metal catalyst[1]. Steam and hydrocarbons enter the reactor as feedstock; generating hydrogen and carbon dioxide as the final product. Hydrogen production is governed by the following reactions:

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$$CH_4 + H_2O \longleftrightarrow CO + 3H_2 \quad \Delta H_{295} = 206\frac{kJ}{Mol} \tag{1}$$

$$CO + H_2O \longleftrightarrow CO_2 + H_2 \quad \Delta H_{298} = -41\frac{kJ}{Mol} \tag{2}$$

$$CH_4 + 2H_2O \longleftrightarrow CO_2 + 4H_2 \quad \Delta H_{298} = 165\frac{kJ}{Mol} \tag{3}$$

The steam forming step, reaction 1, where methane reacts with water to produce carbon monoxide and hydrogen, is an endothermic process. This step requires energy to occur[2]. The second step is the water-gas shift reaction where syngas reacts to recover hydrogen. Here the water-shift reaction is exothermic, which results in a temperature increase across the reactors as water reacts with CO to form CO_2 and more H_2. Through similar reactions, organic material of any composition can be reformed into a gas mixture predominantly composed of CO_2 and H_2 by reacting with high temperature steam. This high temperature conversion makes Trash-to-Gas a favorable technology for the recycling of organic wastes during human space exploration missions.

Assuming daily operations (16 hours on:8 hours off), a crew of four produces roughly 2500 kg of waste trash, metabolic waste, and life support system consumables[3,4]. A TtG system that utilizes these wastes will serve two purposes: maximal recovery of water from waste materials and the production of usable gasses. The main components of the Trash to Gas process consist of three primary steps; steam reforming, methanation, and electrolysis. In Fig 1. illustrates a block flow diagram of the complete TtG process. At high temperatures, oxygenated steam in the steam reformer reacts with organic matter to produce a gas mixture largely composed of hydrogen, carbon monoxide, and carbon dioxide. After condensing and removing excess water, the reformer exhaust gases are fed to a catalytic Sabatier reactor where they are combined with supplemental hydrogen to produce methane. Electrolysis of water obtained from the reformer and Sabatier reactors provides the supplemental hydrogen for needed for methanation while simultaneously producing oxygen used during steam reforming.

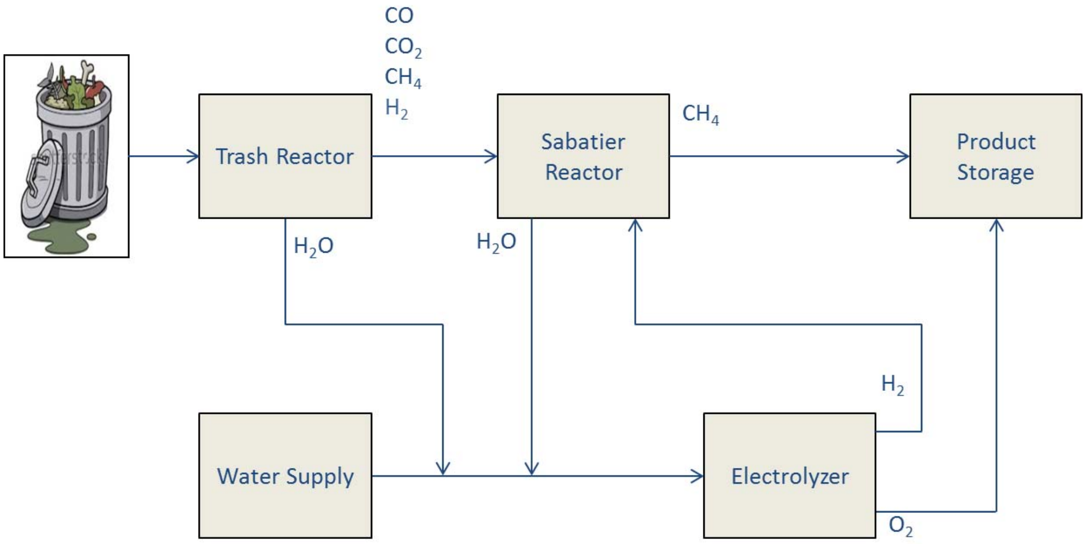


Figure 1. *Block flow diagram of TtG process.*

II. Material/Methods

A. Reactor Specifications

The experimental system consisted of a steam reformer reactor, gas filtration components, condenser and analytical instrumentation to determine the composition of the outlet gas stream in real time. A schematic of the trash being loaded from the top of the reactor is shown in Figure 2. The reactor consisted of a stainless steel pipe, 3 inches in diameter and 37 inches in length. The oxygen flow to produce the oxygenated steam was varied with each test. The reactor had two heaters, where thermocouples were inserted into the reactor through the top and bottom flanges to allow for monitoring and control of the temperature of the trash and the gas as it flowed down the reactor. Preliminary studies have shown that maintaining a reactor temperature of 600 ˚C will maximize carbon oxide production and reduce reaction time[5]. At the different O_2 flow rates there was no statistical difference of hydrogen and carbon production.. There was only a statistical difference found in reaction times, where it was determined that increasing the oxygen flow to 4lpm would speed up the reaction. Upon exiting the reactor, the gas passed through a condenser and particle filter. The amount of water collected by the condenser was measured after each run. The remaining portions of the outlet stream were directed to a Gas Chromatograph (GC) for quantitative determinations of hydrogen, carbon dioxide, carbon monoxide and methane.

A. Waste Characterization

Major wastes sources accumulated during space missions consist of food packaging, food residues, human wastes, hygiene items and clothing[2]. Included in the waste material are small amounts of inorganic matter such as aluminum and plastics fillers from food packages. The waste stream is complex and contains many components including polymers and natural fibers such as cotton and salts. Because of the complex waste stream, a high fidelity waste simulant (HFWS) was created and used in this testing. Table 1 shows a representative example of the waste compositions used for this experiment. Except for the inorganic contaminants, the steam reformer converts all of the items listed in Table 1 into hydrogen, methane, oxygen and carbon oxide products. The gaseous contaminants are removed from the reformer exhaust, and inorganic solid contaminants are recovered as ash exhibiting substantially reduced volume compared to the initial waste.

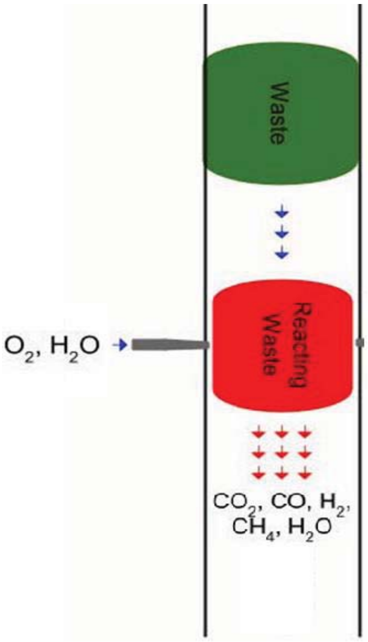


Figure 2. *Schematic of steam reforming reactor [5].*

Table 1. *List of waste type and composition used.*

Waste Type	Title	Composition Vol%
1	Cardboard	50% cardboard, 40% food packaging box, 10% used paper
2	Food/Plant Mix	50% coffee, 5% coffee filter, 20% tea bags, 25% plant
3	High Fidelity Waste	16.2% Polyethylene sheet (150 µm thick), 4.6% Nylon sheet (113 µm thick), 2.3% Aluminum foil (12 µm thick), 21.3%Urine brine, 12.6% T-shirts, 11.2% Fecal Simulant, 8.9% Food, 5.5% Hand/Face Wipes, 4.9% Tissues (Tech wipes), 4.8% Towels 2.4% Shampoo, 1.2% Toothpaste, 2.1% Nitrile gloves, 0.6%Paper, 0.5% MAGs, 0.4% Disinfecting wipes, 0.40% Duct Tape

Wastes on the ISS are currently wrapped in plastic and sealed by tape to make “footballs” for disposal. Thus, similar packaging was used for TtG experiments. The footballs where assembled by placing the waste simulant in a 1 gallon plastic bag then rolling them into a cylindrical shape, followed by duct tape to hold it in place. As shown in Fig. 3, the original dimensions were eight inches in length and two in a half inches in diameter. The first attempt at processing a football made from cardboard, failed due to reactor geometry. Figure 3 shows the densely packed cardboard football and Fig 4. shows the remaining waste pulled from the reactor after the experiment. For these runs there was a large amount of residue left behind; approximately 50% of its original mass. The football got stuck on the oxygenated steam inlet tube, and would not drop into the hot part of the reactor.

Figure 3. *Assembled densely packed cardboard footballs.*

Figure 4. *The densely packed football was unable to be completely broken down.*

To avoid an incomplete run, the footballs were then designed with a hollow center to insure that the entire sample would reach the hot zone. The images in Fig 5. show the assembly of the improved footballs with a 1 inch inner diameter and a 2.5 in outer diameter. The handle end of the screw driver was used as the filler to obtain the 1 inch inner diameter. The hole in the center of the football allowed it to drop around the steam inlet tube and into the hot part of the reactor. Tests using this football design was able to go all the way through, leaving only a trace amount of ash.

Figure 5. *Cardboard football with one inch inner diameter.*

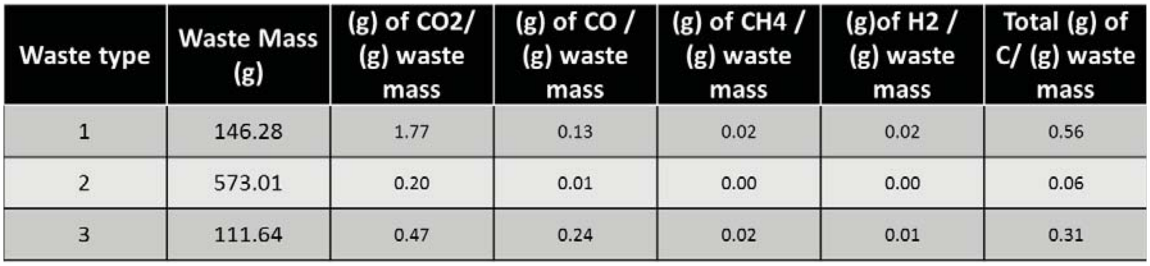
For the Food Simulant a mixture of plant soil, coffee ground, coffee filter, and tea bags were used. Water and ash content of the food simulant was found to be 81.2% and 3.6%, respectively. In making the food simulant footballs the coffee ground, coffee filter, and tea bags were placed in the plastic bag followed by the plant soil. The order of the west being placed in the bags was a personal preference based on the level of difficulty with handling each sample. The coffee ground, coffee filter, and tea bags were all stored in the same container. When gathering the west it would sometimes leave residue around the plastic bag and on my gloves. Once all the waste was in the bags it was then closed and agitated until it appeared to be a homogeneous mixture. In the next step the waste was pressed down with my hand to form a box shape (8 inch width, 12 inch length). The screw driver was then placed on top of the bag, followed by rolling and duct tape to hold it in place. The final detentions were: 8 inches in length and 1 inch inner diameter and a 2.5 in outer diameter.

The high fidelity waste simulant (HFWS) is a mixture of materials based on the LRR waste model[1]. It is intended to include all potential wastes including food packaging, food, human feces, clothing, paper, hygiene supplies and miscellaneous waste. The composition of the waste simulant provide in Table 1. were cut into squares about 1 inch. The food was prepared by mixing all ingredients in a blender, and blending until homogenous[3].

III. Results

The Gaseous products where investigated with each simulant. The amount of carbon oxides, methane, and hydrogen collected with each waste type is shown in Table 2. The ratio of carbon dioxide to carbon monoxide varied with each simulant, ranging from 13:1 to 2:1 with waste type 2 and 1 respectively. Using type 2 waste simulant caused the reformer to take almost twice as long (30 min) as the other waste types to reach its desired temperature of 400°C. When finally reaching 400°C it was then determined that more heat would need to be applied in order for the reaction to begin. Therfore, the heater temperature was increased to 500°C. When introducing the oxygenated steam at 500°C the temperature started increasing, indicating that the reaction was taking place. It is assumed that the high moister content within the food simulant was the cause. The highest average methane production was measured with waste type 1(Table 1.). The type 1 simulant was able to produce 3.53 grams of methane per gram of simulant. A measurement of over twice as much total carbon than waste type 3 was recorded with the type 1 simulant (Fig 6.). The data from Table 1. suggest that the steam reforming step within the trash to gas process will not produce a significant amount of methane compared to the amount of carbon monoxide and dioxide produced. As a result, the large amount of carbon oxides will have to be converted into methane within the Sabatier reactor. The steam reformer also suffered from tar and unwanted hydrocarbon production after each test. Thus the reduction of or combustion of tars production will need to be further investigated in order to optimize the process.

Table 1. *The amount of gaseous product produced with each simulant.*



Waste type	Waste Mass (g)	(g) of CO2/ (g) waste mass	(g) of CO / (g) waste mass	(g) of CH4 / (g) waste mass	(g)of H2 / (g) waste mass	Total (g) of C/ (g) waste mass
1	146.28	1.77	0.13	0.02	0.02	0.56
2	573.01	0.20	0.01	0.00	0.00	0.06
3	111.64	0.47	0.24	0.02	0.01	0.31

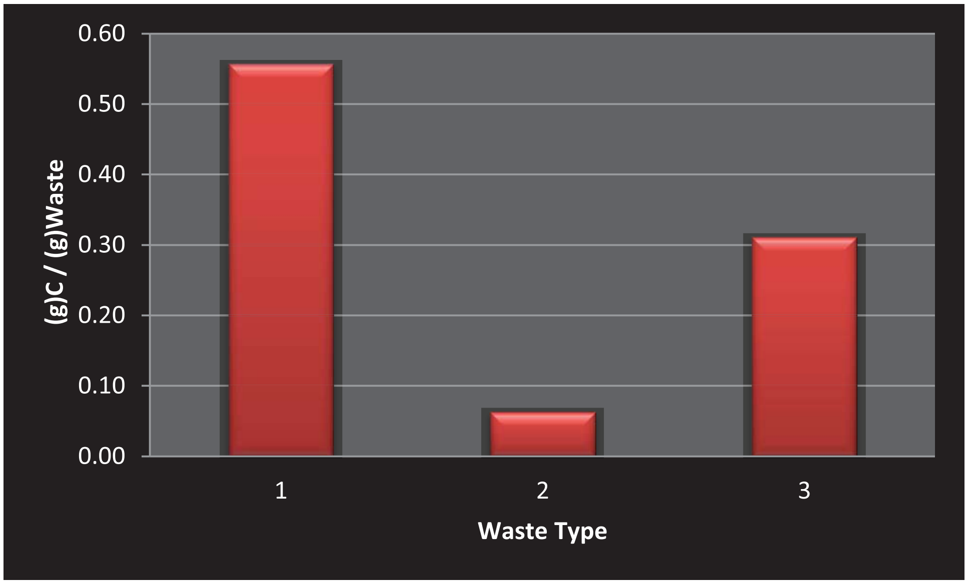


Figure 6. *The amount carbon produced per waste mass with each waste type.*

IV. Conclusion

The different waste compositions investigated in this study allowed us to look deeper into how the waste is packed into the reactor and the amount of hydrogen, methane, and carbon oxides produced with each simulant. Optimization of the by-products produced with from the waste simulant is still under investigation. The process so far has a low methane production, which is important for methane propulsion. The experiments did however prove to reduce the volume of waste. Future work on TtG technologies will focus on minimization of unwanted by-products and the effects of the system in zero gravity. This will lead to further understanding the process and optimization in different operation conditions. Also results from the food simulant suggest that using the waste heat from the reformer exhaust gas to dry the feed as a pretreatment will reduce the amount of energy required to heat the reactor.

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