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Trash or Treasure? Results of Integrated Waste Trade Studies for Moon-to-Mars Missions

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NASA's Logistics Reduction technology development project has been analyzing waste products from human spaceflight and innovating ways to turn the trash burden into resource treasures. Reducing, reusing, and recycling waste products can be a win-win proposition if solutions for waste disposal can also supplement the supply of materials needed in space habitats. The trade studies described here sought to match the most appropriate waste processing technologies to many of the missions envisioned in NASA's Moon-to-Mars architecture. Waste processing technologies being developed by NASA and partner companies were evaluated against current waste disposal notions for lunar surface missions of 30 to 365 days and a Mars transit mission of 850 days round trip. The technologies assessed include trash compaction and trash-to-gas as well as other technologies that can process human metabolic waste, plant waste, and plastic waste. The integrated life support and waste disposal systems were analyzed using an equivalent system mass technique to compare mass, volume, power, and cooling of the relevant systems with and without waste processing, resulting in an estimate of launch mass savings for the different missions. Other considerations discussed include mission factors such as life support system closure, planetary protection, radiation shielding, trash storage volume, odor, and sustainability.

Acronyms and Nomenclature

4BCO2 = 4-Bed Carbon Dioxide Removal System
AOWG = Advanced Organic Waste Gasifier
ATCS = Active Thermal Control System
BPA = Brine Processor Assembly
CDRA = Carbon Dioxide Removal Assembly
CHC = Carbon Dioxide and Humidity Control
CHX = Condensing Heat Exchanger
CM = Crew Member
CWC = Contingency Water Container
ECLSS = Environmental Control and Life Support System
ESM = Equivalent System Mass
EVA = Extravehicular Activity
ISRU = In-Situ Resource Utilization
ISS = International Space Station
LADI = Lunar Auger Dryer for ISRU
MAP = Microwave Assisted Pyrolysis
M2M = Moon-to-Mars
MBCS = Multi-Bag Compaction System
MTH = Mars Transit Habitat
OGA = Oxygen Generation Assembly
Plas-Pyro = Plasma Pyrolysis
PLSS = Portable Life Support System
PR = Pressurized Rover
SH = Surface Habitat
TRL = Technology Readiness Level
TCPS = Trash Compaction & Processing System
TPU = Torrefaction Processing Unit
TtG = Trash-to-Gas
TtSG = Trash-to-Supply Gas
UPA = Urine Processor Assembly
WPA = Water Processor Assembly

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I. Introduction

Part of the National Aeronautics and Space Administration (NASA) Moon-to-Mars (M2M) initiative involves developing technologies that will lead to logistics reduction and recycling on human exploration missions, thus increasing sustainability of future Moon and Mars missions. Processing wastes back into usable commodities generally means bringing additional equipment and using additional resources (e.g., power). Thus, it will take time to reap the benefits of recovered resources to "pay back" or "break even" on the initial investment. In this study, an equivalent system mass (ESM) analysis technique was used to quantify and normalize the resource "costs" and benefits associated with various waste processing technologies under development.[1] This was compared to a base case in which only currently existing waste disposal/processing technologies are used. In either case, any shortfall in consumables required to sustain the crew and mission would have to be supplied from Earth, with an ESM penalty.

Previously reported work has shown that some vehicles and missions can benefit more from resource recovery than others due to other system effects. For example, if all possible water was recovered from wastes in a Mars transit habitat, excess stores of water would begin to build up because some "new" water is introduced from the pre-packaged food the crew is eating each day. At first it may seem beneficial to have extra supplies; however, this surplus water increases the mass and inertia of the spacecraft and leads to additional propellant requirements.[2] In other cases, such as lunar or Martian habitats, the inertia problem does not apply. Additionally, frequent extravehicular activity (EVA), which vents water and gases, is expected in these surface missions. Therefore, the cost/benefit calculation of loop closure changes. In this integrated waste tradeoff study, as many M2M missions and developing technologies as possible were analyzed to try and separate trash from treasure.

II. Human Space Missions and Habitats

NASA's M2M objectives guide the development of architectures, intending to develop an integrated network of systems, to conduct a series of campaigns of human exploration extending from the lunar to the Martian surface.[3] To accomplish these objectives, the analysis and trade of the integrated systems becomes necessary to understand what may best support future campaigns that span early lunar engagement to Martian exploration including consecutive lunar surface missions and the Mars transit.

This analytical study of integrated waste systems focuses on the (1) sustained lunar engagement, which entails pressurized rover (PR) and surface habitat (SH) elements that enable the capability for a frequent (e.g., yearly) mission cadence, and (2) Mars transit via the Mars Transit Habitat (MTH), which consists of a more closed loop base architecture to allow for the 850 to 1,200-day round-trip mission.[4] An 850-day mission was analyzed here. These uniquely challenging missions profiles (e.g., sustained lunar surface and Mars transit) demonstrate two extrema in the M2M Artemis campaign. This study considers ten 30-day Lunar surface missions over 10 years and one 365-day continuous mission, building on the 30-day stay of the Artemis Foundational Exploration segment. The lunar surface missions are accompanied by frequent EVAs that lead to larger waste and commodity exit streams from the habitats, whereas the MTH represents a long-term mission within a mostly closed system where logistics waste could build up over time at a detriment to the overall system. This study analyzes the implications of integrating new technologies related to waste processing and crew systems into the larger mission architecture to understand not only their effects on metrics like system mass, volume, and power, but also the potential for developing highly interconnected systems for improved crew habitability.

Existing habitat and spacecraft architectures tend to focus on currently existing state-of-the-art or proven heritage systems to strike a balance between risk and performance. However, these base architectures may miss out on improved efficiencies or opportunities from resource recycling, reuse, and recovery approaches under development. The analyses reported in these series of studies intend to fulfill M2M goals of both reducing the mass and volume (i.e., launch mass) of logistical supplies that must be carried from Earth to support the missions and crew, and developing architectures that better integrate systems to find those improved efficiencies.

The assumed base Environmental Control and Life Support System (ECLSS) architecture for the missions of interest include those tested and proven on the International Space Station (ISS) for a more closed loop.[5] Due to the nature of the lunar surface mission scenarios, the crew is split across multiple habitats (i.e., two crew members (CM) live in the PR and two live in the SH). The more spacious SH is assumed to handle the water processing via fluid transfer between the habitat and vehicle, and the PR is assumed to carry an open ECLSS architecture. The assumed base architecture for the lunar SH is a regenerative ECLSS including a Urine Processor Assembly (UPA), Brine Processor Assembly (BPA), and Water Processor Assembly (WPA) for enhanced water recovery from the different wastewater streams. It also includes an Oxygen Generation Assembly (OGA), High-Pressure Oxygen Compressor, and Four Bed Carbon Dioxide removal system (4BCO2) for habitat air revitalization, oxygen (O_2) generation, and preparation for EVAs.[6] The smaller PR transfers wastewater and urine to the SH to be processed and accepts potable water and high-pressure O_2 transfer from the SH. Additionally, the PR utilizes the Carbon Dioxide and Humidity Control system (CHC) for carbon dioxide (CO_2) capture, which is vented to vacuum.[7] In contrast, the MTH represents a longer mission duration within a mostly closed environment, so its assumed base ECLSS architecture for the MTH adds a Sabatier Assembly to the SH ECLSS architecture to recover O_2 from CO_2.

Due to the unique limitations associated with each mission (e.g., space and mass limitations in the MTH or multiple different sized habitats on the lunar surface), the way that waste is handled in each mission scenario also differs. For the lunar surface baseline, solid waste is assumed to be hand compacted and stored for disposal within the carriers that delivered the logistics, analogous to the current handling on the ISS.[8] When considering the extended 365-day lunar surface mission, it is assumed that solid waste can be transferred from the PR to the SH via a tunnel, where it can be hand compacted and/or processed prior to disposal in the logistics carriers. While this assumed base architecture accounts for the recycling of some wastes (e.g., wastewater and urine), there are missed opportunities for producing valuable products and commodities from additional solid waste processing that would further reduce logistical masses. These products can be used for a variety of purposes from higher water loop closure to providing nutrients toward the implementation of biological systems.[9]

Because of its space and mass limitations, mass removal from the MTH becomes a mission enabling need.[10] On the MTH, the solid waste is assumed to be hand compacted and jettisoned through a dedicated trashlock.[2] As with the lunar surface missions, there is an unrealized potential of lowering logistical mass and volume with the processing of fecal and solid waste. The waste breakdown by category and mission is shown in Table 1.[11] Processing of these wastes would allow the opportunity of further loop closure, waste recycling, and logistical savings.

Table 1. Waste model for M2M missions.

Parameter	30-day Lunar Surface (per Habitat)	365-day Lunar Surface (PR + SH)	Mars Transit Habitat
Crew Waste[a]	13 kg	316 kg	735 kg
Crew Consumables	31 kg	570 kg	1,267 kg
Food Packaging & Residue	33 kg	1,212 kg	2,006 kg
Crew Waste Collection[b]	13 kg	296 kg	820 kg
Crew Systems Clothing	27 kg	478 kg	1,073 kg
Crew Systems Towels	7 kg	158 kg	368 kg
EVA Waste[12]	133 kg	3,390 kg	265 kg
Moisture Content (avg.)	**17%**	**19%**	**20%**
Total Waste	**257 kg**	**6,420 kg**	**6,534 kg**
Daily Waste Rate	**4.3 kg/CM-d**	**4.4 kg/CM-d**	**1.9 kg/CM-d**

[a] Feces, Brine, Urine Solids

[b] Fecal Canisters, Brine Bags, Urine Filters

III. Waste Processing Technologies

The objectives of this study are to analyze the potential of implementing waste processing technologies within the existing architecture of different habitats to improve loop closure, produce beneficial products, and reduce logistical mass and volume. The analysis builds on prior work.[13] The waste processing technologies fall within three categories: compaction, trash-to-gas (TtG), and fecal processing. Each technology achieves volume reduction of the solid waste, while some technologies may show additional benefits (e.g., water recovery). Individual technologies are described in the subsequent sections.

A. Trash Compaction and Processing

Volume reduction of trash and other waste products is important in limited size space habitats. To date, this has consisted mainly of astronauts hand compacting their trash into various bags. Several types of trash compactors for space have been studied with a range of capabilities. Those analyzed here are manual, Multi-Bag Compaction System (MBCS), and Trash Compaction and Processing System (TCPS).[13] The current TCPS grew out of the heat melt compactor development at NASA Ames Research Center and is planned to be demonstrated on ISS in 2027.[14] Besides compaction, the TCPS recovers water from trash and reduces biological activity, and the resulting dry trash tile can be used for radiation protection in the spacecraft.

B. Trash-to-Gas

TtG technologies process waste thermochemically to convert the waste into a series of gaseous and solid residual byproducts, mostly being ash, water, hydrogen (H_2), and carbon oxides. The benefits to the implementation of TtG technologies are widespread, including volume reduction from conversion of solid material to ventable gasses,[2] mass savings from fecal canister reduction due to processing fecal waste,[13] water recovery for crew use and loop closure,[13] carbon oxide production for use in a biological plant growth system,[15] fertilizer for plant growth,[15] H_2 or methane for propellant production,[16] and the reduction of waste into reusable raw materials such as aluminum or carbon.[16]

The TtG technologies considered within this study include the Advanced Organic Waste Gasifier (AOWG),[17] Plasma Pyrolysis (Plas-Pyro) system,[18] and Microwave Assisted Pyrolysis (MAP) systems.[19,20] The AOWG was developed by Pioneer Astronautics, who built a full-scale hardware test stand[15] designed to convert organic wastes generated during human spaceflight into clean water for mission consumables and gases suitable for venting. The AOWG integrated steam reformation, methanation, and electrolysis to convert organic waste into water, dry vent gas, and a small amount of inorganic residue. At its latest design, the AOWG was a standalone process needing the waste processed to have a moisture content of 43% without requiring additional water to be input to the system. Due to this initial water input requirement, not all waste within this study's model could be processed. This is a potential drawback, as the technology may require more water to be supplied to process all of a mission's waste; however, this is mission dependent. In missions with water excess post-regenerative ECLSS processing, this disadvantage may be inconsequential, allowing for full processing of waste. The AOWG's has solid-to-gas conversion of 88%,[17] with the byproducts being mostly CO_2, CO, CH_4, and H_2.

The Plas-Pyro system considered in this study is a low power plasma-assisted waste conversion system using a CO_2 carrier gas. This system's current state is at a lower technology readiness level (TRL) having only undergone benchtop testing, but its benefits may be substantial over other systems in that it is capable of processing all waste without the need for co-reactants like the AOWG.[18] It was assumed that water in the waste will be 100% removed and recovered, either as a pre-treatment step or as part of the reactor process.[2,13] Downstream of the reactor, the product gases enter a heat exchanger with a water collector, and then pass through gas analysis and ventilation. The Plas-Pyro system is capable of processing all of the solid and fecal waste produced throughout the mission with a demonstrated solid-to-gas conversion of 74% for the benchtop system using a CO_2 plasma. The by-product gases were captured and analyzed showing generation of CO_2, CO, C_2H_4, CH_4, H_2O, and other hydrocarbons.

In addition to TtG for mass removal and volume reduction via gas venting, parallel studies have been performed looking into the viability of producing useful commodities via similar TtG methods, also known as trash-to-supply gas (TtSG). Although not considered in the scope of this study, a few of these technologies are highlighted here. More details of the results trading technologies for TtSG can be found in another work.[16] Two microwave assisted pyrolysis technologies are touched upon here as promising TtSG systems. In both cases, microwaves are used to efficiently heat the waste and break it down into smaller hydrocarbons in the absence of oxygen. The MAP system was developed by Advanced Fuel Research, Inc[19] and processes a diverse waste stream. It includes two microwave zones that break down the waste into gases and carbon char. The second zone is used to catalytically crack the gases produced in the first zone to achieve primarily small molecule gases. Water is removed downstream of the reactor with a condenser and particulates are captured with a filter. The product gases are primarily composed of H_2, CO_2, CO, CH_4, C_2H_2, and C_2H_4. The average weight percent of solids converted to gas by MAP is 82%, with just under 4.8% of the gas being H_2 and over 50% being a carbon oxide.

The MAP-Plastic system is similar in its thermal processing method to the MAP system but has been configured to selectively produce H_2 from plastic waste. This system was developed by Cecilia Energy and is a batch reactor, where waste is dropped onto a catalytic bed heated by microwaves and converted primarily into gases. The batch reactor configuration is described here but other configurations are under development, including a continuous reactor. Water is removed downstream of the reactor with a condenser and particulates are captured with a filter. MAP-Plastic recovers almost 100% of the hydrogen present in the waste as H_2 gas, with the remainder being primarily CO_2, CO, CH_4, C_2H_2 and solid carbon. A summary of TtG technologies analyzed can be found in the next section, in Table 2.

C. Human Waste Processing

The fecal processing technology traded in this study is the Torrefaction Processing Unit (TPU), which is a system that uses mild pyrolysis to sterilize feces and related wastes (wipes and gloves) and produce a stable char residue, while simultaneously recovering moisture and producing small amounts of other gases.[16,21,22] A previous study examined many fecal processing technologies for spaceflight and found torrefaction to be among the most promising.[21] Using the data from previous torrefaction testing, the waste conversion to water was calculated to be 66%; the waste conversion to solid residual char was calculated to be 32%; and the remainder was converted to the gases: CH_4, CO,

CO_2, COS, and H_2S. A large portion of the mission waste is unprocessed in this case, as TPU only processes the fecal deposit bags, requiring the remainder of wastes to be hand compacted for storage or jettison. While the volume reduction of an exclusive waste processing technology is not as abundant as TtG or compaction technologies, there are benefits to its implementation since fecal canisters are reduced, pathogens are eliminated, and water is recycled. Elimination of pathogens is particularly important for future Mars surface missions due to planetary protection policy. Rigid canisters from NASA's Universal Waste Management System toilet are assumed for lunar missions and a collapsible Alternate Fecal Canister, which is still under development, is assumed for the Mars mission.[21,23]

Table 2. Trash to Gas and fecal processing technologies.

Technology	Mass (kg)	Volume (m^3)	Power (kW)	Cooling (kW)	Water Recovery (%)	Solid-to-Gas Conversion (%)
Plas- Pyro[18]	31	0.23	0.96	0.96	100	74
AOWG[17]	90	0.80	0.58	0.58	Varies[17]	88
TPU[22]	22	0.14	0.10	0.10	66	2

IV. Integrated Analysis Approach

A. Integrated Analysis Overview

This analysis aims to demonstrate the full cost and benefit of integrating waste technologies into spacecraft and habitats from a system level approach. To elaborate, the addition of solid waste processing has the potential to save mass and volume in other areas of the architecture, whether that be consumables, trashlock sizing, fecal canisters, or baseline physicochemical ECLSS. This analysis examines different architectures and how the integration of new technologies compare to the current base system for each mission.

As will be shown in the following sections, the benefits of waste processing are mission dependent, but widespread. In all mission profiles, processing fecal waste allows for the reduction of fecal canisters, lowering logistical mass and volume. In particular, lunar surface missions tend to see benefits from technologies that are able to recover water from waste processing due to the inherent water deficit incurred by the mission architecture. Despite recycling wastewater and urine, the venting of CO_2 to vacuum and water venting for cooling during EVAs create paths from which O_2 and water are removed from the system. The recovery of water from waste processing decreases the necessary water delivery via Contingency Water Containers (CWCs).[13] Mars transit missions benefit from technologies that can reduce the volume of the waste generated throughout the mission due to being a mostly closed system during this mission phase. The MTH has a dedicated trashlock in which crew jettisons waste. There is an assumed jettison interval, in which crew jettisons waste every 12 days. Due to this, the dedicated trashlock is sized to contain waste for 12 days, with overhead accounted for.[2] In this scenario, technologies which reduce volume more than the baseline hand compaction case allow for a smaller dedicated trashlock, constituting additional mass and volume savings.

In addition to waste processing technologies, this analysis considers the implementation of entirely new systems, and how that can affect the larger network of the habitat. These new technologies have been considered as a way to increase sustainability of an architecture. Our study does not aim to explore the pros and cons of these technologies, but rather the implications of their use on waste processing if they are added to the M2M architecture. Two cases analyzed here are the addition of In-Situ Resource Utilization (ISRU) to produce water from the lunar surface and the addition of a biological plant growth system to provide the crew with fresh food. The addition of ISRU was analyzed for lunar surface missions, utilizing a lunar auger dryer pilot plant producing 1,500 kg of water.[24] Two cases were analyzed for plant growth systems, a small-scale and large-scale case. Plant system integration has benefits not only for crew psychology and diet,[25] but also for the lowered logistical delivery of imported food and the addition of moisture in the waste stream, allowing for more water recovery when paired with a waste processing technology. Biological systems at a large scale also produce O_2 and uptake CO_2, alleviating the need for full-scale physicochemical ECLSS, which may lead to mass and volume savings. Both the waste processing technology trades and consideration of ISRU and plant growth within the spacecraft architecture are discussed in the following results sections.

B. Equivalent System Mass Analysis Methodology

An equivalent system mass analysis provides a comparison of the different waste management systems by considering the different physical quantities (mass, volume, power, and cooling), associated with each system and how they add up to affect launch mass for the mission. The ESM of each waste processing technology is calculated and compared directly to the ESM of the base waste method (hand compaction of waste), calculating a ΔESM.

Equivalency factors, which are habitat/spacecraft specific and stated in Table 3,[1] are used to convert non-mass physical quantities into an ESM value as shown in Equation (1).

$$\mathrm{ESM} = M + V_{\mathrm{P}}\mathrm{E}_{\mathrm{VP}} + PE_{\mathrm{PE}} + CE_{\mathrm{C}} \tag{1}$$

$$\Delta\mathrm{ESM} = \mathrm{ESM}_{\mathrm{Baseline}} - \mathrm{ESM}_{\mathrm{Technology\ Traded}} \tag{2}$$

Besides the waste system hardware itself, additional factors accounted for and added into the ESM in this integrated waste processing study include fecal collection factors, additional water delivery factors (mass and volume of water and storage needed to make up the ECLSS deficit), and dedicated trashlock for a Mars Transit mission. At this time, spares have not been included for any of the systems. The plant growth analysis also includes consideration of CO_2 and food delivery as well as ECLSS sizing effects. By considering more than the systems' hardware, an integrated system is depicted. Equation (2) represents the change in ESM for each case studied.

Table 3. Habitat equivalency factors.

Habitat	Pressurized Volume (m^3)	E_{VP} (kg/m^3)	E_{PE} (kg/kW$_e$)	E_{C} (kg/kW$_{th}$)
Lunar Surface Habitat	190	17.6	70.3	95.0
Pressurized Rover	32	60.6	116	128
Mars Transit Habitat	400	17.9	68.5	88.1

V. ISRU Considerations

ISRU can be used to produce water from the lunar surface. The existing ECLSS architecture on the lunar surface requires the delivery of additional water stored in CWCs. This analysis considers water extraction from the lunar surface, as a strategy for lowering logistical mass necessary for the delivery of water, oxygen, or fuel. This addition of ISRU was analyzed for lunar surface mission profiles to determine the effect on waste processing trades. A Lunar Auger Dryer for ISRU (LADI)[26] pilot plant producing 1,500 kg of water per year was assumed since the pilot scale is a better match for ECLSS water needs than the full-scale version designed for propellant production. The architecture of the ISRU plant consists of excavator, hopper/sorter, LADI, cold trap, water cleanup, electrolysis, and O_2 liquefaction. In the case of the 365-day mission, the system did not include electrolysis or O_2 liquefaction, as they are not used in this case where all pilot plant water was used to close the ECLSS loop. Table 4 summarizes these system masses.[24] The masses include radiators when cooling is necessary. The equivalency factors for the implementation of ISRU are different than the habitats, as ISRU is assumed to use a different power generation system and module for transit. These equivalency factors are in Table 5.[24]

Table 4. ESM Breakdown for a lunar ISRU pilot plant producing 1,500 kg H_2O/year.

Subsystem	Installation Mass (kg)	Volume (m^3)	Power (kW)	ESM (kg)
Excavator	69	0.00	0.26	84
Hopper/Sorter	32	0.04	0.11	39
LADI	18	0.02	0.51	46
Water Cleanup	13	0.02	0.00	14
Cold Trap	96	0.09	0.25	130
Electrolysis	72	0.0	1.8	179
O_2 Liquefaction	218	1.4	0.2	263
Totals	519	1.6	3.2	755
Total w/o Electrolysis & Liquefaction	229	0.2	1.2	313

Table 5. ESM equivalency factors for lunar ISRU.

Equivalency Factor	Value	Source
E_{PE} (kg/kW$_e$)	35.3	VSAT
E_{VP} (kg/m^3)	17.8	Descent Module

The ISRU analysis utilizes an ESM approach, as previously described. However, due to the mass of radiators being included in subsystem masses, the cooling quantity is not included. Additionally, a calculated mass factor is used to quantify the cost of the total system per amount of water being produced for each mission duration. The mission duration is used to calculate the cost of the plant water production for the mission analyzed. For the 365-day mission, the plant is dedicated to ECLSS water production and run for one full year. For the 10 years of 30-day missions, the ISRU plant is shared with other users (e.g. propellant production) and the cost is weighed across 10 years versus a single 365-day mission. The equations for calculating the mass factor of each mission are shown below.

$$\text{Mass Factor} = \frac{\text{Total ISRU Pilot Plant System ESM (kg)}}{\text{Water Produced Mass}\left(\frac{\text{kg}}{\text{yr}}\right) \times \text{Mission Duration(yr)}} \tag{3}$$

$$\text{Scaled ESM of Pilot Plant Water} = \text{Mass Factor} \times \text{Mission water needs (kg)} \tag{4}$$

VI. Plant Growth Considerations

The addition of a biological plant growth system can be used to provide the crew with fresh food. Two cases were analyzed for the 365-day lunar surface mission in which 7% of the crew's diet would be grown or 68% of the crew's diet would be grown. Each case utilized a different plant growth architecture, as described below. The goal of including plant growth here was not to prove that growing food on this mission is or is not cost effective, but to study the effects of these cases on waste processing trades if plants are grown on the Moon for food someday. An ESM analysis was performed to study the effect of integrated implementation of plant growth systems along with waste processing technologies compared to the base case of plant growth and the hand compaction of waste. The waste technologies analyzed were plasma pyrolysis and torrefaction. The addition of plant growth influences the food mass being delivered with crew, as imported food decreases with food being grown. Additionally with plant growth, inedible biomass is added to the waste model, adding additional moisture to recover. In the large-scale case, this increases the moisture content of the entire waste stream from 18% to 44%. When paired with a waste processing technology, this represents one of many tradeoffs that may occur (i.e., additional water recovered for crew versus the need for larger waste processing systems). Depending on the extent of plant growth desired to supplement crew diet, the amount of crew metabolic CO_2 to support plant growth may be insufficient, thus requiring import of CO_2 from Earth. In these cases, waste processing technologies may present a better option than CO_2 delivery. In addition to the interplay between plant growth and waste processing systems, plant growth systems may also affect habitat/spacecraft ECLSS. Because plants uptake CO_2 and produce O_2, they in part serve as a supplement to the ECLSS functions of CO_2 removal and O_2 generation and may lead to the ability to downsize that ECLSS hardware (e.g., CDRA and OGA).

In addition to the trading of waste processing technologies with plant growth systems, results are shown to depict plant growth cases against a case with fully imported food. This case is used to demonstrate the drawbacks and benefits of the inclusion of plant growth as well as the addition of waste processing technologies to the overall system.

D. 7% Diet Grown

For small-scale plant growth, the remaining imported dry food is scaled in order to achieve 3,000 kcal to each crew member. The amount of food grown is dictated by the salad-only diet as described in the Baseline Values and Assumptions Document (BVAD).[32] The crop growth area, edible and inedible biomass, and photosynthetic reactants and products are shown in Table 6. The total plant growth area for 4 CM is determined to be 5.4 m^2 for this small-scale plant growth case.

The system used to grow the food is based on Sierra Space's Astro Garden.[27,28] This is a hydroponic system consisting of growth modules, water processing modules, and nutrient mixing. As the design for this system was intended for transit applications, a 50% decrease in mass is applied to scale for surface applications, assuming the presence of gravity allows for a much lighter system.[29]

Table 6. Small-scale plant growth diet.

Crop	Growth Area (m^2/CM)	Edible Biomass (kg/CM-d)	Inedible Biomass (kg/CM-d)	O_2 Production (kg/CM-d)	CO_2 Uptake (kg/CM-d)	H_2O Uptake (kg/CM-d)
Cabbage	0.256	0.019	0.002	0.002	0.003	0.453
Carrot	0.488	0.037	0.029	0.008	0.011	0.864
Green Onion	0.055	0.005	0.001	0.001	0.001	0.096
Lettuce	0.119	0.016	0.001	0.001	0.001	0.250
Radish	0.098	0.009	0.005	0.001	0.002	0.173
Spinach	0.066	0.005	0.000	0.001	0.001	0.117
Tomato	0.265	0.046	0.034	0.007	0.010	0.734
Total	**1.35**	**0.14**	**0.07**	**0.02**	**0.03**	**2.69**

A daily crew member mass balance for this case is depicted in Figure 1. As shown in the balance, the addition of the plant growth system provides a small CO_2 removal benefit (0.03 kg/CM-day out) and generates edible biomass

(0.14 kg/CM-day) to offset some of the as-delivered dry food at the expense of the additional plant growth subsystem mass, volume, and power (Table 7).[28] For this study, the existing ECLSS is assumed to be able to withstand the additional moisture load that it needs to condense and process to support plant growth.

E. 68% Diet Grown

For large-scale plant growth, the remaining imported dry food is scaled in order to achieve 3,000 kcal per crew member. The food grown targets the diet described by Liu Hong, et al.[15,30] This diet was derived from their test data for plant growth and is intended to supply 68% of the crew's diet for long duration missions. The crops' growth area, edible and inedible biomass, harvest index, and photosynthetic reactants and products are shown in Table 8.[31-39] Although difficult to make a one-to-one comparison, note that the large-scale plant growth diet parameters (e.g., area, O_2 production, etc.) do not scale linearly with the percent diet grown when compared to the small-scale diet. Reasons for this discrepancy include the different crops considered in either case as well as the use of both substrate and hydroponic growth systems for the large-scale plant growth diet. For the large-scale system, the total plant growth area is 122 m^2 where 50 m^2 is hydroponic growth and 72 m^2 is substrate growth. As shown in Table 8, this large-scale plant growth system provides much higher edible biomass (5.69 kg/day) to the crew and significant potential to offset the ECLSS CO_2 removal (4.92 kg/day CO_2 uptake) and O_2 generation (3.58 kg/day O_2 production) function. There is also a significant amount of inedible biomass (5.2 kg/day) added to the waste stream.

Table 7. Small-scale plant growth system.

	Parameter	Value
Growth Module	Plant Area	5.4 m^2
	Mass	30 kg
	Power	0.45 kW
	Volume	0.57 m^3
Water Processor	Mass	27.5 kg
	Power	0.30 kW
	Volume	0.28 m^3
Nutrient Mixing Reservoir	Mass	75 kg
	Volume	0.30 m^3
Total	Mass	132.5 kg
	Power	0.75 kW
	Volume	1.15 m^3

Table 8. Large-scale plant growth diet.

	Plants	Area (m^2)	Edible Biomass (kg/day)	Harvest Index	Inedible Biomass (kg/day)	O_2 Production (kg/m^2-day)	CO_2 Uptake (kg/m^2-day)	H_2O Uptake (kg/m^2-day)
Substrate	Wheat	60	0.914	40%	1.371	0.04	0.05	7.90
	Scallion	0.5	0.218	90%	0.024	0.06	0.08	9.28
	Beans	1	0.011	40%	0.017	0.03	0.04	2.53
	Potato	6	0.200	70%	0.086	0.01	0.02	1.33
	Carrot	2.5	0.375	60%	0.250	0.03	0.05	3.55
Hydroponic	Leafy	10	1.400	90%	0.156	0.01	0.01	2.24
	Tomato	5	1.429	45%	1.746	0.05	0.07	5.31
	Eggplant	1	0.080	45%	0.098	0.02	0.03	4.78
	Strawberry	5	0.100	35%	0.186	0.01	0.01	0.57
	Cucumber	2	0.200	45%	0.244	0.02	0.03	2.12
	Pepper	2	0.450	45%	0.550	0.04	0.06	4.78
	Chufa	13	0.236	40%	0.355	0.03	0.04	10.35
	Soybean	14	0.078	40%	0.117	0.02	0.02	5.18
	Total	**122**	**5.69**	**-**	**5.20**	**-**	**-**	**-**

The plant growth system in this analysis is based on Kennedy Space Center's developed hydroponic and substrate-grown systems.[40] The hydroponic system includes the pump necessary for water delivery to plant roots. The substrate-grown system includes the media necessary for housing plant roots. In addition to the plant growth system, lighting is necessary. The lighting system was based on commercially available systems (i.e., Fluence Bioengineering's SPYDR2X),[33] and was scaled to the plant growth area for both the hydroponic and substrate growth systems.

Large scale plant growth leads to marked changes in the crew member mass balance as shown in Figure 2. The plant growth system was sized to produce 68% of the crew diet, which is reflected in the large amount of edible biomass (1.42 kg/CM-day) that the crew now ingests but also the much smaller amount of dry food (0.33 kg/CM-day) that now needs to be delivered. Another benefit of such a large plant growth system is the significant offsetting of ECLSS function where the CDRA is shown to be disconnected from the crew mass balance since all of the crew metabolic CO_2 (1.08 kg/CM-day) is now routed to the plant growth system. Even the metabolic CO_2 is insufficient to support all of the plant growth and an additional import of CO_2 (0.15 kg/CM-day), must be accounted for. These benefits, however, come at a cost which includes the mass of the additional plant growth subsystems (Table 9 - 11) and the additional water processing capability needed (Table 12). The additional water processing capability is assumed to consist of a condensing heat exchanger (CHX) in order to remove the additional humidity in the habitat. The CHX sizing is scaled based on the ISS CHX.[41]

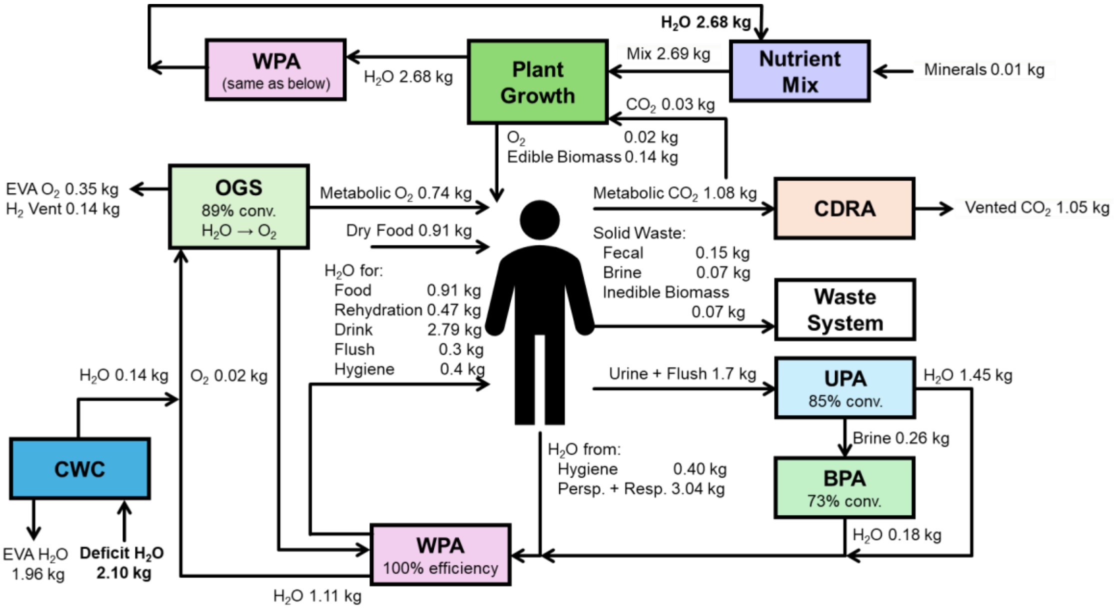

Figure 1. Crew member daily mass balance, small-scale (7%) plant growth implemented.

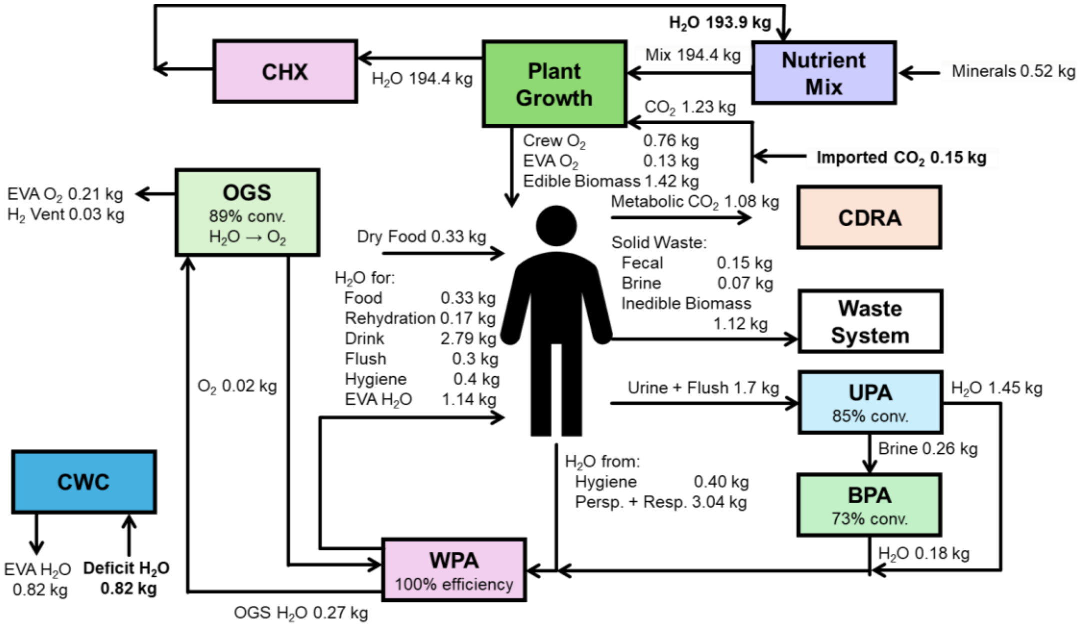

Figure 2. Crew member daily mass balance, large-scale (68%) plant growth implemented.

Table 9. Hydroponic growth subsystem.

	Mass (kg)	Volume (m^3)
System with 2 Trays	1.6 kg	0.007 m^3
30 L Tank	3.1 kg	0.029 m^3
Pump	1.8 kg	0.002 m^3
Total	6.5 kg	0.038 m^3
Total Area	0.4 m^2	
Mass/Volume Factors	16.2 kg/m^2	0.095 m^3/m^2
Large-Scale Growth Area	52.0 m^2	
Large-Scale Mass & Volume	844 kg	4.96 m^3

Table 10. Substrate growth subsystem.

	Mass (kg)	Volume (m^3)
System with 4 Quadrants	1.2 kg	0.011 m^3
Media for 4 Quadrants	4.0 kg	--
Total	5.2 kg	0.011 m^3
Total Area	0.2 m^2	
Mass/Volume Factors	26.1 kg/m^2	0.055 m^3/m^2
Large-Scale Growth Area	70.0 m^2	
Large-Scale Mass & Volume	1,827 kg	3.87 m^3

Table 11. Large-scale (68% diet) plant growth system

	Mass (kg)	Volume (m^3)	Power (kW)	Cooling (kW)
Plant Growth System	2,671	8.8	-	-
Lighting	924	11.5	26.7	-
CHX	789	1.5	0.1	26.8
CO_2 Storage[42]	586	1.7	-	-
Total	**4,384**	**21.9**	**26.8**	**26.8**

Table 12. Scaling and fixed factors for resizing.

Technology		Fixed Factor (C_F)	Scaled Factor (C_S)
ISS Core CHX[43]	Mass	0.4	0.6
	Volume	0.4	0.6
ISS Fan[43]	Mass	0.4	0.6
	Volume	0.4	0.6
	Power	0.5	0.5
OGA[2]	Mass	0.57	0.43
	Volume	0.57	0.43
	Power	0	1
4BCO2[2]	Mass	0.57	0.43
	Volume	0.57	0.43
	Power	0	1

Scaling methodology was applied to multiple systems within this large-scale plant growth case. The ISS CHX system needed to be scaled up to support additional moisture load. The baseline OGA and 4BCO2 systems were scaled down, as CO_2 produced by crew would be taken in by plants and O_2 produced by plants would be taken in by crew. The equations below were used for scaling. Table 12 displays the fixed and scaling factors for each system.

$$\textbf{Mass:}\quad M_{Scaled} = M_{Baseline} \times (C_F + C_S \times \text{Scaled Capacity / Baseline Capacity}) \tag{5}$$

$$\textbf{Volume:}\quad V_{Scaled} = V_{Baseline} \times (C_F + C_S \times \text{Scaled Capacity / Baseline Capacity}) \tag{6}$$

$$\textbf{Power:}\quad P_{Scaled} = P_{Baseline} \times (C_F + C_S \ \text{Scaled Capacity / Baseline Capacity}) \tag{7}$$

VII. Results

Results are found in the subsequent sections with more detailed results for sections F and G in reference 13.

F. Artemis Missions

This study considers ten 30-day lunar surface missions over 10 years as well as one 365-day continuous mission. For the ten 30-day lunar surface missions, all inputs and factors are identical between lunar habitats (SH and PR); differences in results are from ESM equivalency factors. The mission outputs that scale (i.e., multiplied) over 10 missions are waste generated, waste processed, consumables, water recovered and fecal configuration masses. In the SH, TCPS, Plas-Pyro, and TPU trade better than the baseline hand compaction case. In the PR, Plas-Pyro and TPU trade slightly better than the baseline hand compaction case; however, actual volume available in the PR for waste storage is not yet known. Each increase in cumulative mission length leads to a greater benefit from technologies that recover water and lower fecal canister delivery mass. A summary of results is shown in Table 13, where negative ΔESM values represent savings compared to the baseline case of no waste processing (i.e. only hand compaction).

For the 365-day mission, total waste for both the PR and SH is assumed to be processed in the SH. TCPS, Plas-Pyro, AOWG, and TPU all trade better than the baseline hand compaction case. Increasing duration led to a greater benefit from technologies that recover water and process fecal waste. A summary of this analysis is in Table 14.

Table 13. ESM results for 10, 30-Day lunar surface missions.

		Compaction			Trash to Gas		Fecal
Parameter	**Hand**	**Manual**	**MBCS**	**TCPS**	**Plas-Pyro**	**AOWG**	**TPU**
SH ESM (kg)	1,466	1,712	1,539	1,425	1,282	1,520	1,406
SH ΔESM (kg)	**0**	**245**	**72**	**-40**	**-184**	**54**	**-60**
PR ESM (kg)	1,571	1,867	1,665	1,580	1,453	1,695	1,516
PR ΔESM (kg)	**0**	**296**	**94**	**8**	**-117**	**124**	**-55**

Table 14. ESM results for extended 365-day lunar mission.

		Compaction			Trash to Gas		Fecal
Parameter	**Hand**	**Manual**	**MBCS**	**TCPS**	**Plas-Pyro**	**AOWG**	**TPU**
ESM (kg)	3,745	4,254	3,827	3,499	2,768	3,405	3,425
ΔESM (kg)	**0**	**508**	**81**	**-246**	**-977**	**-340**	**-320**

G. Mars Transit Mission

The Mars transit mission is different from the previous lunar missions as there is no water deficit from ECLSS and waste is being jettisoned through a dedicated trashlock. Due to this, there is no water benefit from waste processing. However, there is a cost to technologies that process less waste, as the trashlock is sized according to a combination of unprocessed waste and the waste product of the technologies. Plas-Pyro, AOWG, and TPU all trade better than the baseline hand compaction case. The increase in duration compared to the lunar missions led to a greater benefit from technologies which could lower the fecal canister delivery mass and use less consumables. The TtG systems have significantly less trash to store and jettison compared to that of the compactors and fecal waste processing technologies, leading to less mass for the sized trashlock. The analysis' results are summarized in Table 15.

Table 15. ESM results for Mars transit mission.

		Compaction			Trash to Gas		Fecal
Parameter	**Hand**	**Manual**	**MBCS**	**TCPS**	**Plas-Pyro**	**AOWG**	**TPU**
ESM (kg)	1,130	1,949	1,306	1,149	881	840	960
ΔESM (kg)	**0**	**819**	**176**	**19**	**-249**	**-289**	**-169**

H. ISRU Results

Additional cases were analyzed to consider adding ISRU for both lunar surface mission profiles. The mass factors and total ISRU pilot plant ESM for each mission defined in section V are calculated below. In the ten 30-day missions case, 1,225 kg total H_2O per habitat is required to make up the deficit after ECLSS water processing. The pilot plant produces 1,500 kg H_2O per year, or 15,000 kg H_2O over 10 years, making more than enough over the course of the missions to consider a case where water does not need to be brought to the moon to close the water loop, assuming production is constant and some storage capacity is available. In the 365-day lunar surface mission case, 3,148 kg H_2O is needed to make up the deficit after ECLSS water processing. Due to the pilot plant producing 1,500 kg H_2O per year, a deficit remains even with the implementation of one ISRU plant. This deficit is accounted for with supplied water in the ESM results rather than assuming the ISRU plant arrives early and stores up water for later use.

10, 30-day Missions Per Habitat

$$\text{Mass Factor} = 0.025 = \frac{377\ (\text{kg of ISRU ESM})}{1{,}500\ (\text{kg H}_2\text{O/yr}) \times 10\ (\text{yr})}$$

$$\text{Scaled ESM of Pilot Plant Water} = 31\ (\text{kg}) = 0.025 \times 1{,}225\ (\text{kg})$$

365-day Mission

$$\text{Mass Factor} = 0.21 = \frac{313\ (\text{kg of ISRU ESM})}{1{,}500\ (\text{kg H}_2\text{O/yr}) \times 1\ (\text{yr})}$$

$$\text{Scaled ESM of Pilot Plant Water} = 313\ (\text{kg}) = 0.21 \times 1{,}500\ (\text{kg})$$

The ESM of these cases compared to the baseline system with no ISRU or waste processing are shown in Figure 3, the first two plots coinciding with the ten 30-day missions and the last with the 365-day mission. The dashed outline represents ESM savings due to the decreased water delivery needed when integrating ISRU. In all cases, the addition of ISRU trades better than a case without due to the savings in water and its delivery.

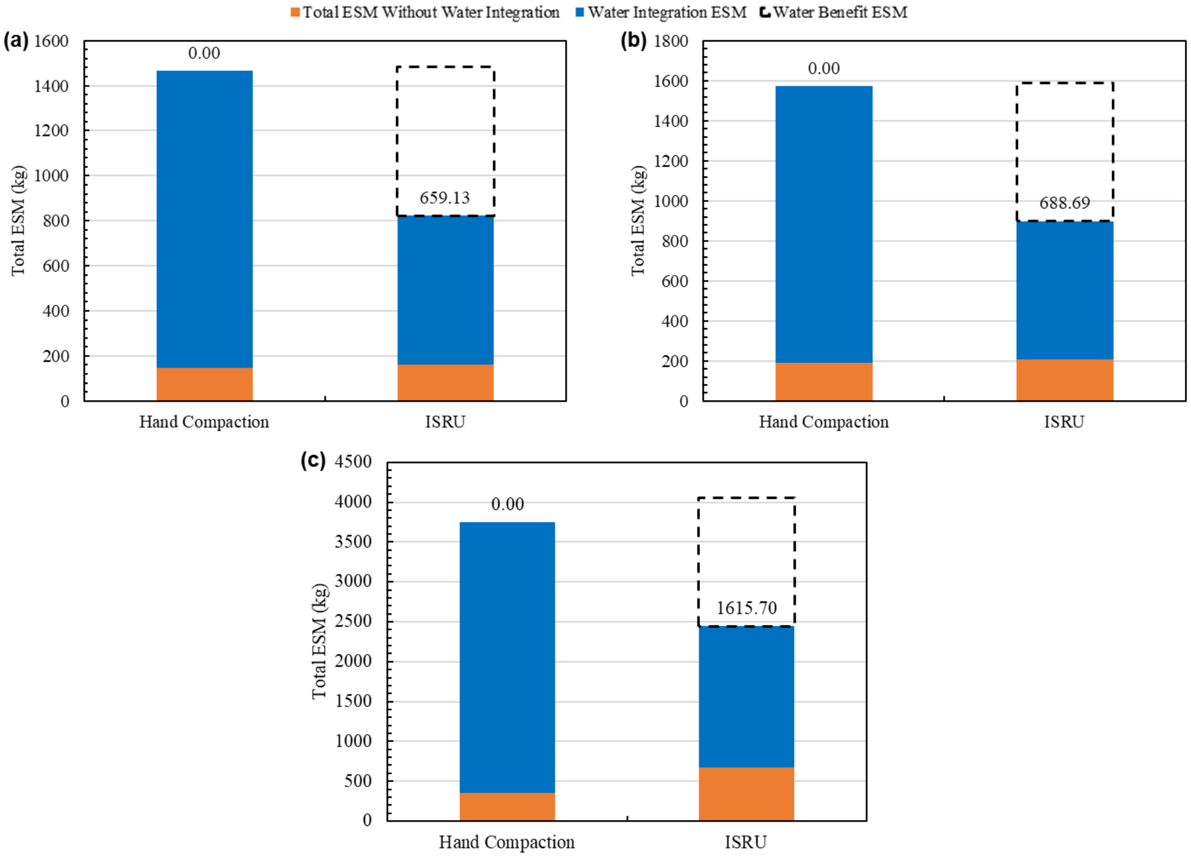

Figure 3. Total ESM and water benefit for the (a) surface habitat, 10, 30-day missions; (b) pressurized rover, ten 30-day missions; and (c) combined surface habitat and pressurized rover, 365-day mission.

I. Plant Growth Results

There are two plant growth cases in which 7% and 68% of the diet is grown. In the 7% food grown case, both architectures integrating waste processing technologies traded better than the plant growth architecture with hand compaction of waste, which was considered the baseline case in this particular analysis. Additionally, the plant growth architecture combined with plasma pyrolysis traded better than the case with no plant growth and waste being hand compacted. In this case, the benefits of water recycling, fecal canister reduction, and food mass reduction had the largest effect. The ESM breakdown is in Table 16.

For the 68% food grown case, both architectures integrating waste processing technologies traded better than the baseline food growth architecture without waste processing. The increased recovery of water, reduction of fecal canisters and full recycling of CO_2 had the largest impact. The resulting ESM breakdown for this trade is shown in Table 17. Here, none of the plant growth cases traded better than the case with no plant growth and waste hand compacted. A breakeven analysis was performed to determine how many consecutive missions would be required for a plant growth case to trade better than the no growth case. The factors multiplied by the number of missions were system consumables, CO_2 imported mass, food mass, water delivered mass, and fecal canisters delivered mass. It took 4 years for a growth case to trade better than a no growth case. This case was plant growth with plasma pyrolysis.

Table 16. Small-scale plant growth ESM for 365-day mission.

ESM Breakdown	No Plants & Hand Compaction	Baseline - Plants & Hand Compaction	Plants & Plasma Pyrolysis	Plants & Torrefaction
Mass	0	0	31	22
Volume	0	0	4	2
Power	0	0	67	7
Cooling	0	0	91	9
Consumables Mass	129	117	185	116
Consumable Volume	15	14	23	15
Fecal Configuration Mass	183	183	25	22
Fecal Configuration Volume	29	29	1	1
Total Mass for Water Integration	3,326	3,250	2,186	3,036
Total Volume for Water Integration	63	62	42	58
Food Mass	3,489	3,256	3,256	3,256
Food Volume	410	383	383	383
Plant Growth System Mass	0	373	373	373
Plant Growth System Volume	0	60	60	60
Plant Growth System Power	0	306	306	306
Plant Growth System Cooling	0	413	413	413
ESM	**7,645**	**8,445**	**7,444**	**8,078**
ΔESM	**-799**	**0**	**-1,001**	**-367**

Table 17. Large-scale plant growth ESM for 365-day mission

ESM Breakdown SH	No Plants & Hand Compaction	Baseline - Plants & Hand Compaction	Plants & Plasma Pyrolysis	Plants & Torrefaction
Mass	0	0	31	22
Volume	0	0	4	2
Power	0	0	67	7
Cooling	0	0	91	9
Consumables Mass	129	146	224	145
Consumable Volume	15	17	28	18
Fecal Configuration Mass	183	234	27	24
Fecal Configuration Volume	29	38	1	1
Total Mass for Water Integration	3,326	2,078	819	1,809
Total Volume for Water Integration	63	39	16	35
Food Mass	3,489	1,921	1,921	1,921
Food Volume	410	226	226	226
CO_2 Mass	0	586	0	586
CO_2 Volume	0	30	0	30
Plant Growth System Mass	0	4,384	4,384	4,384
Plant Growth System Volume	0	385	385	385
Plant Growth System Power	0	1,881	1,881	1,881
Plant Growth System Cooling	0	2,542	2,542	2,542
ECLSS Mass	3,017	2,757	2,757	2,757
ECLSS Volume	126	118	118	118
ECLSS Power	341	190	190	190
ECLSS Cooling	460	256	256	256
ESM	**11,589**	**17,828**	**15,970**	**17,349**
ΔESM	**-6,329**	**0**	**-1,859**	**-479**

VIII. Conclusions

A comprehensive study was conducted to show the system level effects of integrating various waste processing technologies into lunar and Mars missions. Longer missions which had a water deficit generally benefited the most from these technologies. For example, lunar surface missions have a water deficit due to frequent EVA and the 365-

day mission had greater benefit from all waste processing technologies past simple compaction than 10 cumulative 30-day missions totaling 300 days. Even though the 850-day Mars transit mission is longer than either of the lunar cases, there is less benefit from waste processing since mission water demand is less (little EVA) and surplus water actually incurs a penalty on the vehicle propulsion system.

When ISRU was considered as an alternative source of water for the lunar PR and SH, there was a benefit compared to the base case where additional water had to be supplied from Earth. Water recovery from waste technologies was also better than supplying water from Earth, but the ESM cost was higher than getting water from ISRU under the assumptions in this study.

When the lunar base was assumed to include plant growth along with the additional associated resource and waste considerations, the plasma pyrolysis and torrefaction technologies studied both showed benefits compared to hand compacting waste for disposal rather than processing. While an exhaustive analysis of plants versus no plant growth was not the focus of this study, it is clear that waste processing technologies such as those analyzed here are necessary whenever significant plant growth is part of a planetary base.

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