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INVESTIGATION OF BIO-REGENERATIVE LIFE SUPPORT AND TRASH-TO-GAS EXPERIMENT ON A 4 MONTH MARS SIMULATION MISSION

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Future crewed missions to other planets or deep space locations will require regenerative Life Support Systems (LSS) as well as recycling processes for mission waste. Constant resupply of many commodity materials will not be a sustainable option for deep space missions, nor will storing trash on board a vehicle or at a lunar or Martian outpost. The habitable volume will decline as the volume of waste increases. A complete regenerative environmentally controlled life support system (ECLSS) on an extra-terrestrial outpost will likely include physico-chemical and biological technologies, such as bioreactors and greenhouse modules. Physico-chemical LSS do not enable food production and bio-regenerative LSS are not stable enough to be used alone in space. Mission waste that cannot be recycled into the bio-regenerative ECLSS can include excess food, food packaging, clothing, tape, urine and fecal waste. This waste will be sent to a system for converting the trash into the high value products. Two crew members on a 120 day Mars analog simulation, in collaboration with Kennedy Space Center's (KSC) Trash to Gas (TtG) project investigated a semi-closed loop system that treated non-edible biomass and other logistical waste for volume reduction and conversion into useful commodities. The purpose of this study is to show how plant growth affects the amount of resources required by the habitat and how spent plant material can be recycled. Real-time data was sent to the reactor at KSC in Florida for replicating the analog mission waste for laboratory operation. This paper discusses the 120 day mission plant growth activity, logistical and plant waste management, power and water consumption effects of the plant and logistical waste, and potential energy conversion techniques using KSC's TtG reactor technology.

I. INTRODUCTION

As humans continue to research technologies for completing long duration human space travel beyond low earth orbit, it is clear that self-sustainability and closed loop life support methods are required for living and working in deep space or on a planetary habitat. A planetary mission to a destination such as Mars would require complex procedures, a significant communication delay and create seemingly independent operations from support personnel located back on Earth, especially during day-to-day mission operations. This day-to-day level of autonomy and essentially non-existent resupply is something that is not currently an issue on the International Space Station (ISS) or Low Earth Orbit (LEO) space missions. Supporting human life on a deep space mission will involve maintaining an environment that provides food, air revitalization, water reclamation, waste processing, environmental contamination and control during transit and on arrival of a planetary body. [1]

Closed-loop life-support-systems with minimal or no re-supply from earth have significant technological challenges. One way to gather effective data for technology advancement of such systems is to perform testing in analog environments where crew can live and operate under simulated long duration space flight or planetary habitat conditions. Analog research can save money for space technology advancement by performing realistic operational test on the ground, thus bringing technology to higher technology readiness level.

Two crew members on a 120 day Mars analog simulation, in collaboration with Kennedy Space Center (KSC), investigated a semi-closed loop system that combines plant growth, as part of bio-regenerative life support, with the physico-chemical Trash to Gas (TtG) project to recycle waste materials. This paper discusses the 120 day mission plant growth activity, logistical and plant waste management, power and water consumption effects of the plant and logistical waste, and potential waste conversion techniques using KSC's TtG technology.

Regenerative Life Support

Current mission to Mars scenarios require a mass of consumables (food, water, oxygen), which available heavy launchers would not be able to launch on one single vehicle. The average cost to send one kilogram into Low Earth Orbit is $10,000 [2], so resupplying consumables as it is currently done on the ISS with cargo vessels, would not be cost-effective for a mission to Mars. Water and oxygen could be recovered from Martian regolith using In-Situ Resource Utilization (ISRU) technologies [3] but that does not enable food generation. Food production can be achieved by growing plants in greenhouse modules. Seeds are low mass and can be stored for long periods of time and could be regenerated during longer missions. Coupled to bioregenerative life-support systems, controlled-environment greenhouse modules could enable recycling of water, revitalizing the atmosphere and provide food to the crew [4,5,6]. A current ground demonstration of such technology is the closed-loop bioregenerative life-support system MELiSSA (Micro-Ecological Life Support System Alternative) [7]. The pilot plant at the University of Barcelona is still in progress but the ultimate goal is to degrade organic wastes (feces, urea, and inedible parts of higher plants) into simple nutrients using microorganisms and feed these to higher plants, which use carbon dioxide and produce oxygen and food as well as regenerate water.

The benefits of fresh food in the human diet compared to shelf-stable foods and vitamin supplements are indisputable. It was also shown on many occasions during missions on MIR, or on the ISS that cultivating food acts as a stress relief and is thus beneficial for human morale on long-duration space missions [8]. The presence of plants in isolation or in extreme environments was also shown to benefit human psychological well-being [9].

Waste Reduction and Repurposing

Waste management for deep space missions is a serious concern. Accumulated waste on current LEO and ISS missions is stored in large jettison stowage bags and placed into a module for ultimate disposal either being returned to Earth or being burned up on re-entry into Earth's atmosphere. On long duration missions, waste takes up a lot of useful volume in a spacecraft. Evaluating data from historical Space Shuttle Missions and ISS expeditions, waste production has been determined and projected for long duration mission models. The major waste sources generated during a human space flight missions are food packaging and left over food, human waste, hygiene items and clothing. Food packaging, predominantly composed of polymers, is the largest contributor to the waste stream, on a dry mass basis.[10] NASA's Advanced Exploration System Project: Trash to Gas (TtG), has been investigating various technologies that reduce the total logistical mass through reduction, reuse and recycling of waste into useful commodities such as fuel, water and life-support system gases.[11], [12], [13] In 2013, the steam reforming technology was selected from six technologies being studied in the NASA program for further optimization and investigation.[14] TtG converts waste into methane via a two-step process. KSC assembled a steam reforming reactor and is focused on optimizing the reaction shown in Equation 1, for further conversion into methane (CH_4) and water via a Sabatier reactor, (Equation 2).

$$\text{Trash} + O_2 + H_2O \rightarrow CO_2 + CO + H_2 + \text{Ash} + \text{Tar} \qquad [1]$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad [2]$$

The waste data from crew logistical activity and plant growth chambers during the 120 day Mars analog Mission was sent to KSC. At KSC, scientists and engineers operated the steam reformer to demonstrate waste reduction and conversion of crew logistical and plant waste that could occur during the mission. This was the first time the reactor was utilized for processing non-edible biomass.[15]

Mars Analog Habitat

This work took place at the NASA funded Hawaii Space Exploration and Analog Simulation (HI-SEAS) Mission 2. HI-SEAS was a collaborative effort formulated from a NASA grant and led by researchers at the University of Hawaii. The HI-SEAS Mission 2 was primarily focused on a psychological study, simulating a Martian environment with a six-person international crew living in isolation. The isometric dome-shaped habitat is approximately 1,000 square feet, located on the slopes of the saddle region of the Mauna Loa volcano in Hawaii. This 120-day study will be followed by an eight-month and one-year mission, each with a new 6 person crew. The Hi-SEAS Mission 2 Crew members had the opportunity to bring independent research projects to investigate throughout the mission.

Fig. 1: HI-SEAS Mars Analog Habitat, located on the isolated slopes of Mauna Loa.

The habitat architecture features two floors of living space. The main floor consists of a toilet with a shower, kitchen, dining/meeting space, multipurpose space, laboratory, airlock, laundry, and a shipping container for workshop and storage space. The second floor houses a toilet and six crew sleeping quarters. The shipping container was connected to the habitat and mainly used for storage.

Electrical power was generated via an array of 36 photovoltaic solar panels located south of the habitat. The energy generated from these cells was stored on two Sony battery towers located in the shipping container of the habitat. The backup generator was located south of the solar panels, which consumed gasoline for fuel. This backup system was used to charge the Sony batteries during emergency situations when power supply was low, which was usually due to cloudy weather conditions.[16]

The crew received its water from two 500 gallon water storage tanks located outside of the habitat. These tanks were periodically replenished throughout the mission. Water was pumped from these tanks with a standard household Flowtec water pump and tank located in the shipping container. Greywater was sent to two 250 gallon tanks and one 500 gallon tank, located west of the habitat, that were periodically emptied throughout the mission. A small 150 gallon solar water heater was located in the shipping container to provide the crew with warm shower water.[16]

The crew used Sun-Mar waterless composting toilets which would theoretically convert solid waste into a fertilizing soil.[17] The liquid waste was evaporated and vented to the outside of the habitat.

II. MATERIALS AND METHODS

The following schematic in Figure 2 displays the overall flow diagram of the project work and data collection during HI-SEAS Mission 2 and how it was integrated into testing at KSC.

HI-SEAS Plant Set Up

Plants were grown in two different spaces in the HI-SEAS habitat: the living room using the Biomass Production System for education (BPSe) provided by ORBITEC (Figure 3) and the science laboratory using three different kind of lamps: white Light-Emitting Diode (LED) panels and red and blue UFO lamps provided by the Kennedy Space Center, and a multispectral lamp LX60 provided by Heliospectra (Figure 4). This last one only operated during months 3 and 4. Plants in the science laboratory were grown in plastic trays provided by the Kennedy Space Center and previously used in the Deep Space Habitat plant atrium [18].

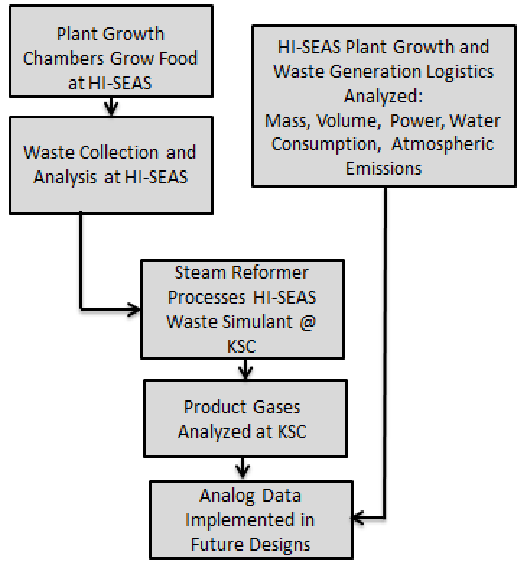

Fig. 2: Project Flow Diagram for HI-SEAS and KSC project integration.

Fig. 3: The ORBITEC BPSe with Microtina tomatoes and Rutgers California Supreme tomatoes.

Fig. 4: Lamp set-up in the sciences lab. Left to right: red and blue UFO LED lamp, KSC white panel, Heliospectra LX 60, and KSC white panel.

Plants grown in the BPSe varied from peas (*Pisum sativum* cv.'Earligreen') to green leaf lettuce (*Lactuca sativa* L. cv. 'Waldmann's Green' and 'Salanova') and red romaine lettuce (*Lactuca sativa* L. cv. 'Outredgeous'), radishes (*Raphanus sativus* cv. 'Pink

Beauty' and 'Rudolf'), and tomatoes *(Solanum lycopersicum* cv. 'Microtina' and 'Rutgers California Supreme'). Plants grown in the sciences laboratory included lettuces ('Waldmann's Green' and 'Outredgeous') and radishes ('Pink Beauty' and 'Rudolf'). The lettuce seeds of 'Waldmann's Green', 'Outredgeous' and the radish seeds of 'Pink Beauty', and 'Rudolf' came from Johnny's organic seeds. The seeds of 'Earligreen' peas and 'Microtina' tomatoes came from the University of Utah. The seeds of lettuce 'Salanova' came from Rijk Zwaan. The seeds of 'Rutgers California Supreme' are NASA seeds which were exposed to space in the Long Duration Exposure Facility (LDEF) satellite between April 6, 1984 and January 20, 1990.

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Plants in the science laboratory were grown in soil using 200 mL of organic coco chips (Roots Organics by Aurora Innovations, Soilless Hydroponic Coco Media) and 250 mL of pre-wetted potting soil (Roots Organics by Aurora Innovations, Original Potting Soil). The ingredients of the coco chips are: coco fiber, perlite, pumice, worm castings, bat guano, kelp meal, and greensand. The ingredients of the potting mix are: coco fiber, coarse peat moss, perlite, pumice, composted virgin forest material, worm castings, bat guano, kelp meal, fish bone meal, soybean meal, greensand, and alfalfa meal. Plants in the BPSe were grown in various combinations of soil: coco chips and potting mix, lava rocks from the surroundings of the habitat and potting mix, and lava rocks only. All the plants were germinated in plant starters "Rapid Rooters" from General Hydroponics (genhydro , CA, USA.

Name of the Element	Percentage in Solution (%)
Nitrogen (N)	4
Phosphorus pentoxide (P_2O_5)	3
Potassium oxide (K_2O)	3
Magnesium (Mg)	0.5
Sulfur (S)	1
Iron (Fe)	0.1
Molybdenum (Mo)	0.002

Table 1: Composition of the fertilizer solution BioThrive Plant Food from General Organics.

The fertilizer solution used was BioThrive Plant Food (NPK: 4-3-3) from General Organics (genhydro), CA, USA. The ingredients of the fertilizer solution are: alfalfa meal, ferric sulfate, kieserite, molasses, potassium sulfate, rock phosphate, seaweed extract, sodium borrate, sodium molybdate, soybean meal. Table 1 gives the exact composition of chemical elements in the solution.

The nutrient solution was made by diluting four teaspoons of the fertilizer into one gallon of water. Plants were watered every day using this nutrient solution.

Each tray in the science lab included two of each: Waldmann's green, Outredgeous, Pink Beauty and Rudolf and there were four trays.

Four experiments were conducted, one per month. The first two were intended to find optimal growth conditions for the above-named species with the following variable conditions: watering and light cycles, light intensities and growth time. The two last experiments had the same growth conditions in terms of light intensity and photoperiod, as well as growth time, so they are replicates of each other.

Harvests occurred once in the first and in the second month and twice in the third and fourth month. During harvests of months 1 and 2, all plants were picked, whereas during the first harvest of months 3 and 4 only radishes were picked because they were ripe before the lettuces. The lettuces grew 5 days longer than the radishes and between radish harvest and lettuce harvest, new radishes were grown during month 3.

Power consumption for lamps in the science lab as well as for the BPSe was measured using a Kill-A-Watt power meter from P3 International. Further information on the plant research performed at HI-SEAS Mission 2 and similar analog missions is reported elsewhere. [19],[20]

HI-SEAS Waste Storage and Collection Process

Mass of the crew member's logistical waste was monitored on a daily basis in the habitat. The waste was divided into several waste receptacles. All receptacles were located in the kitchen unless otherwise noted.

1. Food (coffee grinds, tea bags, leftover crumbs)
2. Hygiene – female (bathroom 1st floor receptacle)
3. Hygiene – male (bathroom 2nd floor receptacle)
4. Paper and cardboard products (majority from food packaging)
5. Tissue, hygiene wipes and cleaning wipes (majority from cleaning and EVAs)
6. Metal cans (majority from food packaging)
7. Metallic wrappers (majority from food packaging)
8. Plastics (majority from food packaging)
9. Non-edible plant biomass and soil – (laboratory receptacle)

Once waste receptacles were full, they were stored in two 50-gallon plastic bins located in the shipping container. Once these plastic bins were full, the trash was hand compressed into smaller "football" sized packages and placed back into the plastic bins. This compression process reduced the volume of the waste. These waste bins were then left in the HI-SEAS airlock and discreetly removed periodically throughout the mission by external "earthly" support. No other option for waste treatment was available at the HI-SEAS habitat. The composition, volume and mass data of the waste was sent to KSC where footballs were re-created and processed in KSC's TTG steam reforming reactor. Future technology developments, funding and collaboration will enable the possibility of supplying an on-site to the HI-SEAS habitat.

KSC Steam Reforming Reactor

The reactor used in this study was described previously[10] and the steam reforming process was selected based on a comparison of multiple technologies.[14] The KSC TtG steam reforming reactor operated at a temperature range between 600˚C and 700˚C. The reactor operated in a down draft configuration. Waste materials were wrapped tightly and compressed into "footballs" before being placed in the upper section of the reactor on top of a bed of alumina beads which acted as a support. The waste was heated to between 300˚C and 500˚C before oxygen and steam were fed into the reactor. The oxygen and steam were fed into the reactor directly below the waste. Once the oxygen and steam feed began, the reaction initiated and the temperature increased to the operating range, and the heaters were no longer needed. The product gases passed downwards through the alumina beads before exiting the bottom of the reactor. The gases were passed through a heat exchanger and condenser to collect water, before the final gas stream was sent to a Varian CP-4900 Gas Chromatograph (GC). The GC measured the amounts of carbon dioxide, carbon monoxide, methane and hydrogen produced.

Three types of waste were evaluated as separate experimental processes in the reactor: cardboard/paper, food/spent plant material and the High Fidelity Waste Simulant (HFWS)[10]. The wastes were similar to those identified during HI-SEAS Mission 2 waste generation results. The cardboard/paper waste consisted of corrugated cardboard, cardboard food packaging and paper. The plastic waste was a mixture of plastic food packaging and plastic utensils. The kitchen/spent plant waste consisted of coffee grounds and spent potting soil, including roots and inedible plant mass. Water content of the wastes was determined from the difference between the mass of the wet waste and the mass of the waste after being in an oven at 105˚C for a minimum of 3 days. Ash content was determined by comparing the mass of the dry waste to the mass after the dry waste was placed in a furnace at 575˚C for a minimum of eight hours.

A flow diagram of the steam reforming system is displayed in Figure 5 and a photo of the reactor system is displayed in Figure 6.

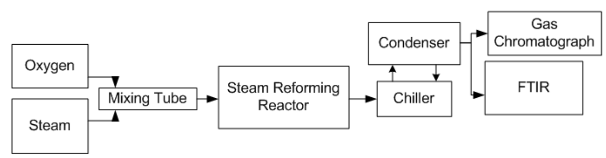

Fig. 5: KSC Steam-Reformer System Flow Diagram.

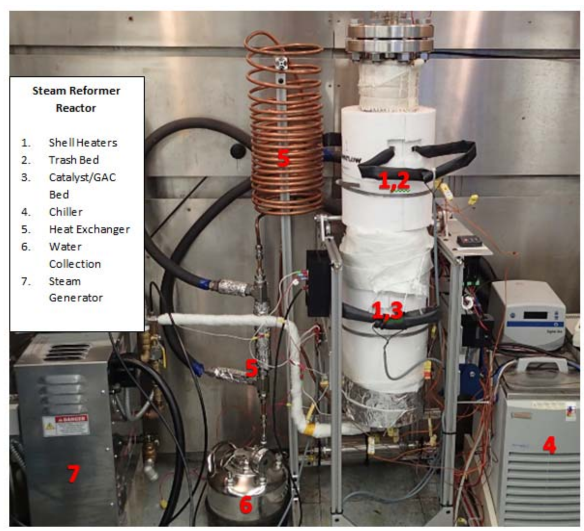

Fig. 6: KSC Steam Reforming Reactor System.

HI-SEAS FTIR Description

A portable Gasmet DX4040 Fourier transform infrared spectroscopy (FTIR) analyzer was used during the first 60 days of the mission to monitor the atmospheric concentration of gases in various locations in the habitat. Complete results of FTIR data collection from HI-SEAS mission is reported elsewhere [15]. It was used to investigate changes in the immediate atmospheric conditions due to plant growth chambers and waste storage located in the HI-SEAS habitat. Twenty three gases were monitored during a 5 minute sequence and were averaged for a final concentration value. Data was collected twice a week between 9 and 11 AM in the six habitat locations. Three of the locations, living room, laboratory (with plants), and the plant/food/metal/hygiene waste storage bin, will be discussed in this report.

III. RESULTS AND DISCUSSION

HI-SEAS Water Consumption

Plants were watered every day with the nutrient solution described in the Materials and Methods section. Each tray in the science lab received 250 mL of nutrient solution daily. If trays appeared to be drier than usual (since conditions are not controlled, they could vary a lot from one day to another), they would receive 500 mL. Plants in the ORBITEC BPSe were also watered daily but the volume of nutrient solution used daily was not as consistent as for the plants in the lab, since plants grown in the BPSe were mostly for recreational purpose. The overall water consumption of plants used 0.28 gallons on a daily basis. The average water consumption for crew logistical use was 32.38 gallons per day. This value fluctuated depending on habitat activities. Logistical water was used for tasks such as cooking, cleaning, drinking, extravehicular activity (EVA) suit cooling, bathing and laundry. The water usage between logistical activity and plant use is displayed in Figure 7. Overall, plant production utilized less than 1% of the average water consumption by the crew, while providing the crew with fresh lettuces, tomatoes, peas and radishes.

HI-SEAS Logistical and Plant Power Consumption

Table 2 displays the total logistical use and plant light kilowatt hours. Plant light power usage ranged from 7 to 10.1% power use in the habitat over the duration of the mission. In the first month, the lamps were all on a 14-hour photoperiod. Starting month 2, they switched to a 16-hour photoperiod, from 8:00 to 0:00. Power consumption of a given lamp was constant over one photoperiod. Lamps in the science lab had lower light intensities over the first month. The first week of each experiment also had lower intensities than the rest of the month, in order to accommodate lower light level needs of young seedlings. The UFO lamp cannot be dimmed

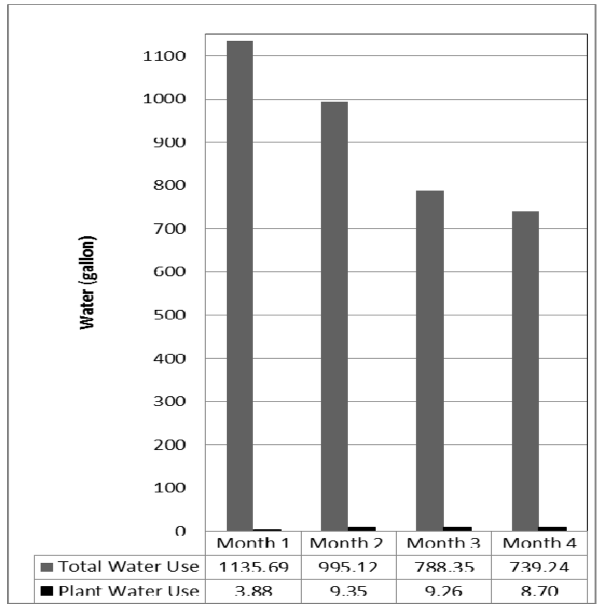

Fig. 7: Water use for total water consumption during logistical activities and plant activity of the 120 day Mars analog mission.

Month	Total Habitat kWh	Plant Light kWh	% Plant Light Use
1	1435	103.9	7.2
2	1482	103.5	7.0
3	1526	134.5	8.8
4	1333	134.5	10.1

Table 2: Water use for total water consumption during logistical activities and plant activity of the 120 day Mars analog mission.

so it operated at a constant light level over the course of the mission. To achieve different light levels, plant trays were moved vertically. This means it had the same power consumption over the four months.

The crew used power for many activities such as cooking (induction cookers, microwave and toaster oven), lighting (standard ceiling fixtures and lamps), exercise equipment (treadmill), waterless composting toilet heaters, cleaning equipment (vacuum), laundry (washer and dryer), small electronics (laptops, projector, EVA equipment etc.), battery charging stations, and so forth. Overall, the largest power consumers were appliances in the kitchen and laundry facility. When inclement weather limited the amount of solar power production, the backup generator was used to ensure lights were able to receive proper amount of light exposure.

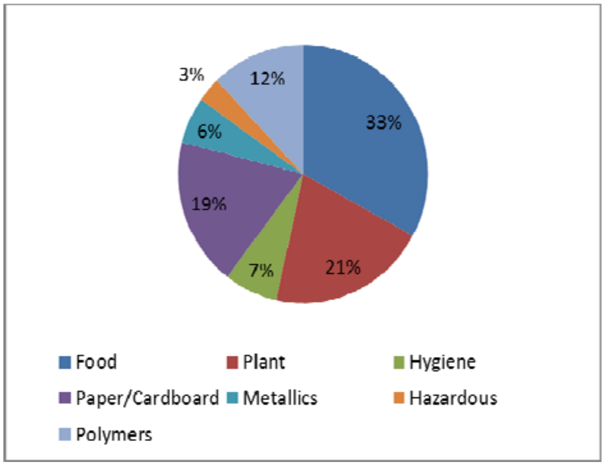

Fig. 8: Mass percentage of waste generated during HI-SEAS Mission 2.

Mass and Volume of Waste Generation at HI-SEAS

The waste accumulated during the HI-SEAS Mission 2 is displayed in terms of mass percent in Figure 8. The largest waste generated materials were food, paper/cardboard and plant waste at 33%, 21% and 19% respectively. The food waste consisted of approximately 80% water in waste coffee filters, coffee grounds, tea bags and left over food/oils from meals. The paper and cardboard content was mostly generated from the food packaging of the crew's dehydrated and shelf stable food products. There was also a large repository of waste cardboard boxes from storage containers that became waste throughout the mission and could not be reutilized. Plant waste consisted of inedible biomass and used soil that was discarded during harvesting sessions. Plant waste also contained residual moisture from water. Initially fecal waste was going to be measured by means of measuring the dry compost and filler material that was removed from the waterless composting toilets, but inconsistency in toilet performance did not enable this metric.

During the HI-SEAS Mission 2, a total of 152 kg of wet and dry waste (not including human, waste water or brine, which is a product of water recovery systems) was accounted for during this 120 day mission (of which only 115 days of waste data was collected).

The total volume of waste collected during the mission was 2.65m^3. After the waste was compressed into footballs, the final volume of waste was reduced to 1.51m^3. Compression of the waste created 43% reduction of waste volume.

During ISS and Space Shuttle Missions, the majority of waste consisted of leftover food and food packaging, and clothing. A model of a one year deep space mission and four person crew was created from the NASA Logistics Reduction and Repurposing (LRR) team based on actual waste data on the ISS and Space Shuttle missions and continues to be updated as more information becomes available.[21] This data presents a waste model with 2,559kg and 19.1m^3 of total logistical waste. These values include wet and dry waste as well as fecal waste and brine, medical and clothing waste.

	Water	Ash	Combustible
Cardboard	19%	7%	74%
Food/plant	81.2%	3.6%	15.2%
HFWS	40.3%	5.9%	53.8%

Table 3: Water, Ash, and Combustible mass percentages of wastes.

	CO_2, g/g	CO, g/g
Cardboard	2.47	0.4
Food/plant	1.85	0.21
HFWS	1.35	0.4

Table 4: Carbon dioxide and carbon monoxide produced from each waste type, relative to the combustible mass.

Reactor Results

Water, ash content, and combustible content of the wastes are shown in Table 3. The combustible content is the amount of mass lost during the ash content measurement.

All wastes were successfully processed in the reactor, demonstrating that plant waste could be converted to methane by the TtG process. Table 4 shows the amount of carbon dioxide and carbon monoxide produced from the three wastes, relative to the amount of combustible material in each waste type, calculated by dividing the amount of each gas produced by the combustible mass of the waste. This represents the amount of carbon recovered from each waste type, and therefore correlates to the amount of methane that could be produced. Cardboard produces the largest amount of carbon, while the HFWS and kitchen/plant waste produce similar amounts of carbon, although it is split differently between carbon dioxide and carbon monoxide.

FTIR Results

The concentration of volatile organic compounds (VOCs) from the HI-SEAS habitat living room, laboratory where plants were grown, and the waste storage bin holding the food/plant/metal/hygiene waste are displayed for selected VOCs in Figure 9. This data reflects the first 60 days of the mission.

Methane had the highest concentration for all three regions. Methane is a greenhouse gas and often emitted

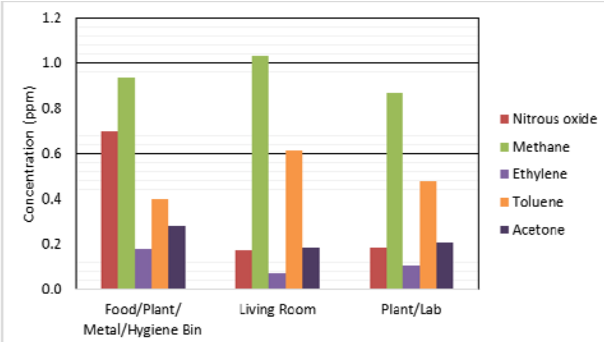

Fig. 9: Concentration of selected VOCs in three regions of the habitat during the first 60 days of the 120 day mars analog mission.

from many natural sources, including human activity. Methane had lower concentration in the plant laboratory which is expected since plants often remove this gas from the atmosphere. Methane is lowest in the plant laboratory and highest in the living room.

Nitrous oxide was relatively high in concentration for the waste storage bin region. This compound is often emitted by bacteria in soils.

Toluene was also of a higher relative concentration to other compounds. Since toluene is added to many polymers, this may have been constantly off-gassing throughout the mission. The laboratory where the plants were growing had the highest amount of carbon monoxide production

Methanol is naturally released from vegetation and microbes which may be why it was higher in the laboratory.

IV. CONCLUSION

Overall, it can be seen from this research that the addition of plants into an analog habitat has very little detrimental effect in terms of utility use such as power and water. Having fresh food available for a crew has been shown on this mission via positive verbal crew feedback and survey data, as well as other analog studies that consumption of plants is beneficial to crew moral and activity on a long duration mission. Plant waste was processed by the Trash to Gas process, demonstrating that it can be recycled. The waste biomass and logistical waste becomes useful as it is incorporated into a closed loop cycle for support of human activity on a long duration missions.

Much of this data and activity opens a portal for further advancement in creating a bio-regenerative closed loop life cycle system that supports human activity as well as recycles waste from missions. These activities well help sustain space travel. This work will be used for future designs into the trash to gas system so that even waste products from plants can be implemented to produce useful products.

V. ACKNOLEDGEMENTS

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