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Benefits of Trash-to-Gas versus Jettison of Waste via Trash-Lock for Mars Transit

Thomas T. Chen[1] and Michael K. Ewert[2]
NASA Johnson Space Center, Houston, TX, 77058, USA

Joel A. Olson[3]
Bennett Aerospace, Kennedy Space Center, FL, 32899, USA

Human exploration missions to Mars pose difficulties due to the significant waste that will be generated during transit, which will need to be carried along or disposed of in some fashion. Waste removal from the spacecraft decreases the spacecraft's mass as well as the associated logistic items necessary for storing the waste. A mission propellant analysis was performed to highlight the mass benefits that may be accessed via waste removal. The propellant mass savings were determined for different waste removal rates (2.9 – 11.6 kg/day) with the highest removal rate leading to the greatest propellant savings of 7,785 kg for an 850-day round-trip mission. Due to these benefits, two methods for waste reduction were studied for the 850-day Mars mission: Trash-to-Gas (TtG) and physical jettison via a trash-lock. The trash-to-gas methods considered were combustion, steam reforming, and pyrolysis, which convert waste into ventable gases (e.g., CO_2, CO, CH_4, etc.). Combustion and steam reforming require a co-reactant (O_2 and/or H_2O). Therefore, additional processing units or integration with the spacecraft's environmental control and life support system (ECLSS) are required to facilitate recycle of the pertinent species. In contrast, pyrolysis is a purely thermal degradation process, which can operate as a standalone system; however, a lower percentage of waste is gasified with pyrolysis. The study herein compares standalone TtG (e.g., Advanced Organic Waste Gasifier, Plasma Pyrolysis, etc.), integrated TtG-ECLSS (e.g., Orbital Syngas Commodity Augmentation Reactor, Incineration/Gasification, etc.), and physical jettison. Each system's mass, volume, power, and cooling requirements were compared via an equivalent system mass (ESM) analysis to ascertain potentially promising technologies that can achieve efficient waste removal while minimizing their own spacecraft load. This study highlights the advantages and disadvantages of the different waste management technologies and provides recommendations on the promising technologies based on the ESM metric and propellant mass savings.

Nomenclature

AFC = Alternate Fecal Canister
AOWG = Advanced Organic Waste Gasifier
CM = Crewmember
ECLSS = Environmental Control and Life Support System
ESM = Equivalent System Mass
EVA = Extravehicular Activity
Inc-Gas = Incineration/Gasification
ISS = International Space Station
KPP = Key Performance Parameter
MAP = Microwave Assisted Pyrolysis
MBCS = Multi-Bag Compaction System
MTH = Mars Transit Habitat
NEP = Nuclear Electric Propulsion
OSCAR = Orbital Syngas Commodity Augmentation Reactor
OGA = Oxygen Generation Assembly
Plas-Pyro = Plasma Pyrolysis
SEP = Solar Electric Propulsion
TRL = Technology Readiness Level
TtG = Trash-to-Gas
WRS = Water Recovery System

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[1] ECLSS Analyst, Crew & Thermal Systems Division, NASA JSC.
[2] SE&I Lead, Exploration Capabilities - Logistics Reduction Project, Crew & Thermal Systems Division, NASA JSC.
[3] Subject Matter Expert II, Laboratory Support Services and Operations II, Mail Stop: LASSO-008.

I. Introduction

The human desire for exploration will lead us to further reaches of space. Considering the current goal of landing humans on Mars by 2040, these long exploration missions will necessitate proper waste management. During a Mars mission, which may extend from 800 to more than 1,100 days round trip, the amount of waste generated by a crew will be substantial, hence, waste storage and management becomes a very important consideration over these long duration missions. Waste removal from the spacecraft during Mars transit presents many benefits over long-term waste storage. The benefits include the the propellant mass savings due to the reduction in spacecraft mass, volume savings, not needing to plan for storage volume away from the crew, and removal of odorous and/or off-gassing waste.

Several prior trade studies, which have examined trash management strategies have reported on these propellant savings [1, 2]. From the work of Olson, *et al.* (2021), a quantitative estimate of approximately 800 kg of propellant savings for each 1 kg/day of waste removal was determined based on an 850-day Mars mission with a nuclear electric propulsion (NEP) system. [2]. Furthermore, this amount of propellant savings is not inconsequential relative to the total vehicle mass. In Ewert, *et al.* (2017), the propellant savings due to waste removal were estimated at approximately 2.5% of the total mass of the split solar electric propulsion (SEP)/chemical system for a 1,040-day Mars mission. [1]

Various methods of waste removal have been and are being developed. This study trades some of the different methods for waste removal, which are categorized under two umbrellas: (1) physical jettison of waste and (2) trash-to-gas. Physical jettison of waste is specific to the launching of the waste, as-is, into space. The conceptual construction of such a waste removal system may consist of a combination of an airlock (e.g., the crewlock or dedicated trash-lock) and a jettison mechanism to facilitate its waste ejection at an appropriate velocity away from the spacecraft. Sepka, *et al* (2022) highlights some of the considerations for a physical jettison system including existing jettison mechanisms, airlock design, waste trajectory analysis, and a trade of different jettison system configurations. [3]

The trash-to-gas (TtG) method refers to the thermal processing of crew waste into chemically non-reactive, ventable gases. Waste is placed into a reactor to undergo thermal degradation via combustion, gasification, or pyrolysis. Depending on the chemical process, the products may vary but tend to consist of water (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and/or hydrogen (H_2). TtG technologies have previously been compared in Anthony & Hintze (2014) and Olson, *et al.* (2021) [2, 4, 5]. These methods are attractive due to their mass reduction via a potentially easier ejection method, i.e., gas venting. Additionally, because waste is being ejected as a gas, there are fewer concerns about space debris that may pose a collision risk with the spacecraft or a planet. Furthermore, although not focused on in this study, the TtG products may also be recovered as valuable commodities for reuse under a different scenario. However, unlike physical jettison where all waste is eliminated from the spacecraft, TtG converts a percentage of the solid waste into a gaseous product with some ash and/or solid residual inherently being retained, which would necessitate long-term storage or its own separate disposal system.

The objective of this work is to trade both the physical jettison and trash-to-gas methods and to understand their advantages and disadvantages. An equivalent system mass (ESM) analysis is performed to provide a metric for the overall mass, volume, power, cooling, and crew time costs associated with different physical jettison and TtG systems. The ESM may be compared in conjunction with the waste removal ability and potential propellant savings to identify favorable waste removal configurations. The results of this analysis may be used to help identify potential technology downselects as well as highlight potential areas for continued development.

II. Analysis Methodology and Assumptions

The waste removal architectures are traded by comparing their ESM, which is a type of analysis for comparing different physical quantities that are representative of a system (e.g., mass, volume, power, etc.), by converting them into a single metric. Equivalency factors, which are spacecraft specific, are used to convert physical quantities (e.g., volume, power, thermal load, and crew time) into an ESM value as shown in Equation (1).

$$\mathrm{ESM} = M + V_P E_{VP} + P_E E_{PE} + C E_C + T E_{CT} \tag{1}$$

In the equation, ESM is the equivalent system mass (kg); M is the system/subsystem mass (kg); V_P is the pressurized volume (m^3); P_E is the electrical power usage (kW_e); C is the heat load (kW_{th}); T is the crew time (CM-hr); and $E_{VP}/E_{PE}/E_C/E_{CT}$ are the volume/power/cooling/crew time equivalency factors which are provided in Table 1.

A. Mission Assumptions

This study looks at an example Mars transit mission as it represents a long duration mission with limited opportunities to easily eliminate waste without dedicated hardware. The spacecraft and its equivalency factors were based on NextSTEP contractors' and the Mars Integration Group's Mars Transit Habitat (MTH) concepts [6, 7]. Table

1 describes the pertinent spacecraft features. Note that this particular MTH concept considers a SEP/chemical system whereas there are also mission profiles based on NEP and other approaches as well. The sensitivity to the power equivalency factor is analyzed in Section III.C.1 Power Cost Sensitivity.

The mission profile assumes an opposition class mission in 2039 of 850 days in total length [8]. This represents 300 days for Earth-to-Mars transit, 50 days in Mars vicinity, and 500 days for return from Mars-to-Earth. This mission duration is similar to that of NASA's latest Moon to Mars approach. [9]

Table 1. Mars Transit Habitat Parameters [6, 10]

Parameter	NextSTEP Mars Transit Habitat
Pressurized Volume (m^3)	320 m^3
Cabin Environment	14.7 psia, 21% O_2
Number of Crewmembers (CM)	4 CM
Propulsion System	Solar Electric Propulsion / Chemical
Volume Equivalency (kg/m^3)	28
Power Technology	Photovoltaics + Batteries
Power Equivalency (kg/kW)	100
Cooling Technology	Radiators
Cooling Equivalency (kg/kW)	93
Crew Time Equivalency (kg/CM·hr)	0.802

B. Waste Model

It is important to have an appropriate waste model to accurately assess the use-case for the different waste removal technologies. The waste model utilized for this analysis is based on an 850-day waste model. Table 2 provides a breakdown of the daily waste generation rate for both the physical jettison and trash-to-gas methods. The total waste generation does differ between the two methods. This difference is due to the frequency of waste removal, which may necessitate different storage methods for a subset of the waste. Feces represents a particularly odorous waste material. In the case of the physical jettison of waste, an optimal jettison interval may range from approximately 1 – 3 weeks as shown in a prior study [3]. Therefore, feces are assumed to be stored in appropriate long-term storage containers, i.e., the alternate fecal canister (AFC). In contrast, TtG methods continuously process and vent waste; therefore, its associated waste storage time is comparatively much shorter. For TtG, feces are assumed to be contained in canister liners that are processable by the TtG system. The effect on the total waste generation rate appears to be small at a 0.08 kg/CM·day difference between physical jettison and TtG, but over 800 days of transit, the total mass and volume difference is rather appreciable at 262 kg and 1.71 m^3.

Table 2. 850-day Waste Model Waste Generation Rates

Waste Category	Waste Generation Rate (kg/CM·day)	
	Physical Jettison Waste Model [a]	Trash-to-Gas Waste Model [b]
Food Waste and Packaging	0.83	0.83
Fecal Canister/Liner and Feces	0.26	0.18
Clothing and Towels	0.32	0.32
Wipes + Gloves + Trash Bags	0.23	0.23
Hygiene + Healthcare	0.23	0.23
Urine Filters & Hoses	0.10	0.10
MAGS + Miscellaneous	0.02	0.02
Total	1.99	1.91

[a] The physical jettison waste model assumes the use of the AFC.

[b] The trash-to-gas waste model assumes the use of reusable fecal canisters and disposable canister liners.

C. Analysis Assumptions

Additional assumptions have been made to simplify the analyses of the physical jettison and TtG systems or are based on the spacecraft limitations. With regard to waste management, waste is typically compacted to improve its storage efficiency. Based on the results of a prior analysis [3], much of the study provided herein will assume a powered mechanical trash compactor being used to provide a reasonably high compaction density at a low mass, volume, and power cost. The mechanical compactor is assumed to be operated daily to reduce waste volumes.

Regarding physical jettison, waste jettison may occur from either a crewlock, which is assumed to be already existing on the MTH due to its necessity for contingency extravehicular activities (EVAs), or a dedicated trash-lock, which may be sized according to the desired jettison frequency. Ideally, the size of the trash-lock equals that of the waste volume generated over the time interval between jettison events. When utilizing a crewlock for jettison, no additional mass or volume costs are incurred since it is assumed to be already existing. In contrast, the addition of a dedicated trash-lock does incur mass and volume costs for its inclusion into the MTH. In addition to the waste that is ejected into space, there is some air loss from the airlock despite a depressurization protocol. The air loss is determined assuming a nominal depress and air-save operation to 2 psia, which is prescribed on the International Space Station (ISS), and venting of the remainder. [11]

As detailed in Sepka, *et al.* (2022) [3], dedicated trash jettison mechanisms for space are rare. However, there are deployers in use on the ISS, such as the Nanoracks Kaber deployer, that may lend itself to this type of use and is assumed for these early conceptual assessments. Using the Kaber deployer assumes consumable usage for each jettison consisting of a jettison stowage bag and flyaway piece, which is attached to and separates from the deployer with the trash payload. An additional cost associated with physical jettison is an increase in airlock spares if they are operated more frequently than the current standard. Linearly scaling airlock spares mass is assumed where nominal operation is designated as weekly actuation. This may not be wholly accurate to the real spares amount but provides some weighting on the dependence of airlock spares versus jettison frequency.

In regard to TtG, the waste processing systems considered for this study include the:

- Advanced Organic Waste Gasifier (AOWG), an oxygen-enhanced steam reforming technology ($CH_4 + H_2O \rightarrow CO + 3\ H_2$)
- Orbital Syngas Commodity Augmentation Reactor (OSCAR), which is able to operate in either a combustion ($CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$) or pyrolysis mode, i.e., OSCAR-C or OSCAR-P
- Incineration/Gasification (Inc-Gas)
- Plasma Gasification (Plas-Gas)
- Microwave-Assisted Pyrolysis (MAP)
- Plasma Pyrolysis (Plas-Pyro)

The TtG assumptions mirror those from Olson, *et al.* (2021) with updates to TtG parameters if new information has since become available [2, 5]. For the system-level mass balance which determines the inputs and outputs from the TtG system when processing the requisite amount of waste, the TtG systems were assessed as part of either a standalone or integrated system with the ECLSS. Depending on the TtG system, they may necessarily be integrated with the ECLSS. For example, the OSCAR-C is a combustion reactor meaning it requires O_2 to react with the solid waste. As a standalone system, OSCAR-C would require an exorbitant amount of consumable O_2 to be carried alongside for waste processing. However, the ECLSS including the Water Recovery System (WRS), Oxygen Generation Assembly (OGA), and Sabatier assembly may be able to work in conjunction to process H_2O, CO_2, etc. products from the TtG system to recover and recycle the necessary reactant flow. Therefore, the gasification and combustion reactor systems (i.e., OSCAR-C, Inc-Gas, and Plas-Gas) are assumed to be part of an integrated system with the ECLSS. The exception to this is the AOWG that is being developed by Pioneer Astronautics, Inc under a NASA contract. Despite this oxygen-enhanced steam reforming system requiring both O_2 and H_2O as co-reactants, it has been developed with its own internally integrated electrolyzer and methanation subsystems such that it may operate as a standalone system. Pyrolysis systems (i.e., OSCAR-P, MAP, and Plas-Pyro) are purely thermal degradation processes, which do not require any co-reactant, hence they are able to operate as standalone systems. See below for examples of the standalone and integrated TtG architectures.

In addition to the TtG system, the analysis also considers the mass, volume, and power of vacuum lines to facilitate connection of the TtG hardware with space for product gas venting. This is an added ESM cost to TtG waste processing systems akin to how an airlock is needed to facilitate a physical jettison architecture. The mass, volume, and power of the vent lines, valving, sensors, etc. are based on the ISS vacuum system.

D. Technology Overview

Figures 1 – 3 provide representative schematics for the physical jettison, standalone TtG, and integrated TtG and ECLSS architectures. These schematics are useful in depicting the complexity of the waste removal architectures. Considering physical jettison (Figure 1), this architecture relies on various connected subsystems (e.g., compactor, airlock, jettison mechanism, depress and air-save, and the interfaces). Various operational decisions concerning these subsystems and interfaces will need to be considered in the final concept and design. For example, the compactor may be designed for dual-use as a short-term trash receptacle, in which case its location in the spacecraft and number of units should be decided upon. The airlock, which may either be the contingency EVA crewlock or a dedicated trash-lock, has its own considerations. If the crewlock is being utilized, one must consider where trash will be stored in between jettisons. Furthermore, the jettison mechanism may not be a permanent fixture in case it interferes with contingency EVA operations. If a dedicated trash-lock is utilized for waste jettison, then one may also consider its dual-use as a science airlock. However, this may eliminate the use of the trash-lock as a waste storage location as well. As for the jettison mechanism, it needs to be accommodating of various payload shapes and sizes. Despite the variation in trash payload, the jettison mechanism would inevitably be required to meet a minimum launch velocity to ensure the waste maintains a safe distance from the spacecraft. Additional considerations pertaining to the physical jettison architecture include depress and air-save. As shown in Sepka, *et al.* (2022), the amount of air loss over the course of a mission can be significant depending on the specific airlock sizing [3]. Therefore, depress and air-save may be necessary to reduce gas usage. Due to the nature of the air that is being re-directed to the cabin or to storage,i.e., coming from a waste contained location, there may also be additional loads on the trace contaminant control system. Despite its simple looks, physical jettison has many design considerations and planning aspects associated with it.

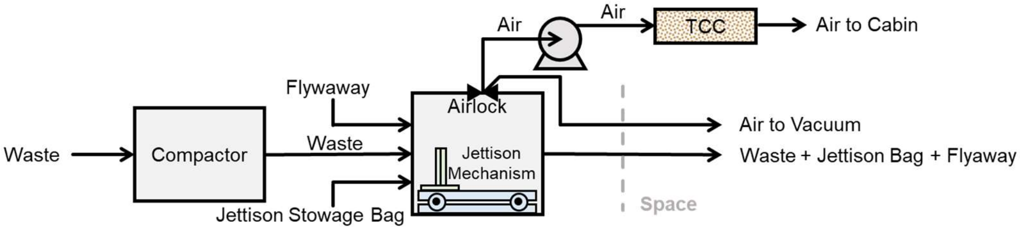

Figure 1. Physical jettison architecture schematic.

The TtG architectures (Figures 2 and 3) can vary significantly in complexity. As a standalone system, such as Plas-Pyro, the schematic appears simple. However, even the standalone system comes with its own list of considerations, including the mode of waste delivery to the reactor, batch or continuous processing, gas venting methods, and solid residual handling and management. For a flight system, it may be preferable to reduce crew interaction with the system as much as possible, so an automated system may be preferable. However, controlled delivery of a variable size and potentially multi-phase feed (i.e., liquid and solid) may present operational challenges. Similarly, the products of the chemical conversion process consist of the gaseous products as well as condensed-phase liquid (recovered as water) and solid residual material. The gaseous products are preferably vented into space; however, careful design needs to be implemented to ensure no contamination or interference with external components or fixtures on the spacecraft occur. The solid residual itself may also be substantial over the course of the mission, so its removal from the spacecraft should also be considered. The TtG conversion efficiencies may dictate preference for long-term storage or solid residual removal via jettison. This is discussed further in Section III.B.3. Solid Residual Removal.

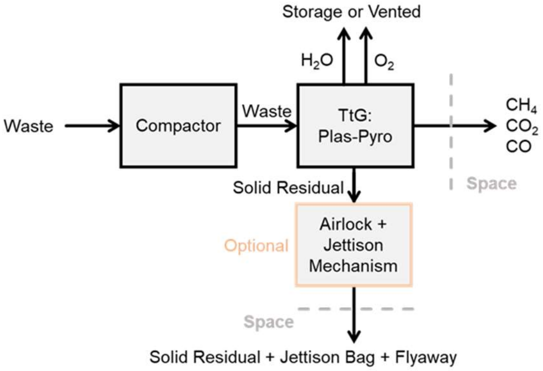

Figure 2. Example standalone trash-to-gas architecture schematic with Plas-Pyro system.

The integrated TtG and ECLSS architecture adds more complexity to the system. Additional concerns relating to TtG system and ECLSS compatibility arise. Each TtG system will produce a different product distribution, which will affect the flow rates to the WRS, OGA, and Sabatier assemblies. Furthermore, there may be additional difficulty in performing the gas separations to deliver specific TtG products to their respective downstream ECLSS. For example, a combustion reactor would generate H_2O and CO_2, which are delivered to the OGA and Sabatier assemblies, respectively. This separation is easy where H_2O may be condensed out. However, if one were to consider a pyrolysis system, which generates a wide product distribution (e.g., CH_4, H_2, and other hydrocarbon products), the gas separation becomes much more difficult. In this case, H_2 is delivered to the Sabatier assembly. However, CH_4 and other hydrocarbons should be vented, and in fact, their delivery to the Sabatier assembly would be detrimental to that system's efficiency. Integration of TtG and ECLSS would require the interconnected effects to be reassessed due to the expected imperfect separations.

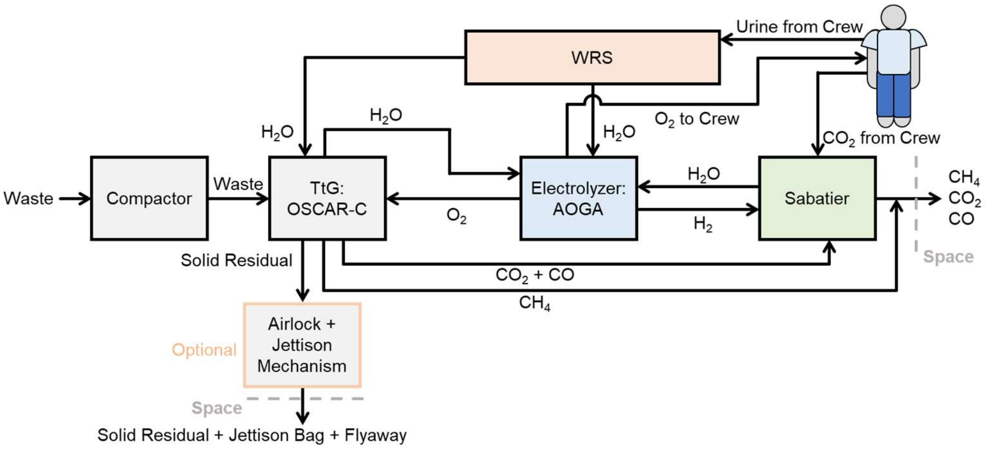

Figure 3. Example integrated trash-to-gas and ECLSS architecture schematic with OSCAR-C.

1. *Physical Jettison Technologies*

The key components of physical jettison are the compactor, airlock, jettison mechanism, and depressurization/air-save pump. The nominal configuration includes:

- Compactor: Multi-Bag Compaction System (MBCS) [11, 12]
- Airlock: Shuttle Orbiter Crewlock or Dedicated Trash-Lock
- Jettison Deployer: Nanoracks Kaber Deployer [13]
- Depressurization Pump: ISS Depressurization Pump [14]

This nominal configuration was determined from the prior physical jettison analysis that found it to be one of the more optimal mass, volume, and power configurations, albeit its ESM is dependent on the specific jettison frequency [3]. The Kaber deployer, which is an ISS microsatellite deployment system, is used as the representative jettison mechanism in that it is amenable to amorphous shapes and varying payload sizes. It does, however, utilize a flyaway piece, which may be reduced in size or eliminated for Mars missions to reduce consumable usage.

2. *Trash-to-Gas Technologies*

The key performance parameters (KPPs) for each TtG system were either measured directly or calculated from reported data. Details on the KPPs and their derivation can be found in Olson, *et al.* (2021) [5] with some updates made herein. The compiled KPPs are shown in Table 3.

A theoretical system-level mass balance that included the TtG and ECLSS was generated to determine the interconnected component flows between systems to facilitate waste conversion and gas venting. The protocol for calculating the outputs from the system-level mass balance are identical to the setup used in Olson, *et al.* (2021) [5]. The ECLSS included the WRS, which purifies water; the OGA, which electrolyzes H_2O to produce O_2 and H_2; and the Sabatier assembly, which converts CO_2 and H_2 into CH_4 and H_2O in order to improve O_2 recovery. The CH_4 product as well as the TtG products not necessary for producing the co-reactant recycle are assumed to be vented to space. The model is based on a crew of 4 that consumes 2.50 kg H_2O/CM·day and 0.84 kg O_2/CM·day and produces 1.00 kg CO_2/CM·day, 3.68 kg H_2O/CM·day (including condensate, urine, and flush), and either 1.99 kg/CM·day or 1.91 kg/CM·day of solid waste (as outlined in Section II.B. Waste Model).

The results of the system-level mass balance are shown in Table 4. The important results from the system-level mass balance are the mass flow rate of vented gas, residual solid, and water. The top half of the table reports the overall system outputs. It should be noted that all the TtG systems produced a net positive amount of water due to water recovery from the waste. However, within this analysis, it is assumed to be most desirable to eliminate mass from the spacecraft, hence excess water is assumed to be vented. The bottom half of the table shows the internal flow rates to the different ECLSS. It will be important to consider the effect of the combined TtG and crew loads on the ECLSS sizing relative to a baseline where it only needs to process crew metabolic loads.

Table 3. Trash-to-Gas Key Performance Parameters

Key Performance Parameter	**Trash-to-Gas System**						
	Gasification		**Combustion**		**Pyrolysis**		
	AOWG	**Plas-Gas**	**OSCAR-C**	**Inc-Gas**	**OSCAR-P** [a]	**MAP**	**Plas-Pyro**
Mass Reported/Scaled (kg) [b]	90 / 90	13.6 / 43	75 / 66	80 / 66	75 / 66	92 / 76	13.6 / 31
Volume Reported/Scaled (m^3) [b]	0.8 / 0.8	-- / 0.34	0.28 / 0.57	0.47 / 0.57	0.28 / 0.57	0.16 / 0.69	-- / 0.23
Power Reported (kW)	0.58	0.2	1.18	1.63	1.29	2.4	0.96 [c]
Solid-to-Gas Conversion (%)	88%	87%	89%	91%	82%	82%	74%
Outlet Concentration:							
CO from Reactor (%)	18.72%	27.79%	3.03%	6.27%	31.21%	31.21%	31.52%
CO_2 from Reactor (%)	50.96%	69.47%	96.64%	93.09%	27.31%	27.31%	38.18%
CH_4 from Reactor (%)	0.96%	2.06%	0.33%	0.64%	41.49%	41.49%	26.27%
H_2 from Reactor (%)	29.36%	0.67%	0.00%	0.00%	0.00%	0.00%	4.03%
Operating Temperature (°C)	800	400	600	600	700	700	300
TRL	5	3	4	3 - 4	--	4	3

[a] OSCAR-P parameters are based on a conceptual design with power estimated as a +50% margin of OSCAR-C's power to account for the higher temperature process. The outlet concentration is assumed to be equal to MAP due to the similar pyrolysis process.

[b] Mass and volume scaling of different systems is based on their operating temperature.

[c] Plas-Pyro power is estimated from commercial-off-the-shelf plasma incineration systems including a +50% margin.

Table 4. Trash-to-Gas System Mass Balance Results for 4 CM

Flow Rate (kg/year)	**Trash-to-Gas System**						
	Gasification		**Combustion**		**Pyrolysis**		
	AOWG [a]	**Plas-Gas**	**OSCAR-C**	**Inc-Gas**	**OSCAR-P**	**MAP**	**Plas-Pyro**
CO Output	869	887	112	238	630	630	908
CO_2 Output	1007	963	1912	1795	1173	1173	541
CH_4 Output	1070	1053	1186	1188	1030	1030	989
H_2O Output	441	459	191	215	425	425	417
Solids Output	206	231	191	156	335	335	461
H_2O to Electrolysis	--	4418	5297	5236	--	--	--
CO_2 to Sabatier	--	3678	5150	4995	--	--	--
CO to Sabatier	--	887	112	238	--	--	--
H_2 to Sabatier	--	494	589	582	--	--	--

[a] AOWG was designed by Pioneer Astronautics, Inc. as a standalone system with its own electrolyzer and Sabatier reactor.

3. *ECLSS Technologies*

The baseline parameters for the OGA and Sabatier are provided in Table 5. When integrated with the TtG, the ECLSS may need to be scaled up to process additional loads. Linear scaling of the ECLSS's mass, volume, and power was assumed. Furthermore, a spares analysis was performed for the OGA and Sabatier to account for increased maintenance and component-level turnover that would arise due to the greater load with TtG integration.

Table 5. ECLSS Technology Parameters

Parameter	Oxygen Generation Assembly	Sabatier Assembly
Consumes / Produces	H_2O / O_2, H_2	CO_2, CO, H_2 / CH_4, H_2O
Nominal / Max Production (kg/day)	5.44 / 9.25 (O_2)	1.46 / 2.47 (H_2O)
Mass (kg)	454	220
Volume (m^3)	0.49	0.21
Peak Power (kW)	4.3	0.93

III. Analysis Results and Discussion

The following sections provide the results and discussion for this analysis. The first section pertains to describing the results of the ESM analysis for physical jettison only. The following section builds up the various components that make up the TtG architecture including the TtG system, its integration with ECLSS, and handling of the solid residual. The TtG system architectures are then compared with a baseline physical jettison configuration to highlight key differences and provide initial estimates on relative favorability from a mass, volume, power, cooling, and crew time standpoint. Lastly, the sensitivity of various analysis inputs is assessed to elucidate how the trade amongst the different waste removal architectures may change with their uncertainty.

A. Jettison Only

An ESM analysis on the effect of different physical jettison configurations (e.g., different compactor, airlock, depress pump, and jettison mechanism parameters) and jettison frequency was performed to elucidate mass, volume, and power optimal configurations. This study continues the analysis, which was presented in Sepka, *et al*. (2022) [3] with updates to values and assumptions when available. Exploring different jettison configurations, the sole subsystem that resulted in a lower ESM waste removal system across all jettison frequencies was the MBCS. This compactor was designed for the Crew Exploration Vehicle for Lunar sortie mission profiles of 18 days of which 11 days are in transit and 7 days are on the Lunar surface [11, 12]. The MBCS is similar to a household compactor which utilizes a consumable compaction bag (0.1 kg every 6 days) to produce a higher density waste product.

The remaining choice of airlock and optional depress/air-save pump subsystems is dependent on the jettison frequency. The airlock options are either the EVA crewlock or a dedicated trash-lock, where the latter is sized according to the estimated waste size for the jettison interval. Table 6 displays the mass, volume, power + thermal, and crew time costs for physical jettison from different airlocks and jettison intervals. The jettison intervals are for 7 (i.e., weekly), 11, and 21 days/jettison. The 7 and 21 days/jettison represent a high and low frequency of trash jettisons, respectively. Whereas, the 11 days/jettison was determined to be the breakeven point between the crewlock and optimized trash airlock, which indicates the interval that results in nearly equal ESM between the two airlock options.

As seen in Table 6, decreasing the jettison interval for the crewlock configurations results in significantly greater gas loss and spares resulting in an increasing ESM. In contrast, because the dedicated trash-lock is sized according to the expected trash size, the gas losses are comparatively insignificant. In this case, the hardware mass and volume are most affected by the jettison interval (i.e., increasing hardware size with longer jettison interval). The hardware size varies significantly because of the need to construct the additional trash-lock. The result is that the dedicated trash-lock configurations favor shorter jettison intervals to keep the airlock size small. Thus, the trade between the crewlock and dedicated trash-lock centers around weighing the airlock gas losses from the crewlock against the additional trash-lock mass and volume costs. Another important trend to note is how much the consumables (i.e., flyaway and stowage bag) mass and volume vary with jettison interval. The flyaway and stowage bag consumables are largely a function of the total number of jettisons. With an increase from 38 to 114 total jettisons (i.e., 21 to 7 days/jettison), the consumables mass and volume increase by 51.0 kg and 0.3 m^3, respectively. As the jettison interval continues to decrease the consumable mass increases drastically due to the interval's effect on the total number of jettisons (i.e., Total Jettisons = 800 days ÷ Jettison Interval [days/jettison]). An interval of 3 days/jettison results in an increase in consumable mass and volume of 166 kg and 0.9 m^3, respectively, relative to 21 days/jettison. This observation suggests that it would be highly desirable to eliminate use of the flyaway to provide a more mass and volume optimal system, that is less dependent on the jettison frequency.

Table 6. ESM Breakdown for Different Airlocks and Jettison Frequencies (800 days of transit)

Parameter	Shuttle Crewlock			Optimized Trash Airlock		
Airlock Volume (m^3)	5.1	5.1	5.1	0.23	0.36	0.68
Jettison Interval (days/jettison)	7	11	21	7	11	21
Total Jettisons (# jettisons)	114	73	38	114	73	38
Gas Loss Mass (kg)	152.1	95.3	49.0	2.8	2.8	2.9
Consumables Mass (kg)	161.5	107.4	106.4	161.5	108.6	110.5
Hardware Mass (kg)	214.4	214.4	264.3	284.6	323.9	454.4
Spares Mass (kg)	41.0	26.1	13.7	11.8	10.2	8.2
Total Mass (kg)	569.2	443.1	433.3	460.8	445.5	575.9
Gas Loss Volume (m^3)	0.28	0.17	0.09	5.5×10^{-3}	5.5×10^{-3}	5.6×10^{-3}
Consumable Volume (m^3)	0.55	0.35	0.25	0.55	0.35	0.25
Stored Trash Volume (m^3)	0.23	0.36	0.68	0.23	0.36	0.68
Hardware Volume (m^3)	0.23	0.23	0.25	0.36	0.49	0.84
Spares Volume (m^3)	0.56	0.36	0.19	0.02	0.02	0.02
Total Volume (m^3)	1.84	1.46	1.46	1.17	1.23	1.80
Volume ESM (kg)	52.3	41.6	41.4	33.8	35.5	51.9
Power × Duty Cycle (W)	6.6	6.1	5.6	5.9	5.6	5.4
Power + Thermal ESM (kg)	1.3	1.2	1.1	1.1	1.1	1.0
Total Crew Time (hr)	59.0	47.2	38.2	59.0	47.2	38.2
Crew Time ESM (kg)	47.4	37.9	30.7	47.4	37.9	30.7
Total ESM (kg)	670.2	523.8	443.2	544.2	519.5	656.5

* All configurations from this table assume use of the MBCS and depress pump for air-save.

A benefit of using a dedicated trash-lock for jettison is the reduced gas losses. Because of its proximal sizing relative to the amount of generated waste, the gas losses are very small. Therefore, it is possible to operate a dedicated trash-lock configuration without a depress pump, saving hardware mass, volume, and power. The optimal crewlock and dedicated trash-lock configurations are shown below in Table 7. The table is specific to a 12 day per jettison interval, which is the breakeven point. A dedicated trash-lock is favorable for jettison intervals of less than 12 days/jettison, whereas the use of the EVA crewlock is favored for jettison intervals of greater than 12 days/jettison. Thus, depending on the desired or allowable trash storage duration, the choice of airlock may change. These configurations will define the baseline used to compare against different TtG architectures.

Table 7. Optimal Crewlock and Dedicated Trash-lock Configuration's ESM

Parameter	Shuttle Crewlock	Dedicated Trash-Lock
Airlock Volume (m^3)	5.1	0.39
Jettison Interval (days/jettison)	12 (breakeven)	
Depress Pump?	Yes	No
Total Mass (kg)	432.0	440.9
Volume ESM (kg)	40.4	35.7
Power + Thermal ESM (kg)	1.5	1.0
Crew Time ESM (kg)	36.5	21.5
Total ESM (kg)	510.1	499.1

B. Trash-to-Gas versus Physical Jettison

Sections 1 to 3 below provide the steps for constructing the ESM of the TtG systems including their own hardware, integrated effects, solid residual management, and waste model differences. These components are important for capturing the key features of a TtG system as well as for comparing TtG versus physical jettison on equal footing.

1. *Trash-to-Gas Only*

The first ESM component of a TtG system is its own standalone hardware. Table 8 provides the ESM breakdown of each TtG system as well as the baseline jettison configurations. From this comparison, some key discrepancies may be elucidated between the two methodologies for waste removal. One can see that the mass of the TtG systems is smaller than that of physical jettison, but there is a significantly greater power and cooling need. This observation underlies the basic principles that dictate each waste removal method's operation. For TtG, the objective is to construct a system that is able to affect chemical change of the waste to generate ventable gases. Therefore, the TtG hardware and consumables masses are smaller contribution to its ESM, but it uses significantly more power to promote solid waste to gas conversion. For physical jettison, the objective is to construct robust hardware that allows deployment of the solid waste into space as-is. Therefore, physical jettison configurations are constituted by larger mass contributions, which include the jettison mechanism, flyaway, gas losses, and additional trash-lock.

Multiple TtG systems appear to trade comparably with the physical jettison systems, such as the AOWG, Plas-Gas, and Plas-Pyro. However, there are additional considerations that need to be accounted for in the overall system ESM calculation. These include any integrated effects, as well as accounting for the incomplete solid-to-gas conversion and potential retention of solid residual for the TtG systems. Moving forward this ESM analysis will focus on a subset of the waste removal systems to reduce the number of comparisons. The TtG systems further considered are the AOWG, OSCAR-C, MAP, and Plas-Pyro, which will be compared against the dedicated trash-lock for jettison.

Table 8. ESM Breakdown of the Trash-to-Gas System Only Compared to Physical Jettison

Parameter	Trash-to-Gas							Physical Jettison	
	AOWG	**Plas-Gas**	**OSCAR-C**	**Inc-Gas**	**OSCAR-P**	**MAP**	**Plas-Pyro**	**Crewlock**	**Dedicated Trash Airlock**
Mass (kg)	289.6	227.6	258.0	258.0	258.0	271.2	211.8	432.3	442.3
Volume (m^3)	2.23	1.63	1.93	1.93	1.93	2.08	1.48	1.42	1.26
Volume ESM (kg)	63.5	46.3	54.9	54.9	54.9	59.2	42.0	40.5	35.8
Power (kW_e)	0.74	0.36	1.34	1.79	1.46	2.56	1.13	0.006	0.005
Power ESM (kg)	74.3	36.3	134.4	179.4	145.6	256.4	112.8	0.6	0.5
Cooling (kW_{th})	0.74	0.36	1.34	1.79	1.46	2.56	1.13	0.006	0.005
Cooling ESM (kg)	68.8	33.6	124.3	166.0	134.7	237.3	104.3	0.6	0.5
Crew Time (hr)	141.9	141.9	141.9	141.9	141.9	141.9	141.9	44.8	26.9
Crew Time ESM (kg)	113.8	113.8	113.8	113.8	113.8	113.8	113.8	35.8	21.5
System ESM (kg)	610.1	457.7	685.4	772.1	707.0	937.9	584.7	509.8	500.6

2. *Integrated Effect*

Certain TtG systems may be integrated with the ECLSS to allow for proper function due to the need for recycling specific co-reactants. The TtG systems that would need to integrate with the ECLSS include Plas-Gas, OSCAR-C, and Inc-Gas. Otherwise, these systems would need to supply their own co-reactant (i.e., O_2 and/or H_2O) or provide additional processing units to allow recycle. Neither of these other scenarios are considered in this work.

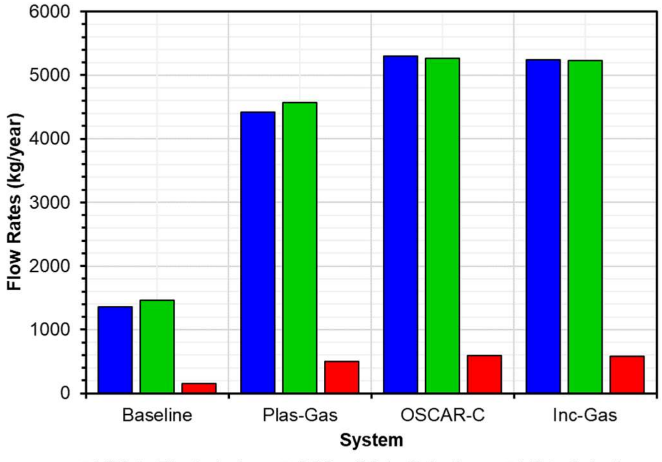

Figure 4. Integrated TtG loads on the ECLSS.

Figure 4 shows the different loads on the electrolyzer and Sabatier systems as a result TtG and ECLSS integration. The figure shows the baseline flow rates of H_2O to electrolysis, CO_2 + CO to Sabatier, and H_2 to Sabatier as well as the flow rates for the integrated systems. The baseline ECLSS OGA and Sabatier process 1,360 kg H_2O/year, and 1,460 kg CO_2/year from the crew along with the stoichiometric amount of H_2. Combustion requires

O_2 as a co-reactant and produces H_2O and CO_2. Gasification utilizes H_2O and/or O_2 co-reactants and produces CO_2, CO, and H_2. The integrated ECLSS processes the TtG products to recover their required co-reactants. As shown in the figure, integration leads to a very large increase in the flow rates to the ECLSS.

Table 9 shows the net effect of integration compared to the baseline OGA and Sabatier. The change in the mass, volume, power, and cooling of the hardware due to OGA and Sabatier scale-up to process the greater loads, and the change in the mass and volume of the spares needed due to increased duty cycles of the systems are provided. It is clear from the table that the increased load on the ECLSS due to integration results in large increases to the mass, volume, power, and cooling of the ECLSS hardware and spares. An increase in size of the OGA and Sabatier unit as well as greater power consumption are needed to account for the additional TtG loads. The increased ECLSS size coupled with the higher duty cycle results in a very marked increase in the spares items. The total integrated ECLSS effect appears to far outweigh the mass, volume, and power of the TtG hardware itself. These results suggest that TtG systems, which require integration with the ECLSS, may be infeasible.

There may be efficiency gains with TtG systems that integrate their own electrolyzer and/or Sabatier reactor. Such systems may not be limited to the same design as the ISS OGA and Sabatier assembly, which may allow for more efficient packaging of the multiple units, operation at optimal points specific to the TtG system, implementation of internal heat integration networks, and more. The AOWG is an example of a system, which contains its own electrolyzer and Sabatier reactor, that appears to trade reasonably well.

Table 9. Net Change in Mass, Volume, Power, and Cooling due to Trash-to-Gas + ECLSS Integration

Parameter	**OGA Effect**			**Sabatier Effect**			**Total Integrated Effect**		
	Plas-Gas	**OSCAR-C**	**Inc-Gas**	**Plas-Gas**	**OSCAR-C**	**Inc-Gas**	**Plas-Gas**	**OSCAR-C**	**Inc-Gas**
Hardware:									
ΔMass (kg)	31.5	76.5	73.3	110.0	149.2	146.4	141.5	225.7	219.7
ΔVolume (m^3)	0.03	0.08	0.08	0.10	0.14	0.14	0.13	0.22	0.22
ΔPower (kW)	3.2	4.2	4.1	1.3	1.7	1.7	4.5	5.9	5.8
ΔCooling (kW)	1.8	2.4	2.4	1.3	1.7	1.7	3.1	4.1	4.1
Spares:									
ΔMass (kg)	365.9	400.8	370.5	207.3	241.0	241.0	573.2	641.8	611.5
ΔVolume (m^3)	0.38	0.41	0.38	0.20	0.23	0.23	0.58	0.64	0.61

3. Solid Residual Removal

Another consideration from these TtG systems is that none of them are capable of converting 100% of the solid waste into ventable gases. Approximately 6% of solid waste is non-gasifiable ash, which limits the solid-to-gas conversion to a maximum of 94%. Depending on the type of TtG system, the amount of solid residual, which remains after reaction can vary significantly. The solid-to-gas conversion specifies how efficient each TtG system is at converting the waste. Combustion and steam reforming (e.g., OSCAR-C = 89.2% and AOWG = 88.4%) tend towards higher solid-to-gas conversions, whereas pyrolysis tends to be lower (e.g., MAP = 81.1% and Plas-Pyro = 74%).Thus, TtG systems will invariably produce solid residuals. These solids may be retained and stored or jettisoned into space.

The trade between these two options depends on the size of the solid residual versus that of a jettison system. The lower overall cost, i.e., ESM, between the storage or jettison option dictates the preferred choice.

Table 10. Comparison Between Solid Residual and Physical Jettison System ESM [a]

Parameter	**AOWG**	**OSCAR-C**	**MAP**	**Plas-Pyro**
Solid-to-Gas Conversion (%)	88.4%	89.2%	81.1%	74%
Solid Residual Mass (kg)	451.2	418.9	735.2	1011.4
Solid Residual Volume (m^3) [b]	1.50	1.40	2.45	3.37
Solid Residual ESM (kg)	**494.0**	**458.6**	**804.8**	**1107.21**
Mass per Jettison (kg/jettison)	67.7	62.8	110.3	151.7
Jettison + Flyaway ESM (kg)	**253.5**	**253.1**	**266.6**	**289.2**

[a] Jettison analysis for an 800-day transit (roundtrip); jettison interval = 120 day/jettison (i.e., 7 jettisons total); use of the crewlock, depress pump, Kaber deployer and slide table.

[b] Assume solid residual density = 300 kg/m^3

Table 10 provides a comparison between the solid residual and physical jettison system ESMs for different TtG methods. As shown in the table, the amount of solid residual remaining is a direct function of the solid-to-gas conversion. A jettison system was designed for solid residual removal assuming a long jettison interval was feasible due to the inert and sterile nature of the solids after TtG processing. The jettison system's ESM is far less variable to the different TtG methods compared to the solid residual ESM. The results of this comparison show that for the currently assessed mission duration even a relatively high solid-to-gas conversion, such as 89.2% from OSCAR-C, will still lead to an amount of solid residual (ESM = 458.6 kg) that outweighs a jettison system (ESM = 253.1 kg) designed for its removal. At these mission durations the physical jettison system for removal of the solid residual appears to always be favored.

4. *Total ESM*

The sum of the ESM components for different TtG systems as well as its comparison to physical jettison with a dedicated trash-lock is shown in Table 11. In addition to the ESM contributions due to the TtG hardware, integrated effect, and jettison system for solid residual removal, there is an additional component accounting for the different waste models. As indicated in Section II.B. Waste Model, the waste models differ in regard to how feces is stored (i.e., AFC for physical jettison and canister liner for TtG). The resultant difference in the waste model leads to a mass and volume savings for TtG relative to the physical jettison of 262 kg and 1.71 m^3 for an 800-day transit period. These savings equate to a -310.4 kg ESM applied to the TtG methods compared to the physical jettison.

Of the examined systems, the ESM of the standalone AOWG and Plas-Pyro appear to be comparable to that of physical jettison from a dedicated trash-lock. OSCAR-C is largely disfavored due to its need to integrate with the ECLSS and the large effect that has on the ESM. MAP operates using microwaves as the heating source which, in the ground unit, led to high power consumption that is detrimental to its ESM. Despite the additional complexity that the TtG systems add, the AOWG and Plas-Pyro trade reasonably well based on this analysis. The AOWG operates requiring O_2 and H_2O co-reactants to promote oxygen-enhanced steam reforming, hence it requires its own electrolyzer and Sabatier. However, its high conversion efficiency (88.4%) and optimized design appear to have led to a capable system for waste removal. In contrast, the Plas-Pyro system has only been operated at the sub-scale and is relatively low TRL (= 3). However, the ability to operate as a standalone TtG system without need to recycle, coupled with a separate jettison system for the solid residual, allows for sufficient waste removal from gas venting without detriment by its relatively low conversion efficiency (74%).

Comparatively, the physical jettison from a dedicated trash-lock system appears to be simpler in terms of operations. Its main detractors are the currently assumed consumable flyaway and stowage bag masses for each jettison and the relatively high frequency of jettisons (e.g., weekly or bi-weekly). A waste-specific jettison system is still conceptual. Therefore, various design considerations as well as optimizations could significantly alter the system mass, volume, and power in beneficial or detrimental ways.

Table 11. Sum of the ESM Components for the Different Trash-to-Gas and Physical Jettison Configurations

ESM Component (kg)	Trash-to-Gas				Physical Jettison
	AOWG	OSCAR-C	MAP	Plas-Pyro	Dedicated Trash-Lock
TtG System ESM	610.1	685.4	937.9	584.7	--
Integrated Effect ESM	--	1863.4	--	--	--
Jettison System ESM	253.5	253.1	266.6	289.2	500.6
Liner vs AFC ESM	-310.4	-310.4	-310.4	-310.4	--
Total ESM	553.2	2491.5	894.1	563.5	500.6

5. *Propellant Analysis*

In addition to the mass, volume, power, and cooling costs, it is also important to understand how these waste removal systems are beneficial in the context of the mission. The ESM focus looks at trying to design the most compact and energy efficient system, but in a larger context, the ability of the waste removal systems to perform their function also leads to marked effects on the mission. A propellant mass versus waste removal analysis was performed, which examined a 2039 Mars mission opportunity of 850-days or 1150-days in length depending on the propulsion system (i.e., NEP/chemical or SEP/chemical, respectively). Figure 5 displays how different waste removal rates from the spacecraft can lead to propellant mass savings through reduction in the overall spacecraft mass, which reduces momentum during major propulsive maneuvers. The slope of 674 kg/(kg/day) and 294 kg/(kg/day) for the

NEP/chemical and SEP/chemical cases, respectively, indicates how much propellant savings is achieved for each kilogram per day of waste removal. Removal of all the waste according to the solid waste model from this analysis (Physical Jettison = 8.0 kg/day and TtG = 7.6 kg/day) would result in 5,370 and 5,150 kg of propellant mass savings for a NEP/chemical system or 2,330 and 2,230 kg of propellant mass savings for a SEP/chemical system, which are not inconsequential. In the case of the physical jettison waste model, the mass savings account for approximately 3% and 5% of the propellant mass for the NEP/chemical and SEP/chemical systems, respectively.

In addition to choosing the lowest ESM system, it is also important to consider system robustness and performance decay of a system throughout an entire mission. TtG systems may experience decreasing solid-to-gas conversion over the course of a mission due to fouling, catalyst deactivation, etc. and may need to rely more and more on its accompanying physical jettison system to ensure complete waste removal. Furthermore, a sole physical jettison system should contain ample spares to ensure that it can be repaired and continue to operate in the case of a component failure. These are all important considerations as these technologies continue their development into more mature systems.

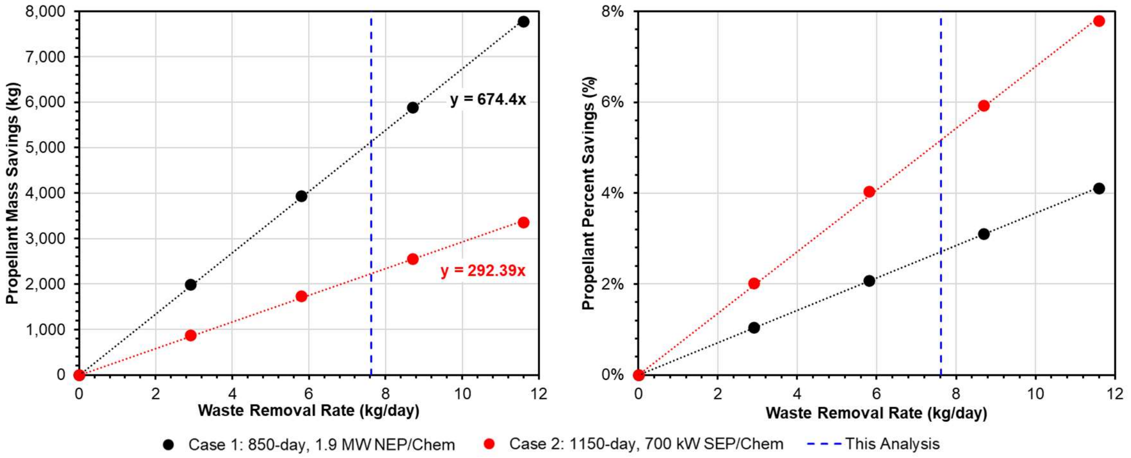

Figure 5. Propellant mass savings and percent change versus waste removal rate for an 850 and 1150-day mission with NEP/chemical or SEP/chemical systems. The dashed blue line indicates this paper's waste model assumption.

C. Input Sensitivity

This analysis has thus far examined a specific cost of power, waste model, and a solid-to-gas conversion of the TtG systems. However, the sensitivities to these inputs are also important due to the large uncertainty.

1. *Power Cost Sensitivity*

Current assessments of Mars architectures trade both nuclear and solar options for propulsion and power. Depending on the choice of power source as well as any advancements, the cost of power may change. The current power equivalency factor is based on NextSTEP contractors' concepts for a MTH, which baselined solar as the primary power system. Our designation of the power equivalency factor is based on available data from these MTH designs. However, the power equivalency factor may also be varied to simulate uncertainty in the cost of power regardless of the power system. Figure 6 plots the total ESM for the different TtG and physical jettison systems versus the power equivalency factor ($E_{PE} = 20 – 140$ kg/kW$_e$). The results from this sensitivity analysis show the TtG technologies to be more dependent on the power cost compared to physical jettison as shown by their steeper slopes. The reason for this is that TtG systems inherently require more power to affect chemical conversions of the solid waste. The power cost effect is only consequential for systems which trade comparably to begin with (e.g., AOWG, Plas-Pyro, and physical jettison).

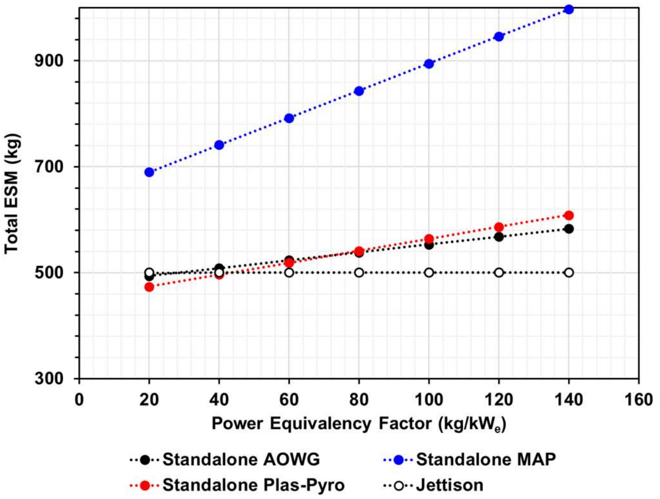

Figure 6. Sensitivity of ESM to the power equivalency factor.

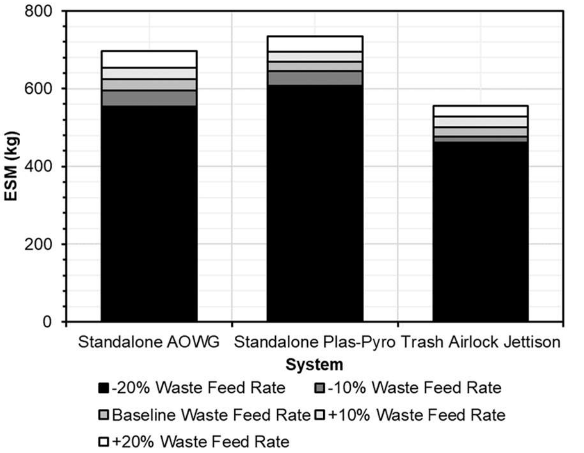

Figure 7. Sensitivity to the waste feed rate with baseline: Jettison = 1.99 kg/CM·day and TtG = 1.91 kg/CM·day.

2. Waste Generation Rate Sensitivity

Another factor which carries great uncertainty is the waste generation rate. The current waste model is based on ISS waste generation rates as well as assumptions made for Mars transit. Figure 7 shows the ESM of the AOWG, Plas-Pyro, and dedicated trash-lock systems with waste feed rates varied by ±20%. For all three systems, the ESM trends proportionally with the waste feed rate. Furthermore, the magnitude of ESM change between the systems are all nearly the same. Therefore, no specific waste removal method appears to be least invariant to the waste generation.

3. Solid-to-Gas Conversion Sensitivity

Variation in the TtG solid-to-gas conversion can arise due to differing waste compositions that are being processed, fouling of the different TtG system components (e.g., the reactor or heater), catalyst degradation, and many other reasons. The effect of variation in the solid-to-gas conversion by ±10% on the different TtG system's ESMs is shown in Figure 8. The plots show both cases where there is no physical jettison such that the solid residual from TtG is assumed to be stored long-term and where there is physical jettison to remove solid residual. Note that a maximum solid-to-gas conversion of 94% is assumed due to non-gasifiable ash. With no physical jettison, the solid-to-gas conversion has a very large effect on the overall ESM. Assuming ~7.5 kg waste/day being generated, each percent lower in conversion results in approximately 60 kg of additional solid residual that inevitably needs to be stored. In the case of a physical jettison option, the TtG systems still experience an effect of the solid-to-gas conversion albeit a much smaller one. That is because the jettison mechanism is relatively invariant to the amount of waste that it needs to remove until either the trash-lock or jettison mechanism needs to be scaled up. Plas-Pyro, which at its baseline already has a low solid-to-gas conversion (= 74%), may require scale up of its jettison mechanism since the amount of solid residual for each deployment is greater than the upper limit for the Kaber deployer. As should be evident, the trash-lock jettison system is invariant to solid-to-gas conversion since it is designed to deploy all waste into space.

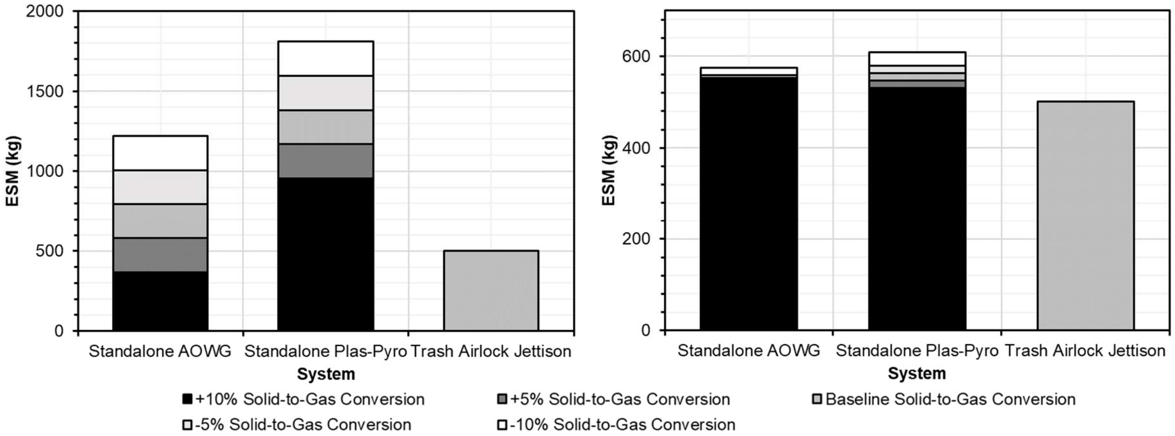

Figure 8. Sensitivity to the solid-to-gas conversion (left) without and (right) with a physical jettison system for removal of solid residuetal from the TtG systems. Baseline conversion: AOWG = 88.4% and Plas-Pyro = 74%.

IV. Conclusion

An ESM trade study analysis was performed to compare different waste removal methods (i.e., physical jettison and TtG) for a Mars Transit Habitat. This study provides the ESM analysis of a baseline physical jettison case and examines the important components that make up the mass, volume, power, and cooling costs associated with a complete TtG system. These considerations include the TtG hardware itself, any additional effects due to TtG and ECLSS integration, and consideration of solid residual management. Based on the propellant analysis, it is evident that the equivalent system mass for a well-designed physical jettison or trash-to-gas system is much less than the propellant cost of keeping unnecessary waste on board the MTH.

Key to the design of a physical jettison system is trying to utilize the available airlock space as efficiently as possible. In the case of jettison from a crewlock, longer jettison intervals are favored to reduce the gas losses that are inherent to each deployment. In contrast, utilizing a dedicated trash-lock allows greater flexibility in its design to limit gas losses by building a trash-lock specific for the jettison interval. However, this comes at the cost of the dedicated trash-lock infrastructure. Therefore, the most optimal physical jettison configuration balances the jettison interval versus either the gas loss mass for a crewlock jettison or the airlock hardware cost for a trash-lock jettison.

In contrast to physical jettison where mass considerations are important, TtG systems are more reliant on the power and cooling cost necessary to cause the chemical conversion process. From this analysis, it was found that a standalone system is preferred because integration with the ECLSS leads to an exorbitant ESM cost associated with ECLSS scale-up and spares needs. Furthermore, inherent to TtG is the solid residual that remains due to incomplete solid-to-gas conversion. This analysis indicates that for all TtG systems considered, it was beneficial to operate a backup physical jettison system for the sole purpose of removing the remaining solids after TtG processing.

From the TtG options studied, the standalone AOWG and Plas-Pyro systems appear to trade comparably to the physical jettison system. These two TtG systems along with the physical jettison system appear to be viable methods of removing waste effectively from a spacecraft. Note, however, that there are many additional considerations and gaps that should also be considered as these technologies mature. In particular, the low TRL of the assessed systems as well as the lack of understanding of the current spares and maintenance needs for these systems may lead to large uncertainty. Furthermore, as humanity works towards more sustainable space missions, the potential reuse of TtG products (e.g., O_2 and CH_4) should also be considered, especially for missions that don't have as much momentum change as the MTH. These studies are suggested future work.

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