Trash to Gas: Converting Space Trash into Useful Products

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NASA's recent re-focus on exploration beyond Low Earth Orbit includes a need to shift to developing *in-situ* resource utilization (ISRU) technologies. These technologies aid in self-sufficiency when exploring distances beyond Low Earth Orbit and will reduce the mass requirements during a launch. One such ISRU development is the Trash-to-Gas (TtG) project. The goal of TtG is to convert waste generated by humans in spaceflight to valuable products, such as water and oxygen for life support and gases for rocket fuels. Simulated trash samples, which account for the ratio of waste types during a typical mission, were processed in a thermal degradation reactor. The primary output of this reactor is water and a gas with high carbon dioxide concentration. This carbon dioxide output can be converted into methane through a Sabatier reaction. This methane can be used as rocket propellant on a liquid oxygen/liquid methane vehicle. The reactor's thermal degradation process was performed under varying temperature and gas flow conditions to determine the optimal conditions to maximize carbon dioxide output for a standard amount of trash simulant while minimizing tar production. In addition, reactor scalability testing was performed by varying simulant amount.

Nomenclature

AES	=	Advanced Exploration Systems
CH_4	=	Methane
CO	=	Carbon monoxide
CO_2	=	Carbon dioxide
FTIR	=	Fourier transform infrared spectrometer
GAC	=	Granular Activated Carbon
GC/MS	=	Gas chromatography-mass spectrometer
HFWS	=	High Fidelity Waste Simulant
ISRU	=	in-situ resource utilization
KSC	=	Kennedy Space Center
LEO	=	Low Earth Orbit
LRR	=	Logistics Reduction and Repurposing
NASA	=	National Aeronautics and Space Administration
Slm	=	standard liters per minute
TtG	=	Trash-to-Gas

I. Introduction

In recent years with the end of the space shuttle program, NASA has begun to shift Low Earth Orbit (LEO) operations to commercial companies and focus once again on exploration past Earth's orbit. For this to be feasible, the agency must develop *in-situ* resource utilization (ISRU) technologies – essentially, a way to "live off the land". One such ISRU technology being developed by the Kennedy Space Center (KSC) is the Trash-to-Gas (TtG) project, part of the Logistics Reduction and Repurposing (LRR) project of the Advanced Exploration Systems (AES) program. The Trash-to-Gas project aims to ameliorate both the high cost of launch and the waste management issues of any human habitat in space with one technology. Nearly all of the current materials necessary for spaceflight are brought from earth and carried on a spacecraft at launch. This makes a launch almost

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prohibitively expensive, as the price is driven up by the mass required to lift into space. In addition, any trash generated by the astronauts is stored in the spacecraft or habitat, taking up a considerable amount of the craft's limited volume before being thrown out to burn up in the atmosphere during re-entry. Through the Trash-to-Gas system, this waste could be repurposed to aid in spaceflight. On Earth, waste-to-energy technologies are already in use in various stages of development in the USA and throughout the world. In the United States, combustion facilities process close to 12% of the nation's total municipal solid waste for energy recovery[1]. KSC is investing the use of an incineration reactor to thermally degrade trash samples. The products of this initial combustion reaction are intended to be water and a flue gas primarily consisting of carbon dioxide. The water can be condensed and electrolyzed, and the resulting hydrogen and the separated carbon dioxide will be converted into methane in a Sabatier reactor according to Equation 1.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{1}$$

The remaining oxygen from electrolysis can be fed back into the incineration reactor to continue the degradation process. Methane has many uses, but a major application here is as a rocket propellant. It is estimated that a crew of four running this process for a year on a lunar base would create enough fuel for a lunar ascent vehicle[2].The most recent aim of the project was to determine the ideal operating conditions of a laboratory scale reactor, focusing on the reactor temperature and the amount of airflow that needs to be supplied to process 100g amounts of waste simulant. Once those conditions were determined, the reactor was run with 50g and 200g amounts of simulant to establish the process' scalability.

II. Experimental System

A. Waste Simulant

A standardized waste model was necessary for the study of various waste processing technologies across multiple NASA centers. A High Fidelity Waste Simulant (HFWS) was developed and used for this project. The HFWS is a mixture of packaging materials, food, human waste, clothing, and other materials. It was formulated from a waste model developed based on waste characterization records from previous ISS and Space Shuttle missions[3]. The records indicated that the bulk of the waste generated was from food packaging – composed primarily of polyethylene, nylon, and aluminum. Clothing, Maximum Absorbency Garments (MAGS), other hygiene items, human waste, and disposable crew supplies were also found in the waste. The food, urine brine, and fecal simulant were made separately using the same waste model. The exact simulant composition is given in Table 1. The solid components were cut into 1-inch squares and the food simulant was processed in a blender before being mixed with the remaining components. Each HFWS sample was placed into the reactor in a mixed state in order to perform the study under realistic space waste processing conditions.

Table 2 – Food, Urine, and Fecal Simulant Composition

Category	Mass %
Polyethylene sheet (150 µm thick)	16.2%
Nylon sheet (113 µm thick)	4.6%
Aluminum foil (12 µm thick)	2.3%
Urine brine	21.3%
T-shirts	12.6%
Fecal Simulant	11.2%
Food	8.9%
Hand/Face Wipes	5.5%
Tissues (Tech wipes)	4.9%
Washcloth	4.8%
Shampoo	2.4%
Toothpaste	1.2%
Nitrile gloves	2.1%
Paper	0.6%
MAGs	0.5%
Disinfecting wipes	0.4%

Duct Tape	0.4%

Table 1 - Waste Simulant Composition

Food	Mass %
Juice	41%
Dried apricot	11%
Tortilla	21%
hot dog	27%
Urine Brine	**g/L**
urea	70
NaCl	11.5
KCl	12
$CaSO_4$	1.3
$NaNO_3$	7
NaH_2PO_4	5
K_2SO_4	30
Fecal Simulant	**Mass %**
yeast	16.5%
cellulose	5.5%
PEG	2.7%
Peanut Oil	11.0%
Miso	16.5%
KCl	2.2%
$CaCl_2$	0.5%
water	45.1%

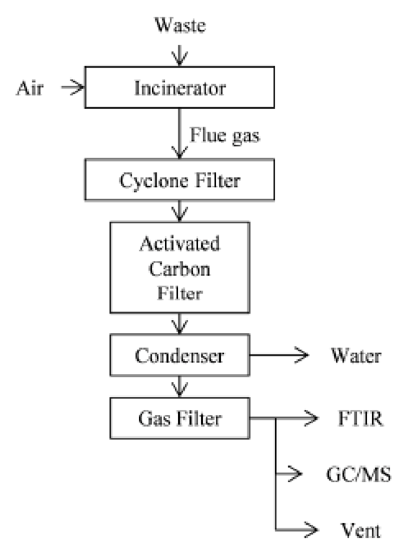
B. Reactor Setup and Test Matrix

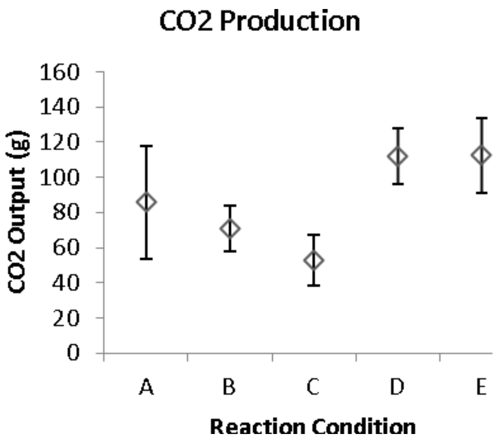
The primary component of the current experimental system is a large reactor, encased by two heaters. The reactor included two sieve plate platforms evenly spaced inside. Waste samples were loaded into the reactor to sit on the top plate. Product gas exited through an outlet at the bottom of the reactor to pass through a cyclone filter, a filter of granular activated carbon (GAC), a condenser for the water vapor component of the flue gas, and a final filter of glass wool. The gas was then directed to a Gas Chromatograph/Mass Spectrometer (GC/MS) and a Fourier Transform Infrared Spectrometer (FTIR) for analysis. The GC/MS provided qualitative analysis of the product gas, identifying each component, while the FTIR provided quantitative measurements of the primary components – carbon dioxide, carbon monoxide, and methane - in the gas. Thermocouples were also placed at various points of the reactor and filtration components to monitor and record temperatures for the duration of the reaction. The condensed water was collected in a reservoir for measurement and future analysis. Figure 1 shows a visual representation of this flow path.

Three factors were modified in a series of experiments to determine the ideal operating conditions, and scalability, for the incineration process. Table 2 describes the five reaction conditions that varied temperature and air flow rate for processing 100 grams of HFWS. The total air flow was split to flow through the top and the bottom of the trash in the reactor. Initial testing had demonstrated that restricting flow to the bottom of the reactor resulted in incomplete combustion of the trash and increased tar production, while restricting flow to the top would result in impractically long reaction times[4]. Conditions A and D specified a total flow of 5 L/min throughout the duration of the experiment, while conditions C and E specified a total flow of 10 L/min. In each condition, the flow was either left constant through each run or increased/decreased incrementally by 1 L/min. The temperature was increased from 500°C to 600°C in Conditions D and E for identical flow conditions. Once the ideal condition was selected in accordance with the results below, the reactor was run under those specific flow and temperature conditions with 50g and 200g of HFWS to verify the scalability of the reactor output.

Table 1 - Experimental Test Matrix

Condition	Temperature (°C)	Flow (SLM)
A	500	Top: 1 → 4
		Bottom: 4 → 1
B	500	Top: 4 → 1
		Bottom 4
C	500	Top: 5
		Bottom: 5
D	600	Top: 1 → 4
		Bottom: 4 → 1
E	600	Top: 5
		Bottom: 5





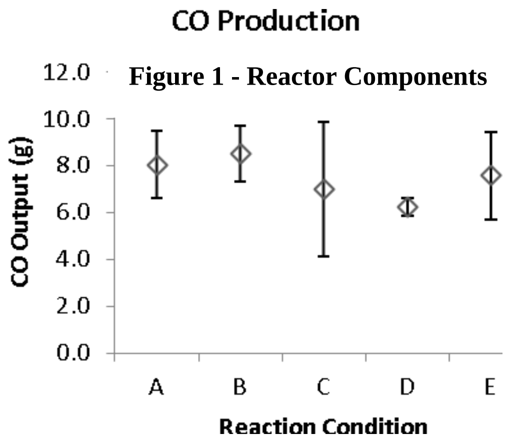


Figure 1 - Reactor Components

III. Results

A. Operational Condition Tests

The average carbon dioxide, carbon monoxide, and water outputs, as well as reaction times for each condition in the test matrix are shown in Figure 2. Carbon dioxide production was determined to be primarily temperature dependent, with little to no correlation evident between gas production and air flow. Conditions D and E, set to the higher temperature of 600°C, resulted in the greatest carbon dioxide production, and approached near 100% conversion of the total carbon content in the waste to carbon dioxide, carbon monoxide, and methane. The ratio between carbon dioxide and carbon monoxide production increased from about 10:1 to 15:1 with the temperature increase from 500°C to 600°C. Air flow had an effect on reaction time, with the lower reaction times corresponding to the conditions with 10 SLM of air flow – conditions C and E. Trace amounts of hydrocarbons, ammonia, and nitrous oxide were detected by the GCMS, and a considerable amount of tar had to be physically cleaned out of the reactor components following each run. Ash and unreacted aluminum were found in the reactor following each run. Overall, based on the balance of high carbon dioxide and water production along with the low reaction time, Condition E was selected as the best temperature and air flow operating combination.

B. Scalability Tests

A series of experiments to verify the scalability of the process were then conducted under the temperature and flow requirements for Condition E. Figure 3 shows the average carbon dioxide production, total volume of air flowed through the duration of the reaction, and reaction time. These three quantities, along with the ash content remaining in the reactor, linearly increased corresponding with the increase of simulant mass. Carbon dioxide and ash content were seen to double as simulant mass did, while the necessary volume of air and reaction time multiply by 1.7 with doubling simulant mass. The reactor's efficiency varied with simulant amount. As previously mentioned, the carbon content in 100g of waste was converted to carbon dioxide, carbon monoxide, or methane at 100%. This was not the case for the 50g or 200g simulant samples, which achieved 86.8% and 91.3% conversion respectively. The case is similar when looking solely at conversion to carbon dioxide, the desired product of the incineration reactor for this study, which varied between 75-90%. Operationally, the incineration reactor experienced numerous clogs and other interruptions when processing the 200g samples to a higher degree than when processing the smaller sample masses, but this likely indicates that the reactor was not sized for that high mass amount. Overall, even with the slight variations in conversion efficiency, the production and reaction time data demonstrate that reasonable estimates can be made for reactor performance when scaling to potential final conditions.

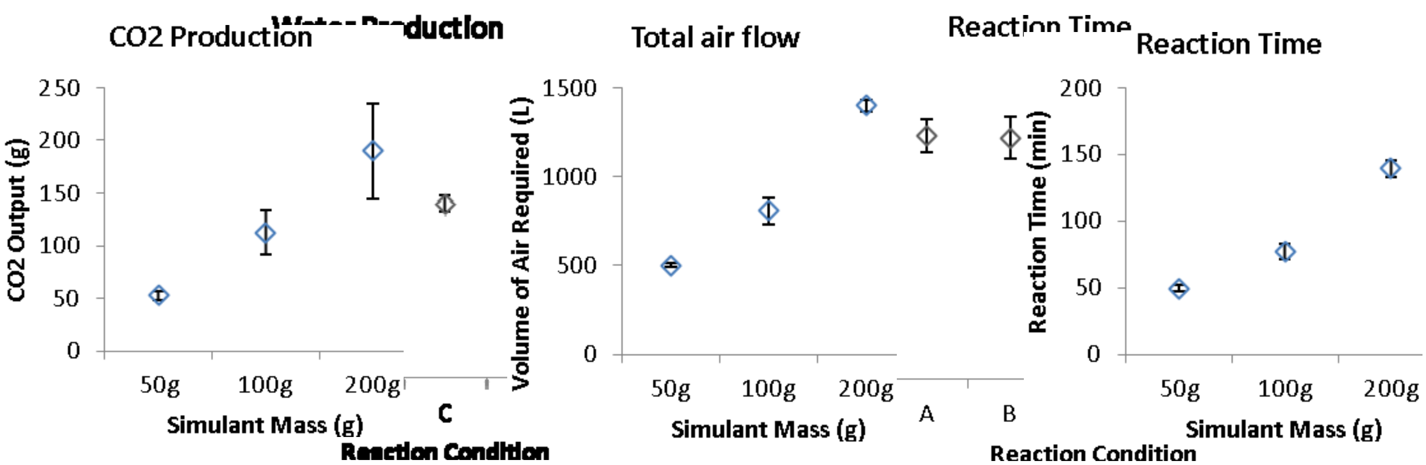


Figure 2 - Gas Production, Water Production, and Reaction Time for each test matrix condition

Figure 3 - Carbon dioxide production, required air volume, and reaction time for increasing simulant mass

IV. Discussion

Reliable data could not be obtained for the production of water with this experimental setup as the condenser was unable to maintain a subzero temperature throughout the run and some of the water vapor was seen to condense in the fluid lines away from the condenser and water reservoir in the 200g simulant mass experiments. A future version of the reactor system will need to include a condenser that can stay at low temperatures consistently. A loading mechanism for the waste and a design that would allow for practical levels of maintenance would be necessary for the final Trash-to-Gas system. For each trial in each experiment, regardless of reactor condition, tars accumulated in the condenser and filters at levels that would be unacceptable for a closed loop environmental life support system in space. The risk of polluting the limited environment of a spacecraft or habitat for humans is a limiting factor for this and similar space waste management technologies. Catalytic cracking of long-chain hydrocarbons is a possible method to mitigate the risk of environmental contamination and is currently being investigated at the Kennedy Space Center.

The average production rate of carbon dioxide was 1.46g CO_2/min when processing 100g of waste simulant. Given an estimated operational frequency of 16 hours per day for 350 days a year, the current reactor system would produce approximately 490kg CO_2/year. A Sabatier reactor could theoretically convert this to 178.4 kg of methane in a year. NASA's Exploration Systems Architecture Study estimates that the ascent state of a Lunar Exploration Mission requires around 4,000 kg per year of O_2/CH_4 propellant[5]. At a mixture ratio of 3.6:1 by mass, this means that the ascent state will require 870 kg of CH_4. Therefore, the current TtG system will need to be scaled by a factor of 4.8 to meet this requirement. Based on the LRR waste model for a four-person crew on a one-year mission that estimates the generation of approximately 2100kg of trash in a year[3], the scaled up system would be able to re-use more than 20% of that waste to provide a valuable and otherwise costly resource. Further scaling or a more time-efficient system could utilize a greater portion of that waste and provide even more gas or fuel resources. The LRR project includes the development of other technologies to utilize crew generated waste and the waste left unprocessed by this system could instead go to those technologies.

V. Conclusion

A waste management system that would reduce trash generated by space missions to produce fuel would be highly beneficial for the future of human space exploration. For the current generation of the Trash-to-Gas system, it was determined that a reactor temperature of 600°C with air flow of 10 slm split evenly to flow through the top and bottom of the reactor are the most ideal conditions to process waste in an incineration reactor. That this reactor process can be scaled up to account for increasing mass of waste to be processed was also verified. Future work for this project may involve scaling up the system to meet the needs of a potential lunar habitat crew, tar contamination control, and other human factors. At the current level of development, a scaled up system would provide enough methane for a lunar ascent vehicle and significantly reduce and reutilize the trash produced by a crew of four astronauts.

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