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# HUMAN FACTOR INVESTIGATION OF WASTE PROCESSING SYSTEM DURING THE HI-SEAS 4-MONTH MARS ANALOG MISSION IN SUPPORT OF NASA'S LOGISTIC REDUCTION AND REPURPOSING PROJECT: TRASH TO GAS

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NASA's Logistics Reduction and Repurposing (LRR) project is a collaborative effort in which NASA is tasked with reducing total logistical mass through reduction, reuse and recycling of various wastes and components of long duration space missions and habitats. Trash to Gas (TtG) is a sub task to LRR with efforts focused on development of a technology that converts wastes generated during long duration space missions into high-value products such as methane, water for life support, raw material production feedstocks, and other energy sources. The reuse of discarded materials is a critical component to reducing overall mission mass. The 120 day Hawaii Space Exploration and Analog Simulation provides a unique opportunity to answer questions regarding crew interface and system analysis for designing and developing future flight-like versions of a TtG system. This paper will discuss the human factors that would affect the design of a TtG or other waste processing systems. An overview of the habitat, utility usage, and waste storage and generation is given. Crew time spent preparing trash for TtG processing was recorded. Gas concentrations were measured near the waste storage locations and at other locations in the habitat. In parallel with the analog mission, experimental processing of waste materials in a TtG reactor was performed in order to evaluate performance with realistic waste materials.

## I. INTRODUCTION

Long duration deep space missions will require many closed loop, self-sufficient and highly sustainable technologies. These long duration and planetary missions will have infrequent, if any, resupply opportunities, and a communication delay from Earth. These conditions will create a seemingly independent operation 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), Low Earth Orbit (LEO) or lunar space missions. Supporting human life on a deep space mission will involve maintaining an environment that provides food, air revitalization, water purification, waste processing, environmental contamination and control during transit and on arrival of a planetary body. Closed-loop life-support-systems with minimal or no re-supply from Earth have the greatest technical challenges to development. [1]

Analog tests, where the conditions of long duration, deep space missions are simulated, can be used to evaluate new technologies. Analog missions place crew in a realistic mission environment and provide a unique and valuable opportunity for investigating how a crew interacts with a system and how crew activities define the requirements of the system. Human factor effects pertaining to waste generation and processing during the Hawaii Space Exploration and Analog Simulation (HI-SEAS) Mission 2 are reported in this paper.

The Trash to Gas (TtG) [2, 3] task is part of the Logistics Reduction and Repurposing (LRR) project [4]. The overall goal of the TtG task is to develop space technology alternatives for converting space waste into a gas that may be converted into high-value products or a gas that can be easily vented as a 'jettison function'. The TtG project team has performed laboratory testing comparing six technologies for processing waste and producing high value products [5]. In August of 2013, steam reforming technology was selected for further development. The Kennedy Space Center (KSC) TtG team converted their previous gasification reactor into a steam reforming reactor to study waste conversion into useful gas via Equations 1 and 2. First, the waste is converted into carbon dioxide and carbon monoxide, which can then be converted to methane. The reuse of discarded materials is a critical component reducing overall mission mass. Current TtG project activities include designing the system for micro-gravity operations, and evaluating the processing system using different waste streams.

 

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

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

Although the TtG technology has proven successful in laboratory studies, a number of assumptions were made to facilitate testing, leading to questions pertaining to the design of a flight unit. For example, a single consistent waste composition was used to allow equal comparison of technologies even though it was known that the waste composition affected the process. Are wastes generated with a consistent composition, day to day over the course of a mission, or do certain wastes get generated during one part of the mission? Can waste materials be segregated and processed in different waste cycles or must the process be able to handle all waste compositions? How much crew time is necessary to operate a waste processing system and how does it compare to other waste disposal options? HI-SEAS was a unique opportunity to answer some of these questions. The following tasks were performed during the mission to help answer these questions.

1. Monitor and characterize wastes generated during the mission.
2. Monitor power and water usage in the habitat.
3. Evaluate crew time and interactions with waste collection, storage, and disposal.
4. Monitor the frequency at which waste needs to be disposed, and if routine, crew Extra Vehicular Activity (EVA) walks are sufficient to dispose of waste out of an airlock.
5. Operate a TtG system at KSC using the waste materials similar to what is generated during HI-SEAS.

### HI-SEAS Mars Analog Habitat Description

Data collection took place at HI-SEAS Mission 2. HI-SEAS was formulated from a NASA grant and led by a collaborative effort 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. After 27 days of the mission, the 6-person crew reduced to a 5-person crew, with one crew member leaving due to health related issues.

The isometric dome-shaped habitat, Fig. 1, is approximately 1,000 square feet, located on the slopes of the saddle region of the Mauna Loa volcano in Hawaii. The habitat architecture and system description has been previously described [6, 7]. Electrical power was generated via solar panels and battery storage. A backup gasoline generator was also available.

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. Greywater was sent to two 250 gallon tanks and one 500 gallon tank that were periodically emptied throughout the mission. The crew used two Sun-Mar waterless composting toilets which would theoretically convert solid waste into a fertilizing soil [8]. The liquid waste in the toilets was evaporated via a heater and vented to the outside of the habitat.

## II. MATERIALS AND METHODS

### HI-SEAS Waste Storage and Collection Process

Mission 2 crew members were given a 4 month supply of food and logistical materials at the start of the mission. These items were divided up and stored in storage bins in the shipping container of the habitat. The mission food consisted of dehydrated vegetables and meats as well as other shelf stable products. The packaging of most items was in the form of plastic, metal cans and cardboard boxes. An image of the 4 month supply of food during the first night of the habitat is displayed in Fig. 2.

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. An image of the kitchen waste collection bins are displayed in Figure 3.

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

Fig. 2: Food and logistical supplies at the beginning of the mission.

 

The waste was separated into the following bins:

1. Food
2. Hygiene – female (bathroom 1st floor receptacle)
3. Hygiene – male (bathroom 2nd floor receptacle)
4. Paper and cardboard products
5. Tissue, hygiene wipes and cleaning wipes
6. Metal cans
7. Metallic wrappers
8. Plastics
9. Non-edible plant biomass and soil – (laboratory receptacle)

Basic human factor statistics on crew time spent for preparing trash for operation, including compacting waste and how much of their time would be available to deliver trash to a reactor unit was monitored. The crew did not find it difficult to manually separate the waste materials. This separation was done so the crew member collecting data could easily weigh the different material wastes being generated, rather than having to pick through a mixed bag of trash. This separation of waste may be an ideal solution for future reactor technology that requires material selectivity for efficient operation.

Once waste receptacles were full from the habitat waste bins, they were brought out to the shipping container room and stored in two 50-gallon plastic bins. 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 from the shipping container are displayed in Fig. 4.

Once completely full, these waste bins were then left in the HI-SEAS airlock and discreetly removed periodically throughout the mission by external "earthly" support. There were several occasions where discreet "earthly" support removed waste or delivered supplies. In fact, there was a mid-mission resupply where large plastic bins of items were delivered. These items were either food, equipment or other materials required for the mission completion. Less than half of the crew members were able to receive mail from external entities that knew about the delivery with enough advance notice.

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 football simulants were re-created and treated for conversion in KSC's TTG steam-reforming reactor.

Volume was measured in two stages. First the non-compressed volume of waste was measured by filling up the waste bins in the shipping container without any manual compression. A full waste storage bin in the shipping container is shown in the top right of Figure 4. The trash was then compressed manually into smaller packages called "footballs". Not all trash was able to be made into a "football" so it was placed strategically in the bin. The compressed volume was recorded by the

Fig. 3: Some of the HI-SEAS Mission 2 waste bins in the kitchen.

Fig. 4: Trash storage bins in shipping container.

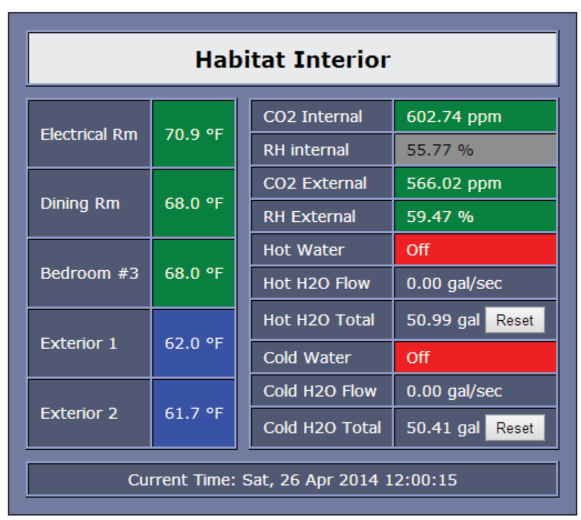


Fig. 5: User interface of sensor system and data collection for certain utility consumption in the habitat.

 

amount of bins that were filled in the shipping container. There was a small amount of air space in the shipping container with the footballs, and this was included in the volume calculations. The compressed waste that did not completely fill up a shipping container was measured with a tape measure and then the volume was calculated.

Utility use was monitored daily with the sensor systems set up by mission support prior to the crew entering the habitat. A display of water consumption using a flow meter was monitored for the daily water consumption of the crew. Interior and exterior habitat temperatures, relative humidity and carbon dioxide levels of the habitat were also monitored from this display as shown in **Error! Reference source not found.**5. A similar data acquisition system was used to monitor the watts that were consumed over a 24 hour cycle. This data was accumulated for the 120 day mission and converted to kilowatt hours.

HI-SEAS FTIR Description

Trace contaminant control and monitoring technologies are helpful to ensure that a crew is not exposed to harmful chemicals. 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 certain gas species at various locations in the habitat. It was used to investigate changes in the immediate atmospheric conditions due to logistical living, plant growth chambers and waste storage facilities located in the HI-SEAS habitat. This device was used on a previous analog mission, NASA's Deep Space Habitat [9].

Data was collected twice each week between 9 and 11 AM in six habitat locations: the shipping container room, food/plant/metal/hygiene waste storage bin in the shipping container, paper/cardboard/plastic waste storage bin in the shipping container, living room, plant laboratory and first floor bathroom. Twenty three gases were monitored during a 5 minute sequence and averaged. The DX-4040 weighs approximately 13.6 kg, which made it easy to carry from room to room in the habitat. **Error! Reference source not found.** displays a crew member taking readings from the FTIR in the shipping container.

TtG Waste Processing

The KSC reactor used in this study was described previously [6] and the steam reforming process was selected based on a comparison of multiple technologies [5]. 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 oxygen

Fig. 6: Crew member taking samples in the shipping container using the portable Gasmet FTIR.

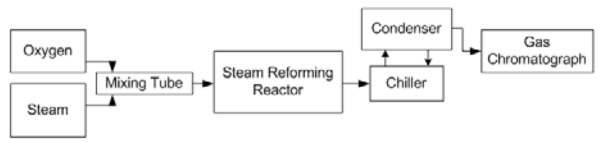


Fig. 7: KSC Steam-Reformer System Flow Diagram.

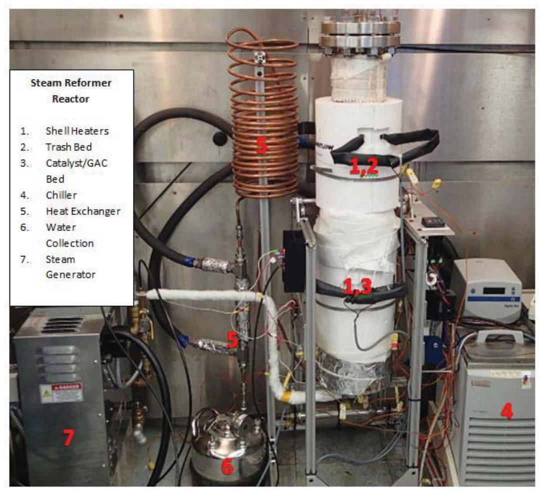


Fig. 8: KSC Steam Reforming Reactor System.

and steam were fed into the reactor directly below the waste. The waste was heated between 300˚C and 500˚C before oxygen and steam were fed into the reactor. Once the oxygen and steam feed began, the reaction initiated and the temperature increased to the operating range, between 600˚C and 700˚C, 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 then 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. A flow diagram of the steam reforming system is displayed in Fig. 7 and a photo of the reactor system is displayed in Fig. 8.

Four types of waste were evaluated as separate experimental processes in the reactor: cardboard/paper, plastics, food/spent plant material, and the TtG High Fidelity Waste Simulant (HFWS). The wastes, other than HFWS, were similar to those identified during HI-SEAS Mission 2 waste generation results, while the HFWS was based off of the Logistics Reduction and Repurposing waste model [10] and had been used in all previous TtG project work. The compositions of HI-SEAS waste simulants are given in Table 1. Materials were collected from laboratories, offices and kitchens at KSC. Spent plant soil was collected from plant growth experiments being performed at KSC.

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 wet waste to the mass after the waste was dried and placed in a furnace at 575˚C for a minimum of eight hours. The combustible mass is the mass that is neither water nor ash.

| Waste Type | Composition by mass |
|---|---|
| **Cardboard** | 50% corrugated cardboard<br>40% food packaging boxes<br>10% used paper |
| **Plastics** | 50% plastic utensils<br>45% plastic food packaging<br>5% nitrile gloves |
| **Food and Plant Mix** | 75% Coffee grounds, tea bags, food crumbs<br>25% spent soil with inedible plant mass |
| **HFWS** | Composition described elsewhere[3] and is based off the LRR project waste model [10] |

Table 1: Composition of HI-SEAS waste simulant and LRR waste simulant materials processed in TtG reactor.

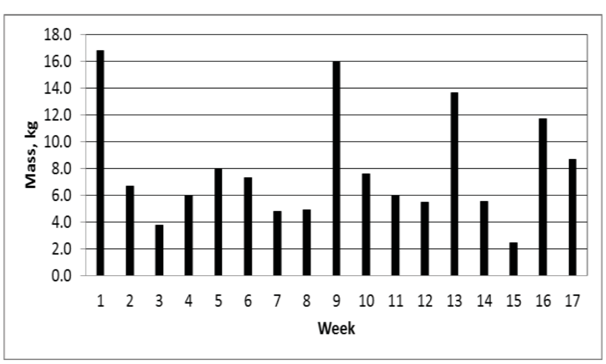


Fig. 9: Total mass of waste generated during each week of the mission.

## III. RESULTS AND DISCUSSION

### Mass and Volume of Waste Generation at HI-SEAS

During HI-SEAS Mission 2, a total of 151.7 kg of wet and dry waste (not including human, waste water or brine) was accounted for during this 120 day experiment (of which only 115 days of waste data was collected). Table 2 displays the mass percentage of materials that were generated during the mission.

Fig. 9 displays the waste generation profile of dry waste during the 120 day HI-SEAS Mission 2. Waste generation fluctuated for a variety of reasons. Every month, a new stock of food was retrieved from the shipping container storage and opened for the month. This activity created an increase in waste production from all of the cardboard and plastic packaging. These peaks are noted at week 5, 9 and 13. After two months in the habitat, the mission had reached its halfway point and also received a mid-mission resupply. This shipment was retrieved by leaving the habitat and performing an extra-vehicular activity (EVA) to obtain the "crashed cargo" that was located in bins along the terrain surrounding the habitat. This resupply provided more food, experimental equipment, and other supplies that came in boxes and packaging, which became logistical waste. Week 16 was one of the final weeks in the habitat where clean-up of experiments and food began, hence the increase in waste generation.

The largest waste materials were food, plant and paper/cardboard waste at 33%, 21% and 17% respectively as displayed in

. Food waste consisted of approximately 65% water in waste coffee filters, coffee grinds, tea bags and left over food/oils from meals. Plant waste consisted of soil, non-edible biomass and water residual. Paper and cardboard content was mostly generated from the food packaging of the crew's dehydrated and shelf stable food products as well as equipment packaging. The large repository of waste cardboard boxes from storage containers became waste throughout the mission and could not be reutilized. Polymer waste was mainly comprised of food packaging and food containers. The hygiene waste contained a mixture of feminine hygiene products, floss, tissues and toilet paper rolls. Metallic waste consisted of metal cans and metallic wrappers from food packaging. Tissue waste consisted of paper towels, tissues and disinfectant wipes from cleaning and EVA activity. Hazardous waste mainly consisted of spent alkaline batteries and desiccant material from food preservative packaging. Initially fecal waste was going to be measured by weighing the dry compost and filler material that was removed from the waterless composting toilets. Inconsistency in toilet performance did not enable this metric.

| Waste Type | Mass Waste Total (kg) | Avg. Mass per Day (kg) | Mass Percent |
|---|---|---|---|
| **Food** | 49.94 | 0.38 | 33 |
| **Plant** | 31.11 | 0.27 | 21 |
| **Paper & Cardboard** | 25.18 | 0.21 | 17 |
| **Polymers** | 18.39 | 0.16 | 12 |
| **Hygiene** | 10.52 | 0.06 | 7 |
| **Metallics** | 8.83 | 0.06 | 6 |
| **Haz Waste** | 4.71 | 0.03 | 3 |
| **Tissue** | 2.99 | 0.03 | 2 |
| **Total** | **151** | **1.21** | **100** |

Table 2: Mass and mass percentage of different types of waste generated from crew activity and plant growth in the HI-SEASAS Mission 2 habitat.

| Date | Crew Member Time per session | Number of Crew Members in Session | Total Compression Session Time |
|---|---|---|---|
| **10-Apr** | 49 | 1.5 | 74 |
| **17-Apr** | 25 | 1 | 25 |
| **4-May** | 45 | 1 | 45 |
| **30-May** | 80 | 1 | 80 |
| **16-Jun** | 15 | 2.75 | 41 |
| **7-Jul** | 41 | 1 | 41 |
| **23-Jul** | 65 | 1 | 65 |

Table 13: Dates, time spent and number of crew members working on trash compression.

The total volume of waste collected during the mission was 2.65m$^3$. Most of the waste could be compacted, however, there were some large containers that were not fully compacted. After the waste that could be compressed into footballs was, the total volume of waste was reduced to 1.51m$^3$. Compression of the waste created a 43% reduction of waste volume. A total of 154 footballs were made. The average mass of the football was 904g with an average volume of 0.006m$^3$.

Throughout the mission, seven trash compression session took place, totalling a time of 371 mission minutes. The distribution of time per session and crew member assistance is displayed in Table 1. This process would be quicker if more crew members were assisting in the process.

During ISS and Space Shuttle Missions, the majority of waste consisted of leftover food, food packaging, and clothing. A model of a one year deep space mission and four person crew was created by the NASA Logistics Reduction and Repurposing (LRR) team based on actual waste data from ISS and Space Shuttle missions and continues to be updated as more information becomes available [4,10]. This model estimates 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.

If the data from HI-SEAS (initially a 6 person crew and reduced to 5 people after 27 days of the mission) is extrapolated for three times the length to a one year mission, the waste would be predicted to total approximately 323 kg for a four person crew. That is approximately 13% of the LRR estimate. Keep in mind the HI-SEAS data does not include as much waste as was included in the LRR model (clothing, feces, urine, brine, medical, etc.). If only hygiene, food, food packaging and food storage is considered from the LRR waste model, a new total of 735kg of waste is used. This is a closer estimate but still only 44% of the predicted model.

The predicted waste volume from the LRR model is 19.1m$^3$. Again, if the HI-SEAS non-compacted waste data is extrapolated to fit a one year mission, the volume would be predicted at 6.73 m$^3$, which is 35% of the LRR model.

One the ISS, astronauts place trash in cargo transfer bags. These bags are then sent on a jettison vehicle where the trash burns up in the atmosphere. Via email correspondence, on January 22, 2014, it was reported from Jacob Cook (NASA, Johnson Space Center) and Michael Ewert (NASA, Johnson Space Center) that NASA astronauts accumulate 0.016m$^3$/person/day of waste on the ISS. The LRR model reports 0.01m$^3$/person/day with trash that is compacted with the Heat Melt Compactor. HI-SEAS data reports a waste generation rate of 0.001m$^3$/person/day with hand compacted footballs (not including other wastes, i.e. clothes, liquids, etc. that are in the LRR model and ISS trash). The HI-SEAS mission generated much less waste than recorded waste from the ISS and LRR model. This was due to not as much waste being considered from the HI-SEAS mission, as well as more efficient food packaging. More analog studies with high fidelity logistic and data from long duration ISS missions can create more accurate models.

A comparison of the mass of packaging used for astronaut food with normal food packaging used at HI-SEAS was done to try and determine why the amount of waste generated during HI-SEAS was so much less. Packaging content of three dehydrated single serving astronaut food items: shrimp cocktail, vanilla breakfast drink, and tea with cream and sugar, were measured.

 

These three astronaut food items contained 51%, 22%, and 49% packaging, respectively. The packaging content of a 60 bar pack of granola bars, a pack of 12 peanut butter cookies and a box of cereal obtained from a grocery store was also measured. These items contained 11%, 19% and 20% packaging, respectively. The common multi-serving food items used at HI-SEAS are packaged more efficiently than single serving astronaut food leading to the lower amount of waste generated during the analog mission than would be expected in a space mission.

HI-SEAS Water Consumption

Figure 10 displays the water consumption for the 120 day mission. The crew used approximately 6.2 gallons/crew member/day with approximately one third of its use being hot water. Water was used in the habitat for logistical use such as drinking, cooking, cleaning, showering, hygiene, laundry and plant watering. The crew was allotted 8 minutes of shower water per crew member per week. The crew washed dishes with two tubs of sitting water (soap and bleach). Water usage would increase on days wehre EVAs occurred due to the extra water required for the liquid cooling garment and water packs that the crew would wear for hydration. Plants used less than 1% of the average water consumption by the crew.

Water usage went down during the middle portion of the mission where activities began to stabilize and increased at the end of the mission as cleaning began for the mission end. During month 4, a rain collector was created and placed outside for water collection. The rain collector provided approximately 10 gallons of water during the few weeks it was used. The average daily hot and cold water, as well as interior relative humidity are shown in Table 4. This water would be available for processing with a TtG reactor.

HI-SEAS Power Consumption

Fig. 10 displays the daily logistical use of power in kilo-watt-hours (kWh) for the 120 day mission. Power consumption totals to 5,776 kWh for the mission. Plant light power usage ranged from 7.0% to 10.1% power use in the habitat per month [6]. 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.

The average daily power use was 50kWh in a day. This information would also be useful to understand how much power is available for a TtG unit if manufactured for HI-SEAS operations.

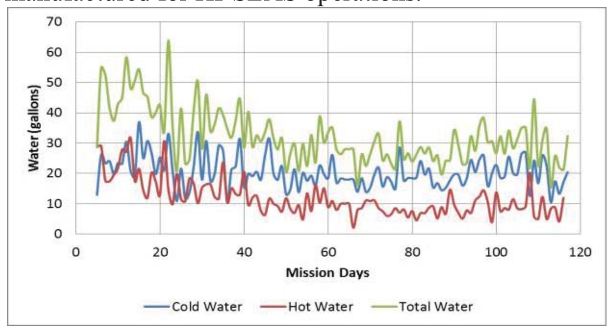


Fig. 10: Daily water usage in the habitat.

| Average Daily Water Use (gallons) | | Relative Humidity |
|---|---|---|
| Cold Water | Hot Water | Avg. Internal RH% |
| 20.46 | 11.92 | 47.34 |

Table 4: Average daily water use and relative humidity in the HI-SEAS Mission 2 Mars analog habitat.

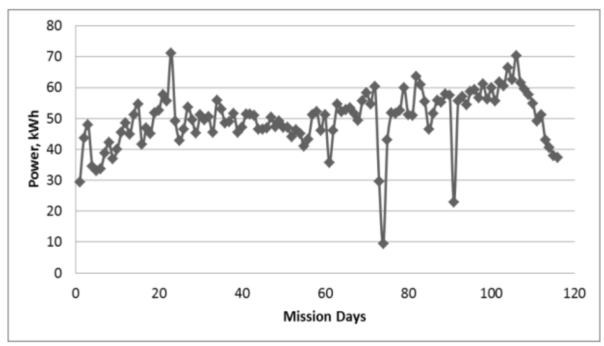


Fig. 101: Daily power usage in the habitat.

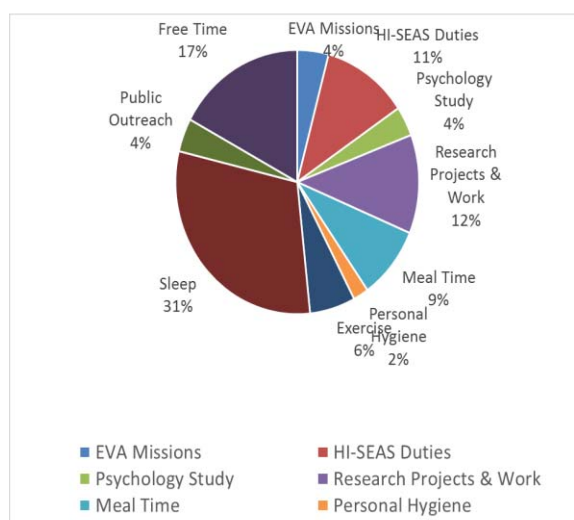

 

Fig. 112: Percentage crew spent on mission activities.

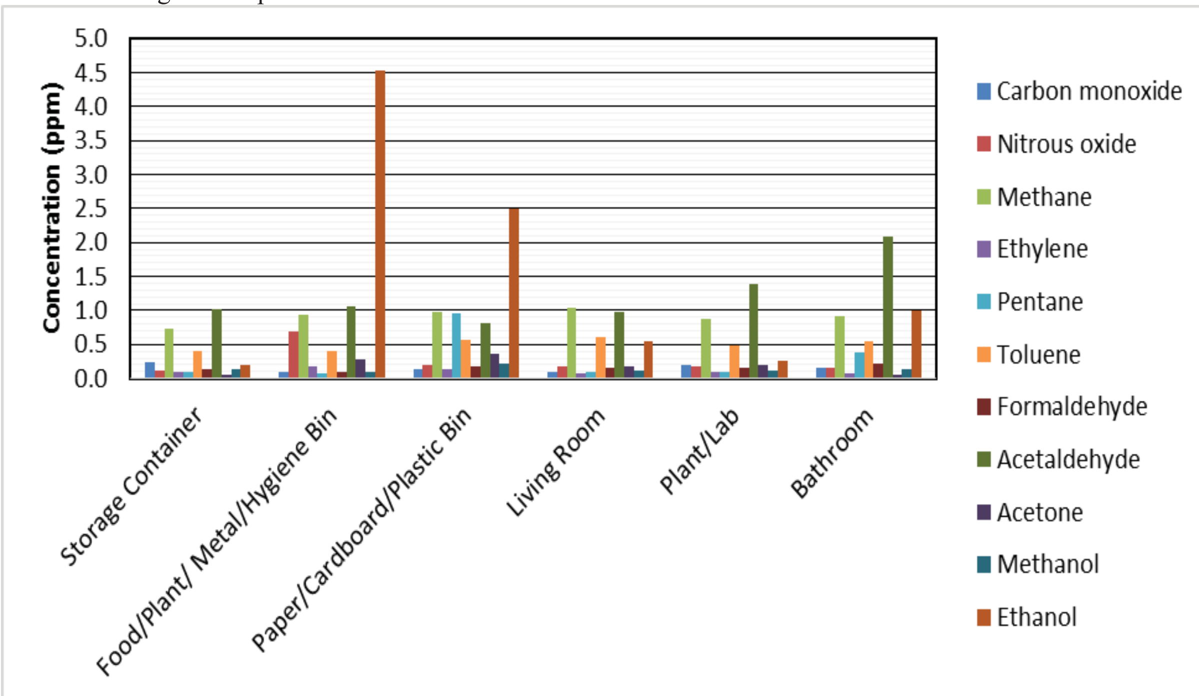


Fig. 123: Average concentrations of selected VOCs at different habitat locations during the first 60 days of the mission.

Crew Time and Activity

There are many things an astronaut would need to do on a scheduled basis to successfully operate a deep space long duration mission or planetary habitat. Crew time is valuable and should not be taken for granted. The HI-SEAS crew was asked to log their time on a daily basis to understand how much free time would be available to operate a TtG unit. Four crew members participated in this study and their daily work performance was averaged and displayed in Figure 12. Activity varies from day to day on a mission. On days where EVAs occur, there may be less free time or less time spent on preparing meals. On a day where no EVAs occur, extra free time for public outreach or sleep might take place. The focus of HI-SEAS Mission 2 was on a psychological investigation where the crew had to take multiple daily, weekly and monthy surveys. This took about 4% of a crew members' active day.

All meals were cooked from scratch and dehydrated products, so meal time (assuming 8 hours of sleep) took nearly 1.5 hours of each crew members' day. Meal time was the most social part of the day where crew would come together to talk and discuss things.

FTIR Results

The concentrations of VOCs from various locations in the HI-SEAS habitat were collected during the mission as previously stated in materials and methods section. The results for selected compounds during the first 60 days of the mission are displayed in

Fig. 12. There were fluctuations during different activity of the first 60 days, but for the sake of simplicity only the general averages are displayed.

These concentration values were compared with OSHA permissible exposure limits [11] and NASA's Spacecraft Maximum Allowable Concentrations (SMAC) for Airborne Contaminant [12]. Concentrations of detected compounds were above the recommended exposure limits except for formaldehyde. The NASA SMAC standard is 0.1ppm for 24 hour exposure duration. The FTIR at HI-SEAS recorded an average value of 0.129, 0.169, 0.164, 0.156 and 0.216 ppm for the areas of the shipping container, paper/cardboard/plastic waste bin, living room, laboratory and bathroom respectively. Formaldehyde is known to be a human carcinogen and is used in resins for manufacturing products such as particle board, plywood and fiberboard [13].

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

The waste storage bins held relatively high amounts of ethanol compared to all other locations. Highest concentrations were found in the food/plant/metal/hygiene bin, tissue/paper/cardboard/plastic waste bin and bathroom. This was expected since ethanol is often a product of fermenting sugars or found on disinfecting solvent wipes of hygiene and other cleaning products [13].

Methane, pentane, toluene and acetaldehyde were also found in higher concentrations than other VOCs. This is most likely a result of natural emissions and off gassing of polymer products (i.e. furniture, carpets, habitat dome cover, etc.).

TtG Waste Processing

All waste types were successfully processed into gasses. The waste was heated before the oxygen/steam mixture was introduced into the reactor to initiate the reaction. The temperature was 300˚C for plastics, 400˚C for cardboard, and 500˚C for the food/spent plant material waste. High initial temperatures were required at the start of the reaction of the food and plant material because of the high water content. When the oxygen and steam was introduced at lower temperatures, the reaction would not initiate due to water evaporation from the waste. If the plastic waste was heated above 300˚C without the oxygen/steam feed, the plastics melted and clogged the reactor.

Results of TtG processing at KSC of three HI-SEAS wastes and the HFWS are shown in Table 6. The amount of carbon dioxide, carbon monoxide, and total carbon produced relative to the wet mass and dry mass, in parenthesis, of waste are shown. The cardboard had the highest amount of carbon recovery from any of the wastes, based on wet and dry masses.

The amount of methane and power that could be produced from the cardboard, plastic, food and plant waste was estimated, and along with the time to all the waste, is shown in Table 7. The amount of methane produced was calculated by first the amount of gaseous carbon that could be from the waste using the experimental data given in Table and the total amount of waste collected in

. The conversion of carbon dioxide and carbon monoxide to methane was assumed to be 100% via the Sabatier reaction. Then, a methane heating value of 14.2 kWh/kg was used to calculate the amount of energy produced, resulting in a total production of 637 kWh. This is roughly 9% of the total energy consumption of the habitat during the mission, and would have been enough to power the lights used for plant growth [6].

The processing time for these wastes was estimated to be 329 hours or about 14 days, based off of experimental TtG reaction data. This time does not include the time to heat up the reactor, so would increase depending on how often the TtG system was run. Without heat up time, TtG would run 12% of the mission. The TtG system could produce almost 2 kW of power while operating, similar to what is produced by small generators.

| Waste Type | Water (%) | Ash (%) | Combustible (%) |
|---|---|---|---|
| Cardboard | 8.1 | 7.3 | 84.6 |
| Plastics | 0.5 | 9.0 | 90.4 |
| Food and Plant Mix | 66.7 | 5.0 | 28.3 |
| HFWS | 40.3 | 5.9 | 53.8 |

Table 5: Water, Ash, and Combustible mass percentages of wastes.

| Waste Type | $CO_2$ (g/g) | CO (g/g) | C (g/g) |
|---|---|---|---|
| Cardboard | 1.64(1.78) | 0.30(0.33) | 0.64(0.70) |
| Plastics | 1.34(1.35) | 0.23(0.23) | 0.48(0.48) |
| Food and Plant Mix | 0.30(0.9) | 0.04(0.12) | 0.11(0.33) |
| HFWS | 0.72(1.21) | 0.18(0.3) | 0.28(0.47) |

Table 6: Carbon dioxide, carbon monoxide and total carbon produced from each waste type, relative to the wet mass and dry mass, in parenthesis, of the waste.

| Waste Type | $CH_4$ (kg) | kWh | Processing time (hr) |
|---|---|---|---|
| Cardboard | 22 | 307 | 98 |
| Plastics | 12 | 168 | 69 |
| Food and Plant Mix | 11 | 162 | 162 |
| Total | 45 | 637 | 329 |

Table 7: Amount of methane and energy that could be produced from HI-SEAS mission waste, as well as the processing time.

## IV. CONCLUSION

The amount of waste produced during the HI-SEAS was measured and is less than would be expected from long duration space missions. The waste was collected, with crew cooperation, in bins separated by waste type. The waste collection data showed that large amounts of waste were generated during certain times, such as when the monthly food supplies were unpacked. At these times, the increase in waste resulted from an increase in packaging material. This indicates that the TtG process must be able to handle a waste stream that will vary in composition, and that it is possible for a crew of five to segregate wastes over a mission.

The time spent on trash compression was monitored, and found to be a very small amount of time. The amount of time required to process all the waste during this mission was 12% of the mission time, based on the reaction rates using the existing reactor at KSC. Based on the time needed to operate the laboratory system, 10% of that operating time would need active crew. A more automated system, would likely require less crew time.

The KSC TtG process successfully processed the three waste types, and could produce 9% of the power needed during the mission. There were differences in the conditions required to process the waste, stemming from the water content and nature of the wastes. No pre-processing of the wastes was carried out in this study. Pre-drying all the wastes should help standardize the reaction initiation.

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