# An Equivalent System Mass (ESM) Analysis for the Universal Waste Management System (UWMS) with and without the Torrefaction Processing Unit (TPU)

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**Equivalent System Mass (EMS) is one of the metrics commonly used in the evaluation of new systems, often performed as part of trade studies. ESM is a technique that makes it possible to reduce several physical quantities describing a system, or a subsystem, to a single parameter expressed in the units of mass. ESM has the following five components: (1) mass; (2) volume; (3) power; (4) cooling; and (5) crewtime. In this paper, results of an ESM analysis are reported for the Torrefaction Processing Unit (TPU) and the Metabolic Solid Waste Storage (MSWS), both considered in conjunction with the Universal Waste Management System (UWMS). The TPU involves sterilization of human solid waste via mild non-oxidative thermal treatment (torrefaction) to produce a stable, relatively odor-free solid product. This product can be easily stored, or recycled, and TPU operation is associated with the simultaneous water recovery from the solid waste. The TPU is designed to be compatible with the UWMS, now under development by NASA. In contrast to the TPU, the MSWS involves no waste processing, which results in the need to store large amounts of unprocessed solid waste. A stand-alone TPU could be used to treat the contents of a waste canister from the UWMS, thus allowing the waste canister to be reused, which significantly reduces the number of canisters required on board. An ESM analysis was performed for the TPU and for the MSWS, and results were compared for the case of a Mars mission and a four-person crew. Results show that the use of the TPU is associated with some advantages as compared with the MSWS, even though system design is more complex.**

## Nomenclature

| | | |
|---|---|---|
| AFR | = | Advanced Fuel Research, Inc. |
| ALS | = | Advanced Life Support |
| $C$ | = | Cooling power requirement (kW) |
| $CT$ | = | Crewtime |
| CDRA | = | Carbon Dioxide Removal Assembly |
| ESM | = | Equivalent System Mass (kg) |
| $ESM_{CT}$ | = | Crewtime ESM for the entire LSS (kg) |
| $ESM_{MSWS}$ | = | ESM for the Metabolic Solid Waste Storage (kg) |

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| | | |
|---|---|---|
| $ESM_{NCT}$ | = | Non-crewtime ESM for the entire LSS (kg) |
| $ESM_{TOTAL}$ | = | ESM of the entire LSS (kg) |
| $ESM_{TPU}$ | = | ESM for the Torrefaction Processing Unit (kg) |
| HMC | = | Heat Melt Compactor |
| ISRU | = | In-Situ Resource Utilization |
| ISS | = | International Space Station |
| LSS | = | Life Support System |
| $M$ | = | Mass (kg) |
| MSWS | = | Metabolic Solid Waste Storage |
| $n$ | = | Number of canister duty cycles per mission |
| $N$ | = | Number of subsystems |
| $P$ | = | Power requirement (kW) |
| PPE | = | Personal protective equipment |
| $t$ | = | Crewtime (h) or (hours per person-week) |
| $t_{LSS}$ | = | Time spent in maintenance and repair of the LSS (h) |
| $t_{mission}$ | = | Time that the crew spends doing useful, mission-related work (h) |
| $t_{work}$ | = | Total crew time that is available to perform work (h) |
| TC | = | Trace contaminant |
| TCCS | = | Trace contaminant control system |
| TPU | = | Torrefaction Processing Unit |
| UWMS | = | Universal Waste Management System |
| $V$ | = | Volume |
| WPA | = | Water Processor Assembly |
| $\gamma$ | = | Mass equivalency factors for volume (V), power (P), cooling (C), and crewtime (CT) |
| $\tau_{cycle}$ | = | Single canister duty cycle (h) |
| $\tau_{mission}$ | = | Mars-mission duration (days) |

## I. Introduction

NEW technology is needed for the collection, stabilization, recovery of useful materials, and for the storage of metabolic and other solid waste in long duration missions. The important considerations include crew safety, comfort, and resource requirements, along with planetary protection.[1–5] This paper addresses the comparative Equivalent System Mass (ESM) analysis of two approaches to on-board solid waste management, both working in conjunction with the Universal Waste Management System (UWMS)[6] under development by NASA: (1) Metabolic Solid Waste Storage (MSWS); and (2) the Torrefaction Processing Unit (TPU), under development at Advanced Fuel Research, Inc. (AFR).[7–9] The above concepts are illustrated schematically in Figure 1.

The first option, shown in Figure 1a, involves the storage of bagged fecal matter in storage containers without any processing other than the addition of activated carbon for odor control and sealing the containers to avoid habitat contamination. The advantage of this UWMS/MSWS assembly is its simplicity, but the storage of the unprocessed fecal matter may pose health hazards, and it requires a large number of storage containers. The torrefaction (mild pyrolysis) processing system, shown in Figure 1b, can be used to sterilize and stabilize feces and related cellulosic biomass wastes (food, paper, wipes, and cotton clothing), and to produce a stable char residue that can be more easily stored or recycled, while simultaneously recovering all of the moisture and producing small amounts of gases. Some volume reduction is also possible. Torrefaction is usually defined as thermal treatment done in the absence of air at temperatures between 200 °C and 300 °C. As shown in Figure 1b, the torrefaction condensibles that leave the TPU are sent to the Water Processor Assembly (WPA) to extract water, whereas the char (solid residue) could be sent to the Heat Melt Compactor to blend with plastic and make radiation shielding disks, among other uses (e.g., activated carbon, construction material). The small amount of gas (mainly $CO_2$) that is produced by torrefaction can be sent to the Carbon Dioxide Removal Assembly (CDRA) and to a trace-contaminant control unit to remove carbon monoxide, hydrogen sulfide, carbonyl sulfide, etc.

Previous NASA sponsored work[7,8] demonstrated that torrefaction processing was effective for a fecal simulant using bench-scale experiments, with both microwave and conventional heating. In subsequent work, the process was operated at full scale for realistic samples (canine and human feces).[9] Since sufficient full-scale operational data are already available, a comparison of the TPU and the MSWS systems can now be performed. The objective of this study was to determine the ESM for both technologies for conditions relevant to the Mars mission.

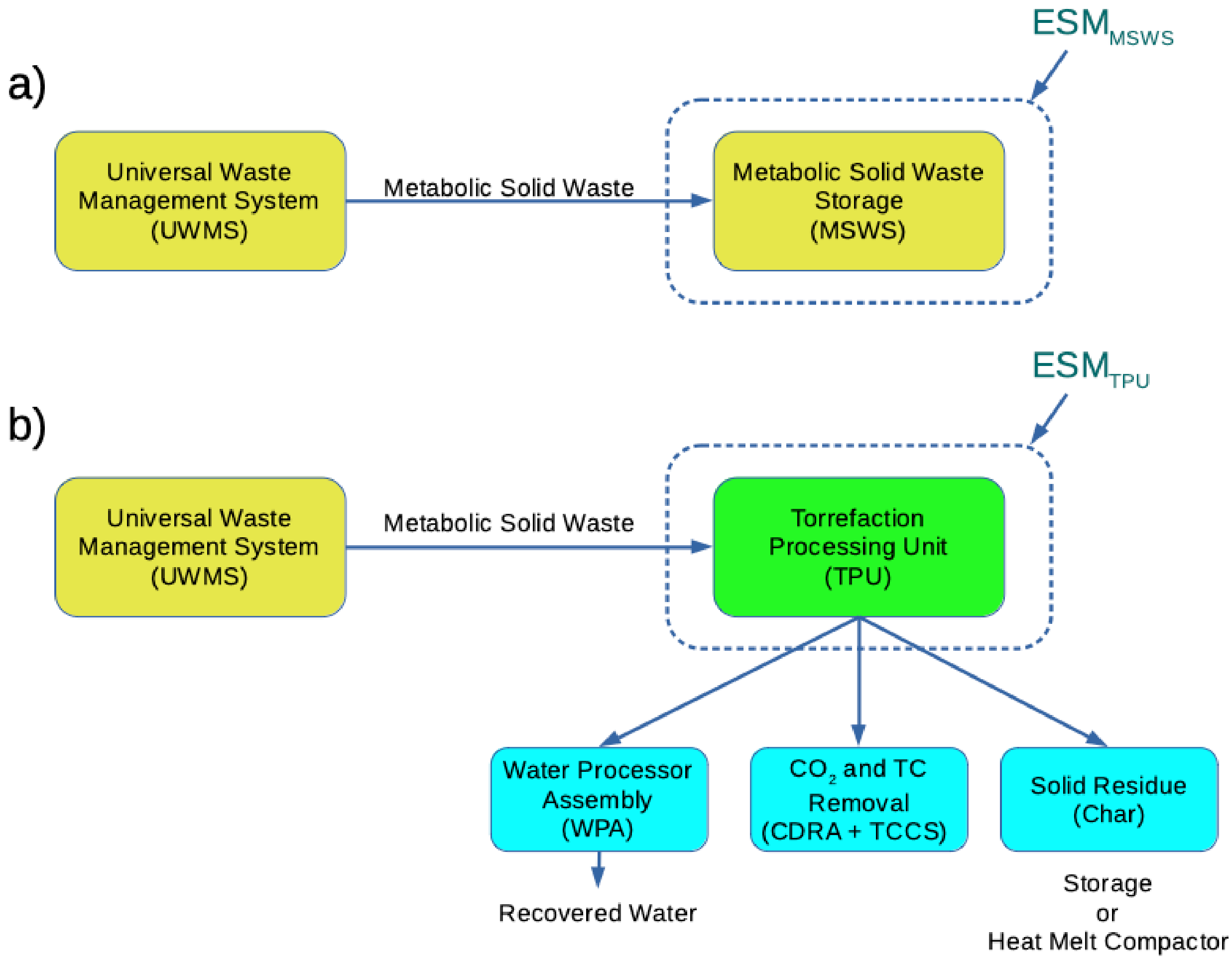


**Figure 1. Two configurations of the Universal Waste Management System (UWMS): (a) with Metabolic Solid Waste Storage (MSWS); and (b) with the Torrefaction Processing Unit (TPU). The sub-systems for which ESM calculations are performed are marked with dashed lines.**

## II. Approach and Assumptions

### A. Approach

ESM is one of the metrics commonly used in the evaluation of new systems, often performed as part of trade studies.[10] ESM makes it possible to reduce several physical quantities describing a system, or a subsystem, to a single parameter expressed in the units of mass (usually kilograms). ESM has the following five components:[10–12] (1) mass; (2) volume; (3) power; (4) cooling; and (5) crewtime. Conversion of non-mass quantities (2)–(5) to their mass equivalents is accomplished through the use of the appropriate conversion factors, which are generally mission-dependent. Thus, the ESM equation for a system composed of $N$ subsystems can be expressed as follows:[10,11]

$$ESM = \sum_{i=1}^{i=N} \left( M_i + \gamma_V V_i + \gamma_P P_i + \gamma_C C_i + \gamma_{CT} t_i \right) \quad (1)$$

where $i$ denotes the specific subsystem, $M$ is mass (kg), $V$ is volume (m$^3$), $P$ is power (kW), $C$ is the cooling power requirement (kW), and $t$ is the crewtime expressed in the units of time (or time per person-week). $\gamma_V$, $\gamma_P$, $\gamma_C$, and $\gamma_{CT}$, are the mass equivalency factors for volume, power, cooling, and crewtime, respectively. Their units are consistent with the ESM components being expressed in kilograms.

It was pointed out by Levri *et al.*[10,11] that, in addition to the above five ESM components, factors such as system functionality, reliability, safety, and crew health should be taken into consideration while comparing alternative systems or subsystems. Such factors are often difficult to quantify in terms of ESM components, however, especially where subsystems are still at a developmental stage, like the TPU and the MSWS. In such cases, it is recommended that a qualitative discussion of reliability and safety issues be provided in addition to the rigorous, quantitative ESM analysis.[10] This kind of discussion can be found in sections III and IV for the TPU and MSWS technology options.

The values of equivalency factors $\gamma_V$, $\gamma_P$, and $\gamma_C$ are considered to be constant for a given mission, whereas two approaches have been used for the evaluation of the crewtime equivalency factor, $\gamma_{CT}$.[5] In the first one, every hour of crewtime is deemed equally valuable, which means that the crewtime equivalency factor, $\gamma_{CT}$, is constant, just like the other equivalency factors. According to Anderson *et al.*,[5] this approach is recommended for general use. The second approach, originally proposed by Levri *et al.*,[11] is based on the assumption that each additional hour of crewtime that is devoted to the maintenance of the Life Support System (LSS) is associated with a larger crewtime mass penalty than the previous hours. In this way, the crewtime equivalency factor, $\gamma_{CT}$, is not constant for a given mission, and it depends on the non-crewtime ESM components (mass, volume, power, and cooling), as well as on the fraction of the total crewtime that is devoted to LSS maintenance and operation. In this work, both methodologies were used, as described below. They are referred to as the cases of constant and variable crewtime equivalency factors. Depending on the mission character, either the constant or variable crewtime equivalency approach may be deemed more appropriate. For example, if the main objective is to "plant a flag," i.e. to prove the feasibility of a voyage, survival, etc., then using crewtime for LSS is not a waste, and the constant crewtime equivalency method is suitable. Otherwise, i.e. when the mission is primarily scientific in nature, crewtime is precious and life-support time should be minimized (the variable crewtime equivalency method).

Furthermore, the ESM crewtime component, $ESM_{CT}$, can be evaluated for two kinds of LSS technologies: (1) an older generation technology, similar to the one used on the International Space Station (ISS); and (2) a newer generation technology, which uses the Advanced Life Support (ALS). The latter case is more relevant to future Mars missions, and ESM calculations for this case produce lower values of the $ESM_{CT}$. The ESM analysis presented in this paper includes both above scenarios, which are referred to as ISS and ALS technologies.

*1. Constant Crewtime Equivalency Factor*

The ESM is calculated using Eq. (1), and the equivalency factors $\gamma_V$, $\gamma_P$, $\gamma_C$, and $\gamma_{CT}$ that are relevant to the Mars mission are shown in Table 1.[5]

**Table 1. Mission-to-Mars Infrastructure Equivalences (Anderson et al., 2018)**[5]

| *Mission/Segment* | $\gamma_V$ *Volume* (kg/m$^3$) | $\gamma_P$ *Power* (kg/kW) | $\gamma_C$ *Cooling* (kg/kW) | $\gamma_{CT}$ *Crewtime* (kg/p-h) |
|---|---|---|---|---|
| Mars mission | 13.40 | 87 | 146 | |
| -- ISS technology | | | | 0.957 |
| -- ALS technology | | | | 0.465 |

*2. Variable Crewtime Equivalency Factor*

Levri *et al.*[11] provide a procedure for ESM calculations that takes into account the fact that $ESM_{CT,i}$, the crew-time component of the ESM for a specific subsystem *i* (e.g., i = TPU or MSWS), depends on the non-crew time components of the entire LSS envisaged for a specific mission, $ESM_{NCT}$. Data for the Mars-mission LSS, which are relevant to the present calculations, are compiled in Table 2 and Table 3. In addition to the above dependence, the $ESM_{CT,i}$ calculation also takes into account the time that is spent on the maintenance and operation of the LSS, $t_{LSS}$, which is a parasitic component of the total crew time that is available to perform work, $t_{work}$. For Mars missions, it is assumed that $t_{work}$ is equal 66 hours per person-week (Drysdale *et al.*[13]). The description of the ESM computational procedure is given below (after Levri *et al.*[11]).

**Table 2. Mass, volume, power, cooling, and crew time for Mars missions (ISS Technology; 6-person crew); adapted from Drysdale *et al*. (1999).[12]**

| | **Mass** (kg) | **Volume** ($m^3$) | **Power** (kW) | **Cooling** (kW) | **Crewtime** (p-h) | **Crewtime** (h/p-week) | **ESM** (kg) |
|---|---|---|---|---|---|---|---|
| Air | 1,936 | | 11.7 | 11.7 | 37.48 | 0.273 | 4,698 |
| Cabin | 1,372 | 600 | | | | | 9,412 |
| Clothes | 16,128 | | | | | | 16,128 |
| Food | 22,522 | | 7.25 | 7.3 | | | 24,211 |
| Waste | 1,866 | 10 | 0.32 | 0.32 | 236.71 | 1.726 | 2,301 |
| Water | 7,516 | 6.53 | 1.89 | 1.89 | 78.9 | 0.575 | 8,119 |
| ESM (kg) | 51,340 | 8,262 | 1,841 | 3,089 | 338 | | 64,870 |

**Table 3. Mass, volume, power, cooling, and crew time for Mars missions (ALS Technology; 6-person crew); adapted from Drysdale *et al*. (1999).[12]**

| | **Mass** (kg) | **Volume** ($m^3$) | **Power** (kW) | **Cooling** (kW) | **Crewtime** (p-h) | **Crewtime** (h/p-week) | **ESM** (kg) |
|---|---|---|---|---|---|---|---|
| Air | 2,087 | 9.8 | 10.233 | 10.233 | 24.17 | 0.176 | 4,614 |
| Cabin | 1,408 | 600 | | | | | 9,448 |
| Clothes | 3,490 | 2.56 | 0.93 | 0.93 | | | 3,741 |
| Food | 21,349 | 20.44 | 1.95 | 1.95 | | | 22,077 |
| Waste | 1,084 | 11.68 | 2.385 | 2.385 | 152.6 | 1.113 | 1,867 |
| Water | 3,296 | 8.94 | 6.966 | 6.966 | 50.9 | 0.371 | 5,063 |
| ESM (kg) | 32,714 | 8,756 | 1,954 | 3,280 | 106 | | 46,810 |

The ESM components are defined in the following equations:

$$ESM_{TOTAL} = ESM_{NCT} + ESM_{CT} \quad (2)$$

$$ESM_{NCT,i} = M_i + \gamma_V V_i + \gamma_P P_i + \gamma_C C_i \quad (3)$$

$$ESM_{NCT} = \sum ESM_{NCT,i} \quad (4)$$

$$ESM_{CT} = \sum ESM_{CT,i} \quad (5)$$

$$ESM_{CT,i} = \gamma_{CT} t_{LSS,i} \quad (6)$$

where

$ESM_{TOTAL}$ - ESM of the entire LSS (kg)
$ESM_{NCT}$ - non-crewtime ESM for the entire LSS (kg)
$ESM_{CT}$ - crewtime ESM for the entire LSS (kg)
$ESMN_{CT,i}$ - non-crewtime ESM for subsystem *i* (kg)
$ESM_{CT,i}$ - crew-time ESM for subsystem i (kg)
$t_{LSS,i}$ - crew time required to support subsystem *i* (h/person-week)
$\gamma_{CT}$ - crew-time conversion factor [kg/(h/person-week)]
$\gamma_V$, $\gamma_P$, and $\gamma_C$ - as in Eq. (1).

The analysis presented here will make it possible to compare two subsystems (*i*) of interest: the TPU and the MSWS.

It should be noted that in this approach, the crew-time conversion factor, $\gamma_{CT}$, is not constant. It depends on the other ESM components (mass, volume, power, and cooling), and also on the fraction of the available crew time devoted to the maintenance and operation of the LSS, as will be shown quantitatively below.

The time spent in maintenance and repair of the LSS, $t_{LSS}$, must be subtracted from the total work time available, $t_{work}$, to yield the total amount of time that the crew spends doing useful, mission-related work, $t_{mission}$. This relationship is shown in Eq. (7) and (8):

$$t_{mission} = t_{work} - t_{LSS} \tag{7}$$

$$t_{LSS} = \sum t_{LSS,i} \tag{8}$$

For a mission to Mars, the following values can be assumed:[13]

$t_{work}$ = 66 (h/person-week)

$t_{LSS}$ = 3.93 (h/person-week)

Time occupied in operation and maintenance of the LSS takes away from time for useful work, and the crew size, and its associated LSS, i.e. also ESM, would need to be increased to accomplish mission goals. For example, if three-fourths of the crew's available work were consumed by the LSS, four identical systems and crews would need to be sent in order to accomplish the goals of the mission, thus quadrupling the ESM. Therefore, the total ESM of the system is the ESM for mass, volume, power, and cooling, multiplied by the ratio of work hours available to perform useful work. This can be expressed mathematically as follows:

$$ESM_{TOTAL} = ESM_{NCT}\left(\frac{t_{work}}{t_{mission}}\right) \tag{9}$$

Combining Eq. (2) with Eq. (9) yields:

$$ESM_{CT} = ESM_{NCT}\left(\frac{t_{work}}{t_{mission}} - 1\right) \tag{10}$$

The crewtime conversion factor can now be obtained by combining Eq. (5), (6), and (8):

$$\gamma_{CT} = \frac{ESM_{CT}}{t_{LSS}} \tag{11}$$

$ESM_{NCT,i}$ and $ESM_{CT,i}$ can be calculated from Eq. (3) and (6), respectively, and the total ESM that may be attributed to subsystem *i*, $ESM_i$, is given by the following expression:

$$ESM_i = ESM_{NCT,i} + ESM_{CT,i} \tag{12}$$

Alternatively, $\gamma_{CT}$ can be calculated from the following relation, which results from combining Eq. (7), (10), and (11):

$$\gamma_{CT} = \frac{ESM_{NCT}}{t_{mission}} \tag{13}$$

An algorithm for computing the ESM associated with a subsystem is given below.

1. Select a baseline mission, e.g., Mars mission.
2. Obtain the data on mass, volume, power, cooling, and $t_{LSS}$ for each of the subsystems in the baseline LSS. Calculate the $ESM_{NCT}$ of the baseline LSS without the subsystem that the new, proposed subsystem would replace. The relevant data for Mars missions are given in Table 2 and Table 3.

3. Calculate $ESM_{NCT,i}$ for the subsystem of interest from Eq. (3). Also, calculate $ESM_{NCT}$ for the total LSS with the subsystem of interest using Eq. (4).
4. Use Eq. (8) to determine the total $t_{LSS}$ for the LSS with the subsystem of interest substitution.
5. Use Eq. (7) to calculate $t_{mission}$ for the LSS with the subsystem of interest substitution.
6. Use Eq. (10) to calculate $ESM_{CT}$ for the entire LSS with the subsystem of interest substitution.
7. Calculate $\gamma_{CT}$ for the LSS with the subsystem of interest substitution. Use Eq. (11) or Eq. (13).
8. Calculate $ESM_{CT,i}$ using Eq. (6).
9. Add $ESM_{NCT,i}$ from step 3 to $ESM_{CT,i}$ from step 8 to obtain $ESM_i$.

## B. Assumptions

*1. General*

- The Mars-mission duration:
  $\tau_{mission}$ = [Mars transit (2 x 180 days)] + [Mars surface habitat (600 days)] = 960 days = 2.63 years =
  = 137 weeks = 23,040 days
  For the sake of simplicity, no distinction was made between Mars transit and Mars surface habitat for the purpose of ESM calculations.
- Crew size: 4 persons
- Solid metabolic waste collection: semipermeable bags (0.150 kg per bag) placed in canisters (20 bags per canister)
- Metabolic solid waste generation: (4 persons) x (1.5 defecation/person/day) x (0.150 kg/defecation) = 0.900 kg/day
- Single canister duty cycle (waste generation and collection, canister loading, waste processing/storage, etc.):

$$\tau_{cycle} = \frac{20\,bags}{\#\text{ of persons} \times 1.5\,\dfrac{bags}{person\,day}} = 3.33\,days = 80\,h$$

- Number of canister duty cycles per mission: $n = \tau_{mission}/\tau_{cycle} = 288$
- Weight of (wet) metabolic solid waste in a canister: (20 bags) x (0.150 kg/bag) = 3.00 kg
- Weight of other material in a canister (personal protective equipment, PPE, latex gloves, dry and wet wipes, etc.): 0.821 kg

*2. Torrefaction Processing Unit (TPU) versus Metabolic Solid Waste Storage (MSWS)*

ESM components calculated for the TPU and the MSWS scenarios are shown in Table 4, and the values in the table were determined either by measurement or on the basis of assumptions. Some of the underlying premises are listed below.

**Table 4. ESM components (mass, volume, power, cooling, and crew time) for the TPU and MSWS technology options.**

| ESM Component | TPU | MSWS |
|---|---|---|
| Mass, *M* (kg) | 289 | 936 |
| Volume, *V* ($m^3$) | 0.492 | 4.17 |
| (Peak) Power, *P* (kW) | 1.20 | 0.00 |
| Cooling Power Requirement, *C* (kW) | 1.20 | 0.00 |
| Crewtime per mission, *t* (h) | 144 | 72 |
| Crewtime per mission, *t* (hours per person-week) | 1.05 | 0.525 |

- For the TPU, two stainless steel reaction vessels are envisioned: one needed for torrefaction processing, the other one for the collection of metabolic solid waste. The reactors are used interchangeably in a swing fashion. Each reactor vessel weighs 5.603 kg, and there are also additional parts included in the TPU system mass: a stainless steel reactor lid (4.415 kg); a lightweight lid for the vessel used for waste collection (0.500 kg); an aluminum thermal bridge for improved heat transfer (1.112 kg); heaters (0.400 kg); insulation (0.317 kg); a temperature controller (1.000 kg); a condenser (2.000 kg); a trace contaminant control system, TCCS (2.000 kg); 300 teflon bags and ties for torrefied waste storage (16.530 kg), these bags also acting as reactor liners; personal protective equipment, PPE, latex gloves, wipes, semi-permeable fecal bags, etc. (246 kg); and a TPU supporting structure (3.000 kg). Although estimated allowances are made above for the condenser and the TCCS within the TPU, it should be noted that a condenser and a TCCS already in existence in other spacecraft systems may be used synergistically instead. In the case of the MSWS, 300 canisters (0.800 kg each) and 300 canister lids (0.500 kg each) need to be brought from Earth. In addition, activated carbon will be needed in the amount of 1.0 kg/canister to be placed under the lid of each storage canister for odor control and gas/liquid adsorption. The weight of PPE, latex gloves, wipes, semi-permeable fecal bags, etc. (246 kg) is also included in the MSWS mass.

- For the TPU, the system volume includes: the torrefaction-assembly volume (0.136 $m^3$), which includes one reactor, condenser, temperature controller, TCCS, etc.; the volume of an additional reactor, which serves as a waste-collection vessel (0.0179 $m^3$); the volume of 300 torrefaction residue storage bags (0.0922 $m^3$); and the volume of PPE, latex gloves, wipes, semi-permeable fecal bags, etc. (0.246 $m^3$). In the case of the MSWS, the volume of all canisters is 300 x 0.0139 = 4.17 $m^3$. The volume of the activated carbon, PPE, latex gloves, etc. is excluded as these items can be stored inside the canisters prior to use.
- The peak power of the TPU heaters is 1.20 kW, and this value is used in the ESM calculations, even though the actual power consumption is much lower. Also, the cooling power requirement is assumed to be equal to the power demand. Both above assumptions are consistent with the recommendations discussed by Levri *et al.*[11] There are no power and cooling requirements for the case of the MSWS.
- The estimated crewtime demand for TPU start-up and operation is 15 minutes per canister duty cycle, and another 15 minutes for canister unloading and handling. In the case of the MSWS, the total crewtime demand is assumed to be a factor of two lower at 15 minutes per canister duty cycle.
- For both the TPU and MSWS scenarios, the mass and volume of metabolic solid waste is excluded from EMS calculations as this material is accounted for elsewhere in the form of food that needs to be brought from Earth.

## III. Results and Discussion

### A. ESM Calculations for the Case of the Constant Crewtime Equivalency Factor, $\gamma_{CT}$

Eq. (1) was used with data presented in Table 1 and Table 4 to calculate the ESM for the TPU and MSWS, and results are summarized in Figure 2. It can be seen that the ESM for the MSWS system is 48% and 59%% higher than in the case of the TPU scenario for the older (ISS) and newer (ALS) LSS technology, respectively. Furthermore, the metabolic solid waste contains a lot of water, typically ~73 wt%, and the recovery of this water is a great advantage of the TPU over the MSWS. This advantage has not been reflected in the EMS calculations as yet. It could be argued that an ESM credit for the recovered water could be legitimately claimed in the case of the TPU because less water would have to be brought from Earth if large quantities of water are re-utilized thanks to the TPU. The amount of such a credit can easily be evaluated as discussed below.

Assuming that the amount of water in the metabolic solid waste is 73.2 wt%, the mass of water that could be recovered from a single canister is 0.732 x (20 bags) x (0.150 kg/bag) = 2.196 kg. Multiplying this weight by the number of canister duty cycles in the entire mission, which is 288, one finds the total amount of water recovered during the Mars mission to be 632.4 kg. This water occupies the volume of (632.4 kg)/(998 kg/$m^3$) = 0.6337 $m^3$, and the corresponding $ESM_{V,TPU,credit}$ can now be evaluated by multiplying the above volume of water by the volume equivalency factor from Table 1 ($\gamma_V$ = 13.40 kg/$m^3$). Thus, the total ESM credit for water recovery from the TPU is (632.4 kg) + (13.40 kg/$m^3$) x (0.6337 $m^3$) = 641 kg. It can be seen that applying the above ESM credit to $ESM_{TPU}$ data in Figure 2 would reduce ESM to 1 kg and 72 kg for the ALS and ISS technologies, respectively. Although it is unclear at this time what percentage of the water present in the metabolic solid waste can be usefully recovered, it is fair to conclude that the ESM calculations presented above show a tremendous potential for the TPU as an alternative to the MSWS. This is true regardless of whether water recovery is to be implemented or not.

In addition to the lower ESM, and the ability to recover large amounts of water, the torrefaction-based system (TPU) has the advantage over the UWMS in terms of two considerations that are not reflected in the results of ESM calculations. First, the use of the TPU is associated with thermal sterilization and stabilization of the waste, as well as with the significant odor reduction. This has obvious benefits for crew's health and safety, as compared with the storage of unprocessed metabolic waste in the case of the UWMS/MSWS scenario. Second, there is some volume reduction that is associated with the torrefaction process. This means that the solid residue from the TPU will not only be safer to store, but it will take less valuable space on board spacecraft and in the Mars surface habitat.

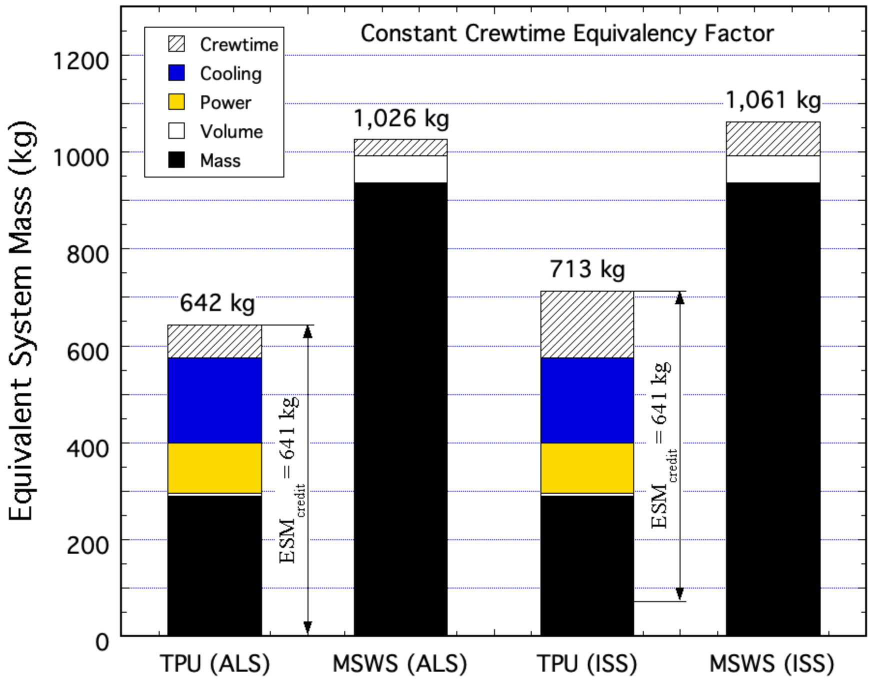


**Figure 2. The ESM and its components for the TPU and for the MSWS calculated for constant crewtime equivalency factors. The calculations were performed for the cases involving ISS and ALS technologies using data from Table 1 and Table 4.**

Data in Figure 2 show that the ESM for the MSWS is dominated by system mass (88%-91%), whereas system mass accounts for only 41%-45% of the total ESM in the case of the TPU. The crewtime component is more important in the TPU system as compared with the MSWS (10%-19% versus 3.3%-6.5% of the total ESM, respectively). The power and cooling components are sizable contributors to the ESM in the case of the TPU (15%-16% and 25%-27%, respectively), and they are zero for the case of MSWS. Finally, the ESM volume component is small in comparison to other components for both the TPU and the MSWS ( ~1% and ~5% of the total ESM, respectively).

**B. ESM Calculations for the Case of the Variable Crewtime Equivalency Factor, $\gamma_{CT}$**

The methodology discussed in section II.A.2 was used to determine the ESM for the case where the increasing amount of crewtime devoted to the maintenance of the LSS is assumed to be associated with an increasing crewtime mass penalty. This means that the crewtime equivalency factor, $\gamma_{CT}$, depends on both the non-crewtime ESM components (mass, volume, power, and cooling) and the fraction of the available crew time that is devoted to the maintenance and operation of the LSS; see, for example, Eq. (7) and (13). Results of computations are shown in Figure 3.

It can be seen that the results are very different from those for the constant crewtime equivalency factor (shown in Figure 2). The ESM values are now quite similar for the TPU and the MSWS, for both the ISS and ALS technologies, and they are all higher than the ESM shown in Figure 2. The overall ESM went up more for the TPU than for the MSWS mainly because the former system has a larger crewtime component, and the variable crewtime equivalency approach tends to penalize systems with higher crewtime more than systems with lower crewtime. If the credit for water recovery is taken into account, however, the TPU option looks much more attractive than the MSWS, with the corrected values of the overall $ESM_{TPU}$ at 684 kg (ALS) and 975 kg (ISS).

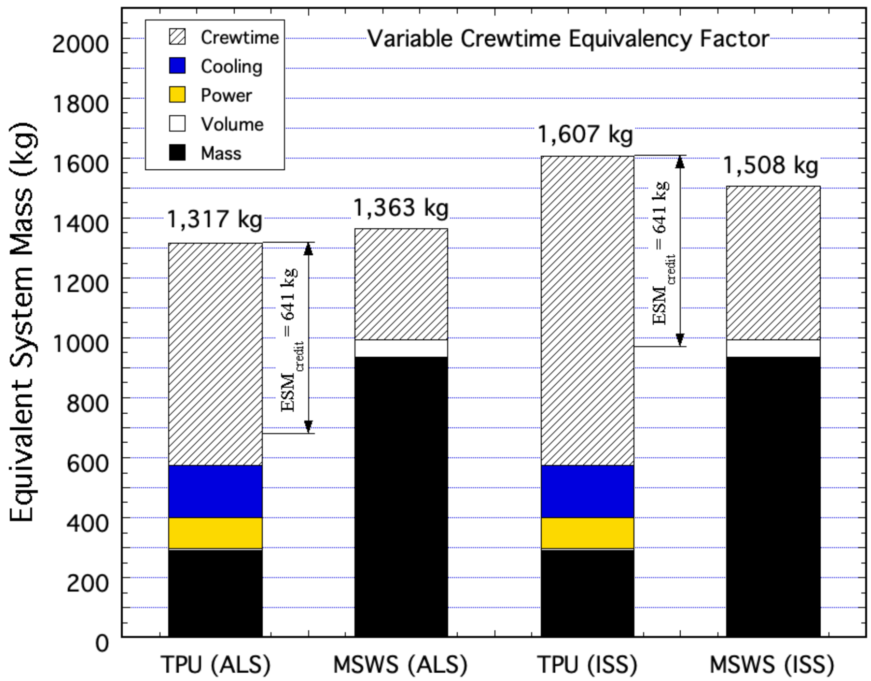


**Figure 3. The ESM and its components for the TPU and for the MSWS calculated for the variable crewtime equivalency factor. The calculations were performed for the cases involving ISS and ALS technologies using Eq. (1) through (13) and data from Table 1 through Table 4. The ESM credit for water recovery is marked for the TPU.**

The breakdown of ESM component contribution to ESM is as follows:

TPU (ALS): 21.9% mass, 0.5% volume, 7.9% power, 13.3% cooling, and 56.3% crewtime
TPU (ISS): 18.0% mass, 0.4% volume, 6.5% power, 10.9% cooling, and 64.2% crewtime
MSWS (ALS): 68.7% mass, 4.1% volume, and 27.2% crewtime
MSWS (ALS): 62.1% mass, 3.7% volume, and 34.2% crewtime

Clearly, ESM is dominated by crewtime for the TPU, and by mass for the MSWS.

## IV. Conclusions

The comparison between the TPU and MSWS systems was carried out for the Mars mission using two LSS technologies: the previous generation life support similar to the one used on the ISS, and an advanced life-support technology (ALS), which is more likely to be used in future missions. ESM calculations were performed using two different methods. One involves the use of a fixed crewtime equivalency factor, whereas the other is associated with a crewtime equivalency factor that depends on the non-crewtime ESM components, and also on the amount of time devoted to the maintenance and operation of the LSS. The conclusions are summarized below.

- The use of the TPU is associated with some advantages as compared with the MSWS, even though system design is more complex for the TPU.
- Results of ESM calculations differ, depending on which computational methodology is used, and also on the kind of LSS considered. The ISS-based technology gives higher values of ESM than the ALS system.
- If the constant crewtime equivalency factor method is used, the ESM for the TPU is much smaller than for the MSWS. The variable crewtime equivalency factor method produces similar results for both systems though. However, if ESM credit is given for the mass and volume of the water recovered by the TPU system, the TPU becomes a much more attractive option than the MSWS, regardless of the ESM-calculation method used.
- The ESM for the MSWS is dominated by system mass, mainly due to the large number of canisters used for waste storage. In contrast, in the case of the TPU, the crewtime, power, and cooling EMS components are important contributors to the overall EMS in addition to system mass. The ESM volume component is small in comparison to the other components for both the TPU and the MSWS.

- In addition to the low ESM, and the ability to recover large amounts of water, the torrefaction-based system (TPU) is associated with thermal sterilization and stabilization of the waste, as well as with the significant odor reduction. There is also some volume reduction resulting from the torrefaction process. This means that the solid residue from the TPU will not only be safer to store, but it will take less valuable space on board spacecraft and in the Mars surface habitat.

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