Will Astronauts Wash Clothes on the Way to Mars?

Michael K. Ewert[1] and Frank F. Jeng[2]
NASA Johnson Space Center, Houston, TX, 77058

Future human space exploration missions will lengthen to years, and keeping crews clothed without a huge resupply burden is an important consideration for habitation systems. A space laundry system could be the solution; however, the resources it uses must be accounted for and must win out over the reliable practice of simply bringing along enough spare underwear. NASA has conducted trade-off studies through its Logistics Reduction Project to compare current space clothing systems, life extension of that clothing, traditional water-based clothes washing, and other sanitizing techniques. The best clothing system depends on the mission and assumptions but, in general, analysis results indicate that washing clothes on space missions will start to pay off as mission durations approach a year.

Nomenclature

adv	=	advanced
AES	=	Advanced Exploration System
ARS	=	Air Revitalization System
CM	=	crew member
D	=	day
ESM	=	equivalent system mass
h	=	hour
ISS	=	International Space Station
JAXA	=	Japan Aerospace Exploration Agency
kg	=	kilogram
kW	=	kilowatt
m	=	meter
min	=	minutes
psia	=	pounds per square inch absolute
sel	=	selection
TRL	=	technology readiness level
UPA	=	Urine Processor Assembly
UV	=	ultraviolet
Vol	=	volume
W	=	watt
WPA	=	Water Processor Assembly
X	=	times
yr	=	year
μ	=	micro

I. Introduction

NASA recently unveiled a new human exploration strategy including International Space Station (ISS) extension, an asteroid mission, and technology development to prepare for Mars exploration missions.[1] These mission durations could spread from months to years. Clothing is an important item in human exploration, keeping crews healthy and comfortable. To date, no spacecraft or space stations have had laundry facilities, so clothing is worn until unusable and then discarded. Mass and volume for disposable crew clothing would be a major penalty in long-duration

[1] AES Logistics Reduction Project SE&I Lead, Crew & Thermal Systems Division, 2101 NASA Parkway, Houston, TX, 77058/Mail Stop EC2.
[2] Life Support Analyst, Barrios Technology, Houston, TX, 77058.

exploration missions. An earlier study estimated that by using disposable clothing, such as on the ISS, the equivalent system mass (ESM) of clothing will be about 11%, or 4850 kg, of the ESM of all life support systems for a four-crew, 10-year lunar outpost mission.[2] ESM is an analytical technique that converts mass, volume, power, cooling, and crew time resources all into "equivalent mass" that must be launched. To reduce launch mass for long exploration missions, reusable clothing along with the best cleaning technology seems wise. But at what point do the savings in clothing mass and volume outweigh the cleaning equipment and any other resources needed to clean the clothes? NASA conducted a detailed study to answer that question.

NASA's Advanced Exploration Systems (AES) Logistics Reduction project reviewed commercial developments in clothing materials and cleaning technologies that could help reduce overall launch mass of an Advanced Clothing System (ACS). Antimicrobial clothing, such as X-static® T-shirts and socks that impregnate silver threads or ions into fabrics, can be worn for up to 14 days and have already been used as ISS crew provisioning items; however, NASA has experienced supply issues with some of these products. Natural antimicrobial wool underwear and T-shirts are recent sportswear developments and have been evaluated as ACS items for exploration missions. Both X-static® and Merino wool clothing are machine washable.

Extending clothing wear time by various sanitizing methods instead of traditional laundering with water was also studied as a way to reduce mass, volume, and/or power. Sanitizing techniques such as ozone or steam cleaning can refresh and enable clothing reuse for several days, but not for dozens or hundreds of times as allowed by water washing. Crew time, clothes drying time, water use, and power/cooling penalties can possibly be reduced significantly with these methods compared to water washing and hot air drying. In this case, perhaps clothes could be worn two to five times longer before disposal, thus reducing the amount of clothes launched by that same amount. Although clothing reuse via laundering or sanitation can reduce spacecraft launch mass and volume, available crew time for laundry may also be limited. To assess the impacts of crew time, this trade study estimated crew time "cost" and included a crew time mass penalty.

Many variables are involved in the decision of whether a space laundry will be beneficial on a given exploration mission. In this study, two different scenarios for the cost of resources were considered and all analysis was done parametrically with time. Current ("baseline") and "advanced" clothing systems were considered and five different cleaning technologies were traded against the current practice of wearing clothes as long as possible and then throwing them away. Although this is referred to as the "disposable" clothing option, it does not imply that the clothes are made specifically to be discarded after one or two uses. In one last case, the effect of adding in other non-clothing items was considered, since this could further reduce launch mass of consumable items.

II. Baseline and Advanced Crew Clothing and Laundry Technology Options

A. Baseline Clothing Items and Individual Mass, Volume, and Usage Rate

Baseline clothing used in this study was based on the ISS Joint Crew Provisioning Catalog Rev. B[3] and AES Logistics Model 2.2.[4] Table 1 lists baseline clothing items, individual masses, volumes, and estimated usage rates. Total clothing mass per crew member (CM) is 0.206 kg/CM-day using baseline clothing items.

B. Advanced Clothing Items and Individual Mass, Volume, and Usage Rate

NASA recently conducted studies that evaluated clothing items made from advanced antimicrobial fabric, modacrylic (synthetic) fiber, and Merino wool, for which wear duration is expected to be longer. Table 2 shows our 'advanced clothing' system items and their individual masses, volumes, and usage rates (some are the same as 'baseline'). The baseline-color T-shirt (sleep) has been replaced with modacrylic shirt and its usage rate is extended to 11 days from 7 days compared to color T-shirts in baseline provisions. Wool briefs and boxers were assumed with usage rates at 3.7 days compared with 2 days using baseline cotton briefs and boxers. It is important to point out that these are assumptions made for this analytical study based on limited comparative testing. These rates have not been proven acceptable. Baseline X-static® T-shirt (14-day wear) was replaced with wool shirt (14-day wear) for the "crew preference" shirts. With these clothing wear-time extensions, total clothing mass is 0.158 kg/CM-day with advanced clothing items.

Table 1. Baseline Clothing Items, Individual Mass, Volume, and Usage Rate

Clothing Item	Washable/ Throw Away (W/T)	Estimated usage rate, days	Mass_sel_1, kg	Mass_sel 2, kg	Mass_sel _3, kg	Vol_sel _1, cm^3	Vol_sel_ 2, cm^3	Vol_sel _3, cm^3	Laundry load, kg/CM-d	Laundry load volume, cm^3/d-CM
Headband,atheletic	W	30	0.1			154			0.0033	5
Athletic Wristbands	W	30	0.02			68			0.0007	2
Athletic shorts, running (nylon)	W	7	0.11			523			0.0157	75
Crew Preference Handkerchief	W	7	0.01			119			0.0014	17
Crew preference shirts, 1=short, 2=long	W	15	0.55 (long)	0.45 (short)		1852	955		0.0333	94
Crew preference colored (sleep) T- shirt	W	7	0.25			412			0.0357	59
Crew preference shorts, 1=boxer, 2=jockey, 3=brief	W	2	0.1 (briefs)	0.1 (boxers)		563	563		0.0500	281
Crew Preferenec Socks (Crew and Ankle) - white[11]	W	7	0.08			387	253		0.0114	55
Crew preference sweater	W	90	0.8			3216			0.0089	36
preference 1=trousers, 2=cargo shorts, 3=cargo pants	W	30	0.35 (cargo shorst)	0.65 (cargo pants)	0.6 (trousers)	1180	2058	1647	0.0181	1697
X-static T-Shirt	W	14	0.3	0.3 (Gray)		3369	3369		0.0214	241
X-static Crew Socks	W	14	0.08 (Blue)	0.08 (Gray)		250	250		0.0057	18
flight name tag	T	180	0.01			14			0.0000	14
JAXA Jacket (Nylon)	T	180	0.45			3216			0.0000	3216
Men's and women's sleepwear top	W	180	0.3			2655			0.0017	15
Men's and women's sleepwear pant	W	180	0.3			2065			0.0017	11
Sum of requirements/CM									0.2058	5809

Table 2. Advanced Clothing Items, Individual Mass, Volume, and Usage Rate

Clothing Item	Washable/ Throw Away (W/T)	Estimated usage rate, days	Mass_sel_1, kg	Mass_sel_2, kg	Mass_sel_3, kg	Vol_sel_1, cm^3	Vol_sel_2, cm^3	Vol_sel_3, cm^3	Laundry load, kg/CM-d	Laundry load volume, cm^3/CM-d
Headband, atheletic	W	30	0.1			154			0.0033	5
Athletic Wristbands	W	30	0.02			68			0.0007	2
Athletic shorts, running (nylon)	W	7	0.11			523			0.0157	75
Crew Preference Handkerchief	W	7	0.01			119			0.0014	17
Crew Preference Shirts, 1=short, 2=long	W	15	0.55 (long)	0.45 (short)		1852	955		0.0333	94
Modacrylic Shirt	W	11.0	0.17			600			0.0155	55
Wool Briefs & Boxers	W	3.7	0.1 (briefs)	0.1 (boxers)		563	563		0.0273	154
Wool Socks	W	12.8	0.08			387	253		0.0062	30
Crew Preference Sweater	W	90	0.8			3216			0.0089	36
Preference 1=rousers, 2=cargo shorts, 3=cargo pants	W	30	0.35 (cargo shorst)	0.65 (cargo pants)	0.6 (trousers)	1180	2058	1647	0.0181	1697
Icebreaker wool shirt	W	14	0.17	0.17 (Gray)		3369	3369		0.0214	241
X-static Crew Socks	W	14	0.08 (Blue)	0.08 (Gray)		250	250		0.0057	18
Flight Name Tag	T	180	0.01			14			0	14
JAXA Jacket (Nylon)	T	180	0.45			3216			0.00	3216
Men's and Women's Sleepwear Top	W	180	0.3			2655			0.0016667	15
Men's and Women's Sleepwear Pant	W	180	0.3			2065			0.0016667	11
sum of requirements/CM									0.1576	5652

C. Mass/Crew Member and Volume/Crew Member of Baseline and Advanced Clothing Using Various Cleaning Options

Figure 1 displays expected clothing mass per crew member versus time with baseline and advanced clothing and three laundry options: 1) disposable clothing; 2) reusable clothing with water-based laundry – 100 reuses; 3) reusable clothing with sanitizer – five uses before discard. Laundry system mass is <u>not</u> included here, but will be in section IV.

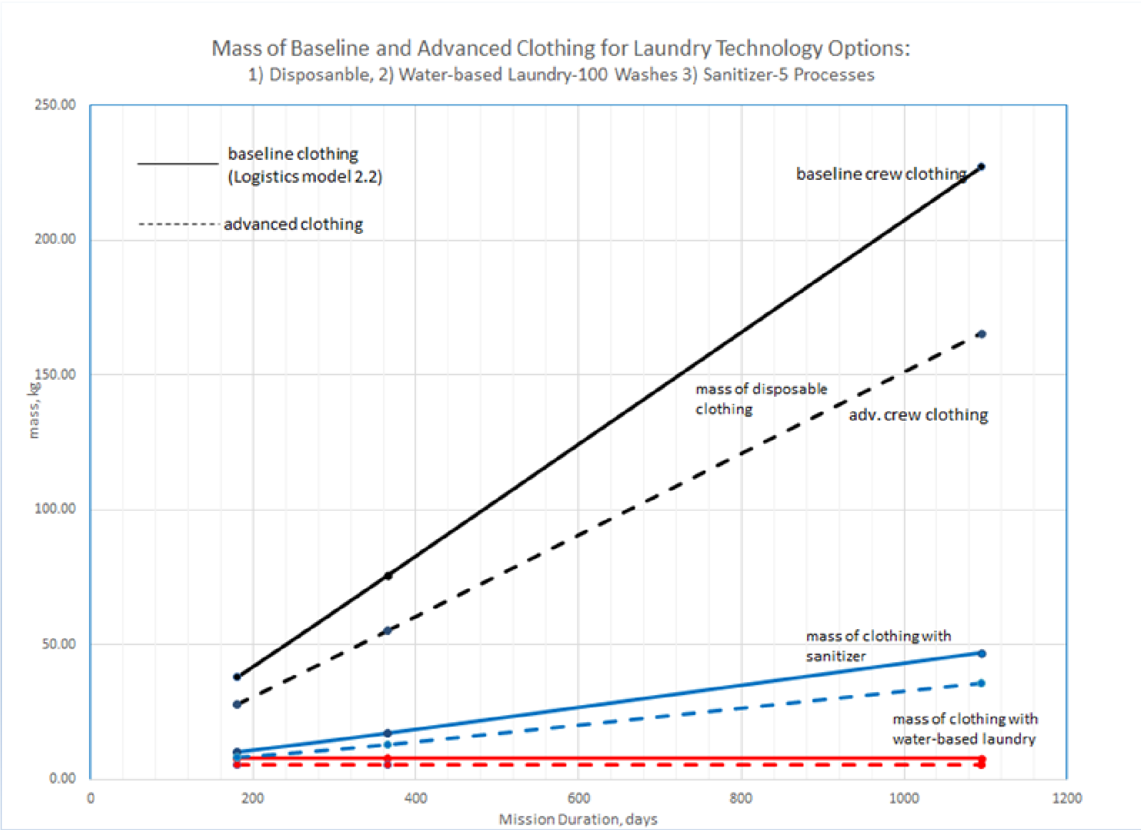

Figure 1. Masses of crew clothing with three laundry options.

Figure 2 depicts expected volume per crew member versus time with baseline and advanced clothing and three laundry options: 1) disposable clothing; 2) reusable clothing with water-based laundry – 100 washes, 3) reusable clothing with sanitizer – five uses before discard. Laundry system volume is <u>not</u> included here. Figures 1 and 2 show that significant savings can be achieved by sanitizing and reusing clothes five times or by washing and reusing them until the end of the mission. However, the other resource "costs" of sanitizing or washing must now be accounted for, and this assumes that the selected clothing sanitizer will be effective enough to allow the stated reuse.

D. Description of Water-based Laundry Options and Resource Use

1. Washer/Dryer Combination Unit

The baseline is a terrestrial washer/dryer combination (combo) unit[5] with the following system properties:

Mass	80 kg
Volume	0.18 m^3
Power	300 W washing / 750 W drying
Clothing capacity	5.3 kg/load
Water use	51 kg/load

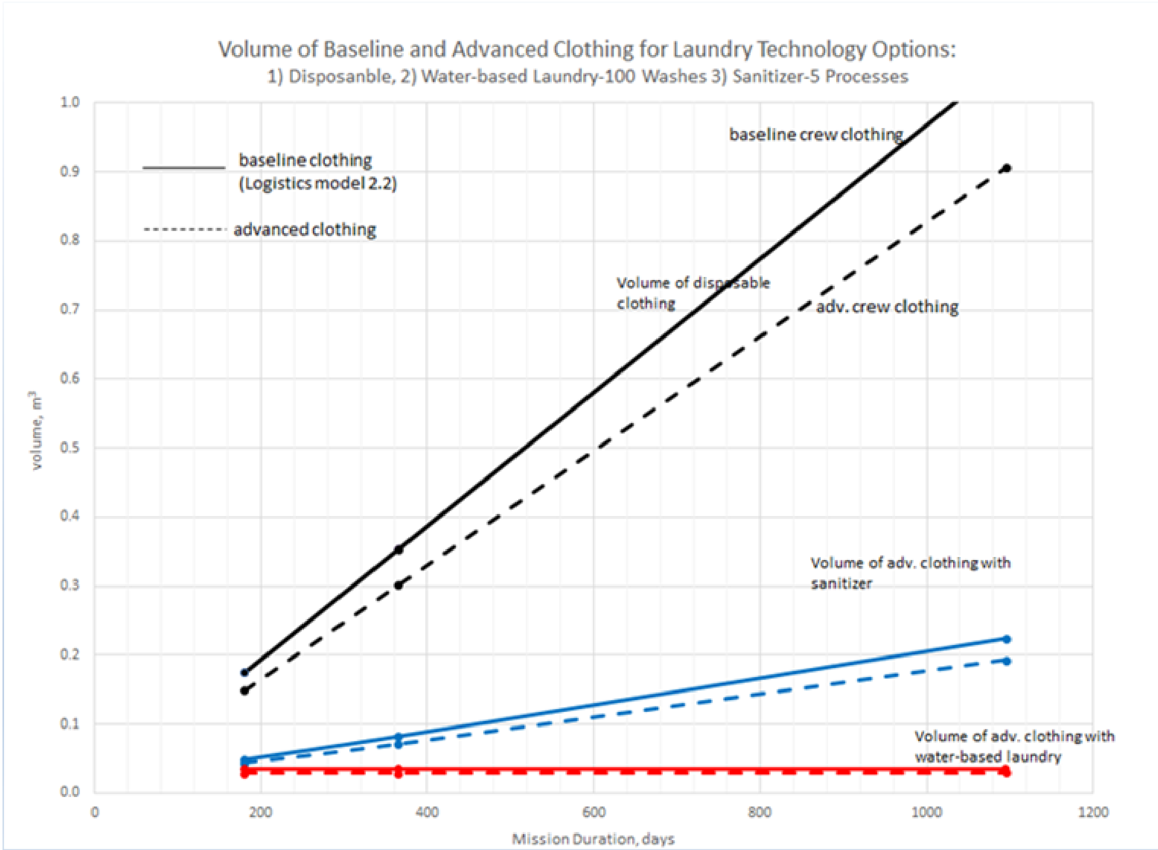

Figure 2. Volumes of crew clothing with three laundry options.

2. Simple Microgravity Laundry[6] – NASA Challenge, Winning Technology

Figure 3 shows a schematic of the simple microgravity (micro-G) belt laundry concept chosen to represent a smaller, simpler water-based cleaning system in this study. Although many other designs are possible, resource use is expected to be similar. The proposed micro-G compatible laundry system is comprised of a laundry belt, a pair of rollers designed to drive the belts, and driving motor and controls. The system (mass, volume, and power) information are:

Mass	14 kg
Volume	0.136 m^3
Power	90 W
Clothing capacity	1.5 kg/load

Part of the “simple” laundry concept in this option is that a heated air dryer is not included, thus the crew must hang or spread moist clothing out in the cabin until it is dry. A disadvantage of the simple micro-G laundry, as well as the washer/dryer combo, is the generation of foamy wastewater that will increase the water recovery system load on the spacecraft.

3. Advanced Micro-G Compatible, Integrated Laundry System

UMPQUA Research Company developed and tested a micro-G compatible 1/8th-scale washing unit with clothing swatches.[7] The test unit demonstrated that no foams were generated. The unit also showed good contact between clothing and water in washing, which should lead to lower water requirements during wash. However, this technology was excluded in this trade study since mass, volume, and power data were not yet available.

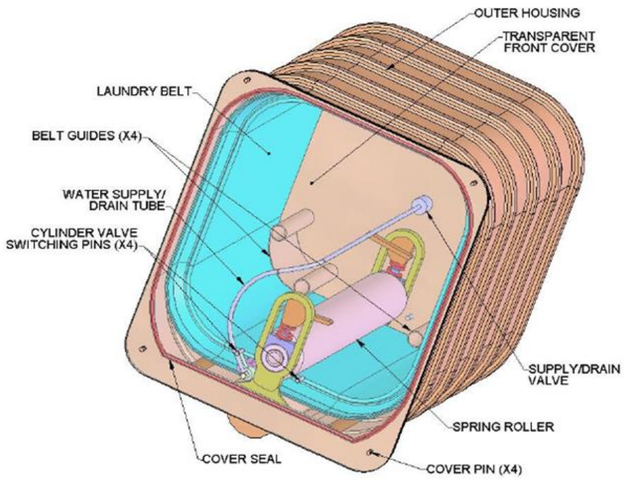

Figure 3. Simple micro-G laundry.

E. Sanitation Laundry Options

Instead of thorough laundering with water (or other solvent) and continual reuse of clothes, "sanitation" seeks to de-odor and essentially eliminate microbes from clothing in order to allow clothing to be worn several times after the sanitation. Desirable sanitation methods would be waterless and nontoxic. Investigated clothing sanitation technologies are existing/commercial technologies used to sanitize sports gear, hospital or hotel facilities, etc. The following sanitation technologies were investigated in this trade study.

Figure 4. ZONO sanitation cabinet.

1. Ozone Sanitation

Ozone has been used for sanitation of clothing, sports gear and other items. Ultraviolet lamps are used to generate ozone. During testing at Johnson Space Center (JSC), clothes were sanitized in bags using ozone with concentration of 2 to 4 ppm for 7 to 8 hours.[8] In ZONO Sanitech® applications, clothing or sports gear are placed in a cabinet with ozone at 7 to 8 ppm for 30 minutes.[9] Catalysts are used to eliminate residual ozone when the sanitizing is finished. Figure 4 depicts a commercially available ozone sanitation cabinet. Concerns of using ozone include its toxicity and the stringent allowable concentration in a closed spacecraft cabin as well as potential material degradation. The maximum ozone concentration in the Occupational Safety & Health Administration (OSHA) Permissible Exposure Limit (PEL) is 0.1 ppm 8-hour time-weighted average.[10]

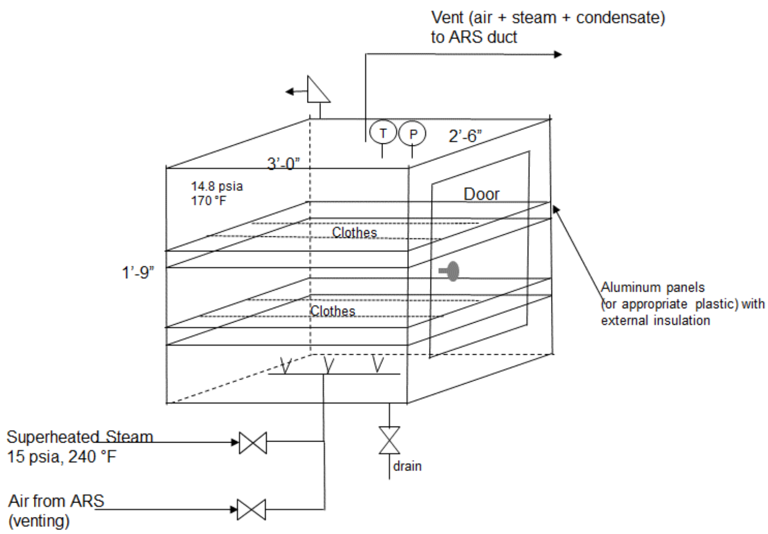

Figure 5. Steam sanitizing box schematic.

2. Steam Sanitizing

"Of all the methods available for sterilization, moisture heat in the form of steam under pressure is the most widely used and most dependable" according to the Center for Disease Control (CDC) "Guideline for Disinfection and Sterilization in Healthcare Facilities" report.[11] For sanitation and odor elimination, steam temperature and sanitation duration could be reduced compared to those used in sterilization. Steam is nontoxic and penetrates fabric, making it a good candidate for clothing sanitation. In this trade study, a sanitation temperature of 77°C (171°F) and sanitation time of 5 minutes were assumed. Tests are needed to define appropriate temperature, degree of superheat, and exposure duration for effective clothing sanitation. Figure 5 is the schematic of a steam sanitizer concept for space, assuming that steam would need to be contained within a spacecraft cabin.

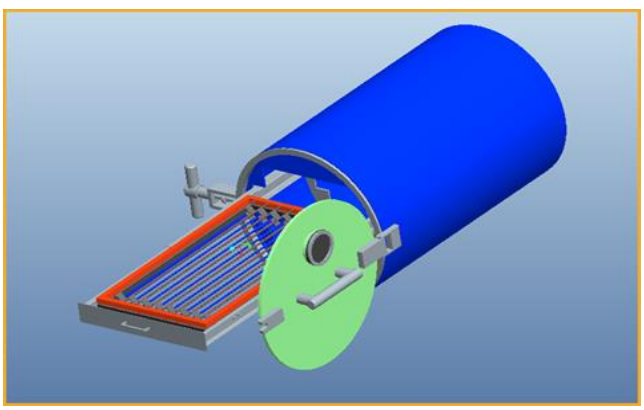

Figure 6. Vacuum sanitation design (Lamar University).

3. Vacuum Sanitation

Although microbes could be categorized into aerobic and anaerobic, most microbes cannot survive in vacuum. However, it has been found that some microbes can survive space vacuum.[12] A Lamar University student study found that E. coli bacteria were eliminated in two out of three tests after 45-minute exposure to vacuum of 0.025 to 0.2 torr.[13] The third sample was inconclusive. The vacuum sanitation technology and system designed by the students was traded in this study. Figure 6 depicts the vacuum chamber designed by the students. Advantages for space sanitation

are simplicity and little power requirement. This study accounted for power to evacuate the chamber and gas lost by venting the last little bit to space.

4. Ultraviolet Sanitation and Integrated Clothing Sanitation Technology[14]

Ultraviolet (UV) light and combinations of various sanitation methods were not included in this trade study analysis since not enough system data were available when the trade study was conducted. They are candidates for further exploration.

III. Basis for Trade Study Analysis

This analysis was conducted assuming a crew of four on a generic space exploration mission that may last from a few months to a few years. The exact vehicles and/or habitats were not specified.

A. Equivalent System Mass and Infrastructure Cost Basis

Equivalent system mass (ESM) is an analytical technique that converts mass, volume, power, cooling, and crew time resources all into equivalent mass that must be launched.[15] The formula for ESM [kg] is:

$$\mathbf{ESM = M + (V*V_{eq}) + (P*P_{eq}) + (C*C_{eq}) + (CT*D*CT_{eq})}$$

Where M = the total mass of the system, including any resupplied items [kg],
V = the total pressurized volume of system [m^3],
V_{eq} = the mass equivalency factor for the pressurized volume infrastructure [kg/m^3],
P = the total power requirement of the system [kW_e],
P_{eq} = the mass equivalency factor for the power generation infrastructure [kg/kW_e],
C = the total cooling requirement of the system [kW_{th}],
C_{eq} = the mass equivalency factor for the cooling infrastructure [kg/kW_{th}],
CT = the total crew time requirement to operate and maintain the system per year [CM-hrs/yr],
D = the duration of the mission segment of interest [yr],
CT_{eq} = the mass equivalency factor for the crew time support [kg/CM-hr].

The ESM infrastructure cost factors used in this trade study are listed in Table 3. Two cases were selected to illustrate how the relative value of different resources can affect the outcome of the analysis. In general, the ISS case has more expensive resources compared to the generic "Exploration" case. This is reasonable because technology advancement should help lower the mass of things like power and thermal control systems. A distinction was not made between microgravity and partial gravity cases in this study. Although a good washing machine can no doubt be designed and built for microgravity, it is quite likely that a system that takes advantage of planetary gravity, as current Earth systems do, will be simpler and cheaper. Advances in water processing could also help the case for washing clothes; however, these cases will require careful analysis of the specific technology and its interaction with cleaning agents, which was considered beyond the scope of this study.

Table 3. Infrastructure Cost Basis in the Trade Study

Infrastructure Cost Factor[4]	Missions	
	ISS	Exploration
Volume[5], V_{eq} [kg/m^3]	67	67
Power, P_{eq} [kg/kW]	476	136
Cooling, C_{eq} [kg/kW]	324	65
Crew time[6], CT_{eq} [kg/CM-h]	0.8	0.6
Expendable of Wastewater Processing, % of wastewater load[1]	3.67	3.67
Wastewater Processing Penalty, kg/(kg/d)[2,3]	12.9	12.9

Notes:
1) Lange K., "Estimates of ISS WPA and UPA Expendables using Alternative Water Processor (AWP) Waste Water Load", spreadsheet.
2) Based on results of ALSSAT Rev. 12 runs, processing cost includes power and cooling.
3) Assuming that the WRS in a spacecraft has enough capacity to process laundry wastewater, no additional hardware is needed.
4) "ALS Baseline values and Assumptions Document", NASA document CTSD-ADV-484, May, 2002.
5) Unshielded volume for ISS, shielded volume for exploration vehicle.
6) Per email from Michael Ewert on 6/25/2014.

B. Amount of Washing and Sanitation per Week

The number of washing or sanitation operations per week assumed are shown in Table 4.

Table 4. Washing and Sanitation Frequency per Week

Crew	4		
Laundry Technologies	Laundry load, kg/week	Washer load, kg	Washes or Sanitizing/week
Washer/Dryer Combo	5.8	5.3	1
Simple Micro-G Washer	5.8	1.5	4
Zono Sanitation System	5.8	By volume	2
Steam Sanitation	5.8	By volume	1
Vacuum Sanitation	5.8	By volume	4

C. Wastewater Recovery Cost

Wastewater recovery cost is a significant penalty in laundry ESM. It was assumed that the ISS multi-filtration process can be used for laundry wastewater. The specific mass of the water processing assembly was estimated at 3.7 kg/100 kg of water processed,[16] assuming no additional hardware requirement beyond the existing system. Power and cooling penalties of the ISS wastewater recovery process were estimated at 12.9 kg per kg/hr processing rate.[17]

D. Mass and Volume of Non-clothing Items that could be Laundered

Non-clothing items, such as dry wipes, wet wipes, dry towels, etc., make up to 50% of the mass of cloth-type items launched.[2,4] Reuse of non-clothing items such as these would save significantly more launch mass if they can also be laundered in the same device. A list of current mass and volume of non-clothing items and estimates of expected mass and volume of reusable non-clothing items are shown in Table 5. It was assumed that some disposable wipes will still be required for certain jobs. But, by reusing certain non-clothing items after washing, 160 kg/yr mass and 0.881 m^3/yr can be saved for a crew of four. Using the simple micro-G laundry, there will be six washes per week including both clothing and non-clothing items. Without non-clothing items, four washes per week will be enough using the simple micro-G laundry. For the washer/dryer combo, an additional half wash load per week would be required. The sanitation methods are probably not as appropriate for many of these non-clothing items, so that case was not analyzed.

Table 5. Mass and Volume of Non-Clothing Items - Original and Projected with Laundry

Item	**Original Mass/yr, kg**	**Mass/yr with laundry, kg**	**Mass/yr Savings, kg**	**Original Volume/yr, m^3**	**Volume/yr with laundry, m^3**	**Volume/yr Savings, m^3**
Dry Wipes	34.0	23.8	10.2	0.209	0.146	0.063
Wet Wipes	97.1	67.9	29.1	0.358	0.251	0.107
Dry Towels	35.4	3.5	31.8	0.147	0.015	0.133
Body Washcloths	12.5	1.2	11.2	0.043	0.004	0.039
Body Towels	73.0	7.3	65.7	0.440	0.044	0.396
Sleeping bag Liners	14.4	2.4	12.0	0.173	0.029	0.144
Non-Clothing Total	**266.3**	**106.2**	**160.1**	**1.370**	**0.489**	**0.881**

E. Estimation of Crew Time for Laundering/Sanitizing

One essential penalty of reusing clothing and non-clothing items is crew time to clean them. Crew time is a valuable resource in space exploration. Reasonable estimation of crew time employed doing laundry is necessary for a meaningful trade study. Through analysis of laundry procedures, the authors and JSC colleagues estimated crew time usage for various clothing and laundry options as shown in Table 6.

Table 6. Estimation of Crew Time used in Washing/Drying/Organizing

Total Crew Time Used in Laundering / Sanitizing (four crewmembers)	
Clothing/Laundry Options	Estimated Crew Time, CM-hr/week
Disposable Clothing	0.50
Automatic Washer/Dryer	1.25
Reusable Clothing & Zono Sanitation System	1.40
Reusable Clothing & Steam Sanitation Box	1.40
Reusable Clothing & Simple Laundry	2.40
Reusable Clothing & Vacuum Sanitation	1.53

F. Trade Study Analysis

Excel® spreadsheets were used to perform trade study analyses between various trade parameters such as baseline or advanced clothing, various laundry options, and ISS or exploration missions. ESM was calculated for the clothing and all resources required to clean it for different mission durations according to the appropriate disposable, laundry, or sanitation case. The lowest ESM total for the entire system is the best from an engineering point of view. However, an important point should be made here. Clothing is a personal thing and human factors are very important in human space missions, even more so when time away from Earth increases. So, it is highly likely that the clothing system and any associated clothes cleaning equipment will not be decided on the basis of minimum ESM alone. Crew input on effectiveness of different cleaning techniques as well as how much of a chore they are to use will also be important drivers. For this reason, experiments on ISS, such as the 2014 Intravehicular Activity Clothing Study, provide valuable data for habitation system development.

IV. Trade Study Results

A. International Space Station Mission

Assumptions:	Four crew members [scaled from ISS crew of six to match exploration mission]
Useful Life of Clothes:	Water-based laundry – 100 X, Sanitizer – 5 X
Duration:	Normally 180 days; no reuse of clothing from previous crews

The ISS mission considered here could represent other space stations with similar resource costs. Results were calculated for a crew of four in order to match exploration mission assumptions below. Figure 7 shows the ESM totals of clothing plus cleaning system for each technology option considered for different time durations. The graphs illustrate that for a nominal 180-day ISS mission using baseline clothing, none of the laundry or sanitizer options can compete with the disposable clothing. The break-even time for the closest two options are:

Laundry Option	Break-even Time (months)
Vacuum sanitizer	10.2
Simple laundry	12.6

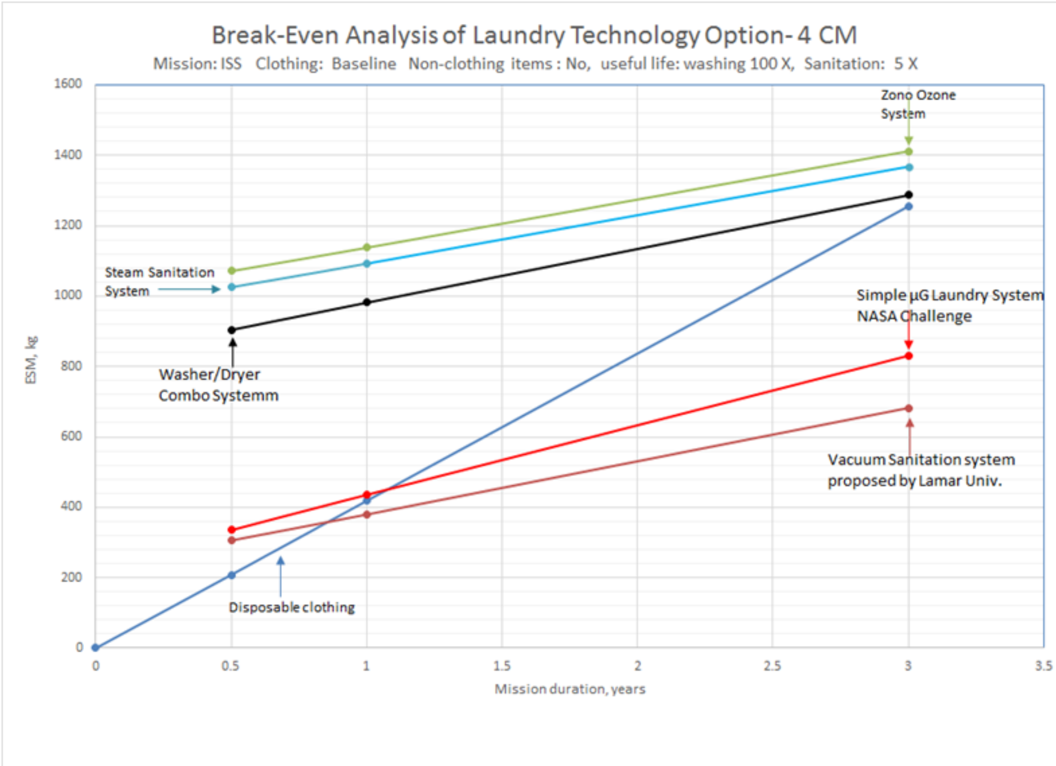

Figure 7. Break-even time with <u>baseline</u> clothing and various cleaning methods for ISS missions.

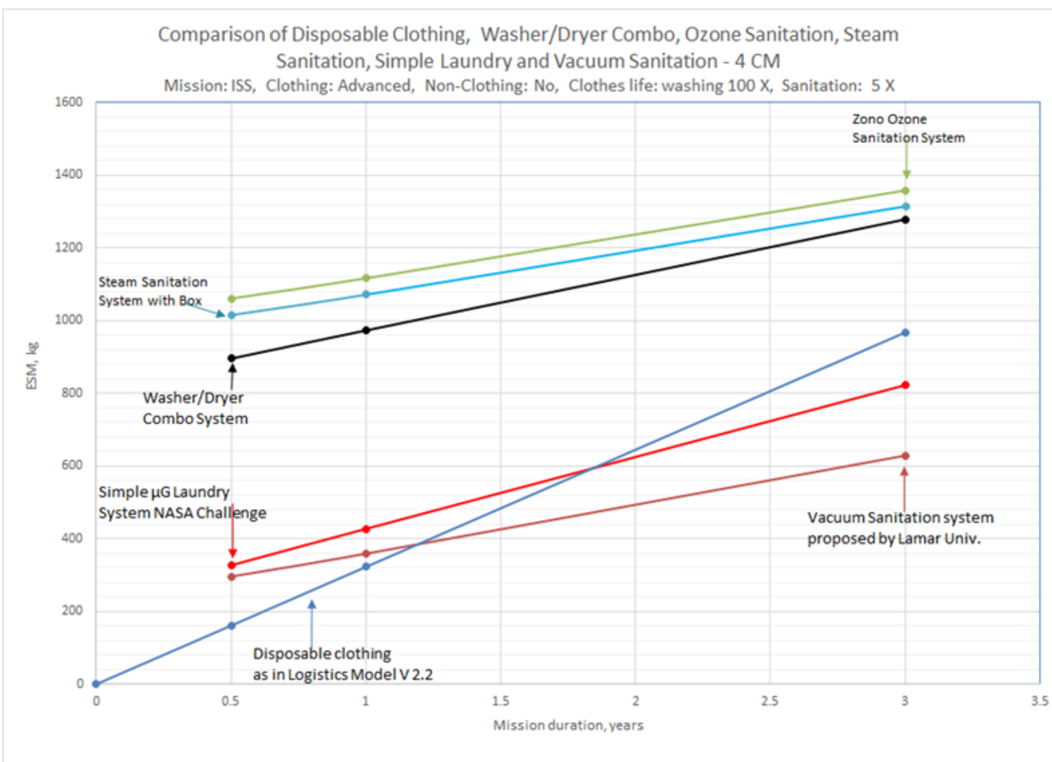

Figure 8. Break-even time with <u>advanced</u> clothing and various cleaning methods for ISS missions.

These breakeven times assume the sanitizer is good enough to reuse each piece of clothing five times longer that current practice. If clothing loses softness or becomes otherwise objectionable after less than five sanitizing operations, the break-even time becomes even longer. Several other options suffer from high power usage and the relatively high cost of power on ISS. The analysis indicates that disposable clothing is the least expensive selection in terms of ESM, unless using washed clothing from previous crews was considered acceptable and sizing issues could be overcome.

Figure 8 depicts break-even time for ISS missions using the ACS. As expected, using ACS, laundry will take even longer to break even compared to disposable clothing since single use wear times are longer.

Figure 9 shows the relative "costs" or components of ESM for each option for a 1-year ISS mission using baseline clothing. This graph illustrates that a relatively large portion of the ESM is mass for the vacuum sanitizer and a relatively large portion of the ESM is wastewater processing and crew time in a simple µG washer. As mentioned above, several other technologies do not fare as well due to the ESM of power and cooling (which is directly related to power use).

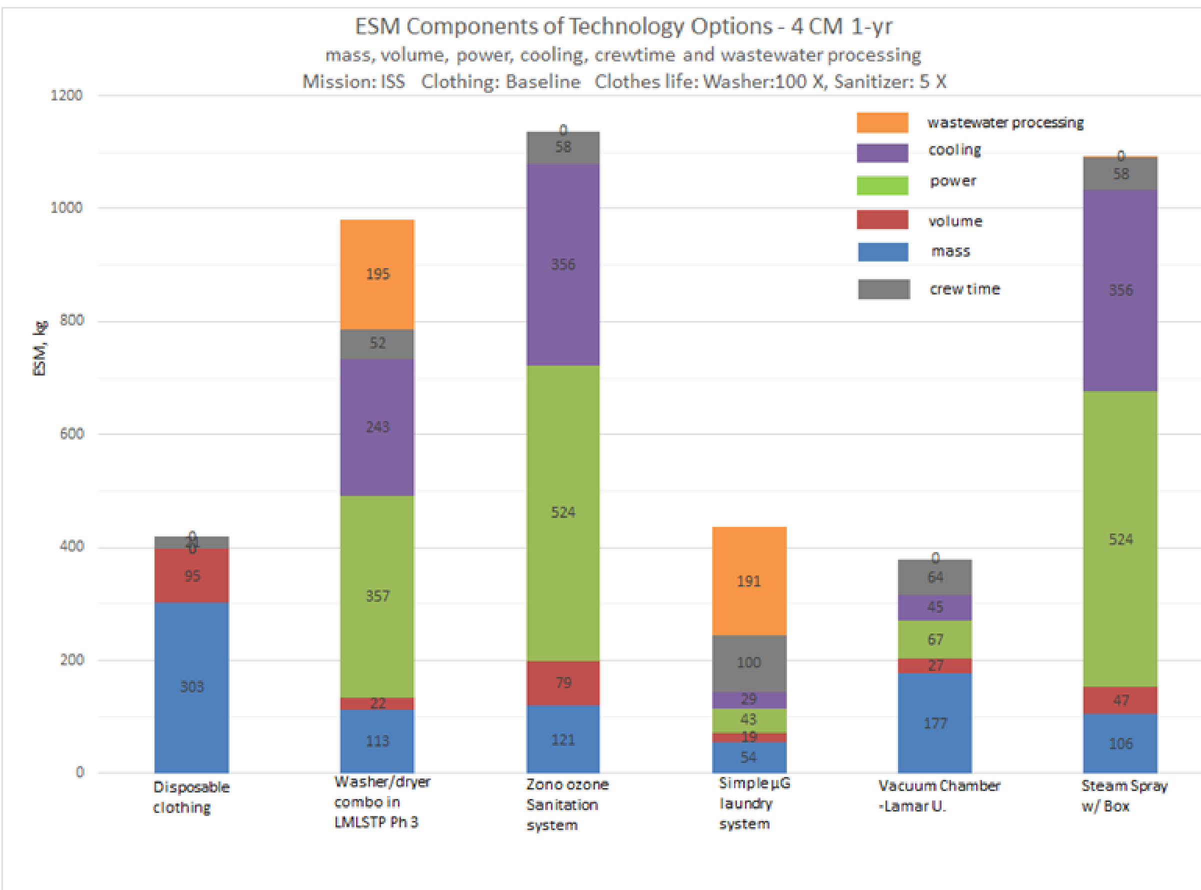

Figure 9. Relative ESM components of laundry options for a 1-year ISS mission using baseline clothing.

B. Exploration Mission Using Advanced Clothing

Figure 10 shows a break-even analysis for exploration missions using ACS, assuming clothing life with washer is 100 washes and with sanitizer is five treatments. Though not shown here, results were also calculated with baseline clothing, and break-even times were somewhat shorter. Figure 10 indicates that, for exploration missions using advanced clothing, vacuum sanitation would break even with disposable clothing in approximate 8.4 month; using simple micro-G washer would break-even in about 14 month. Compared to the ISS mission case, break-even times are shorter for most of the technologies due to the lower resource infrastructure values. Figure 11 illustrates a sensitivity analysis, varying reuse life after sanitation processing from 1.5 to 3 times.

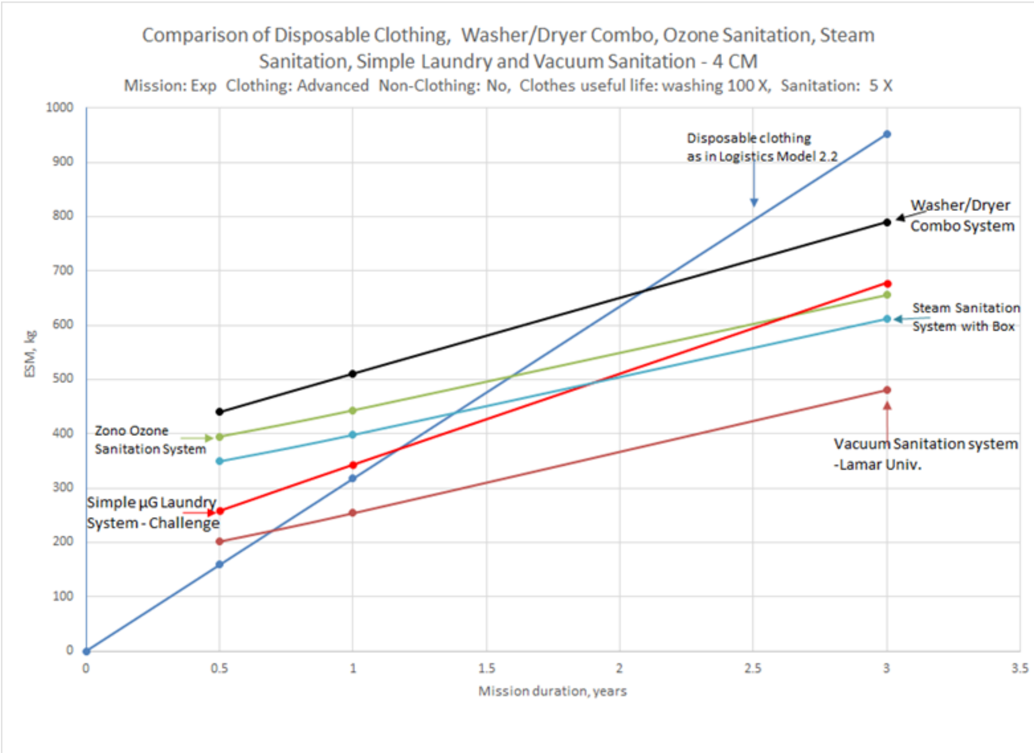

Figure 10. Break-even time using advanced clothing and laundry options for exploration missions.

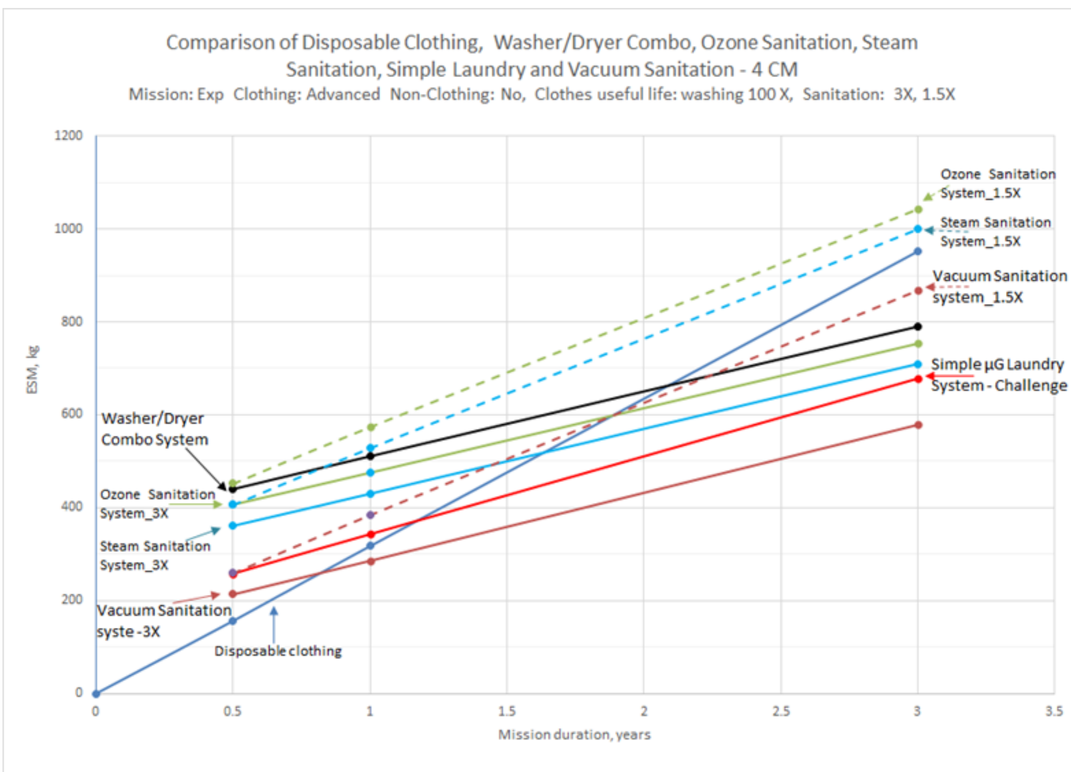

Figure 11. Break-even time for exploration missions using advanced clothing and laundry options (reusing clothes 3 times and 1.5 times as long, after sanitizing).

Figure 12 shows relative ESM components of various laundry options for a 1-year exploration mission. Mass is the largest penalty of all the ESM components of the vacuum sanitizer. Wastewater recovery and crew time are two major ESM penalties for the simple washer in exploration missions. It would have the lowest ESM among the evaluated laundry options if the wastewater processing penalty could be reduced by half. Besides the penalty of water processing, washer/dryer combo is also hurt by the power cost of drying.

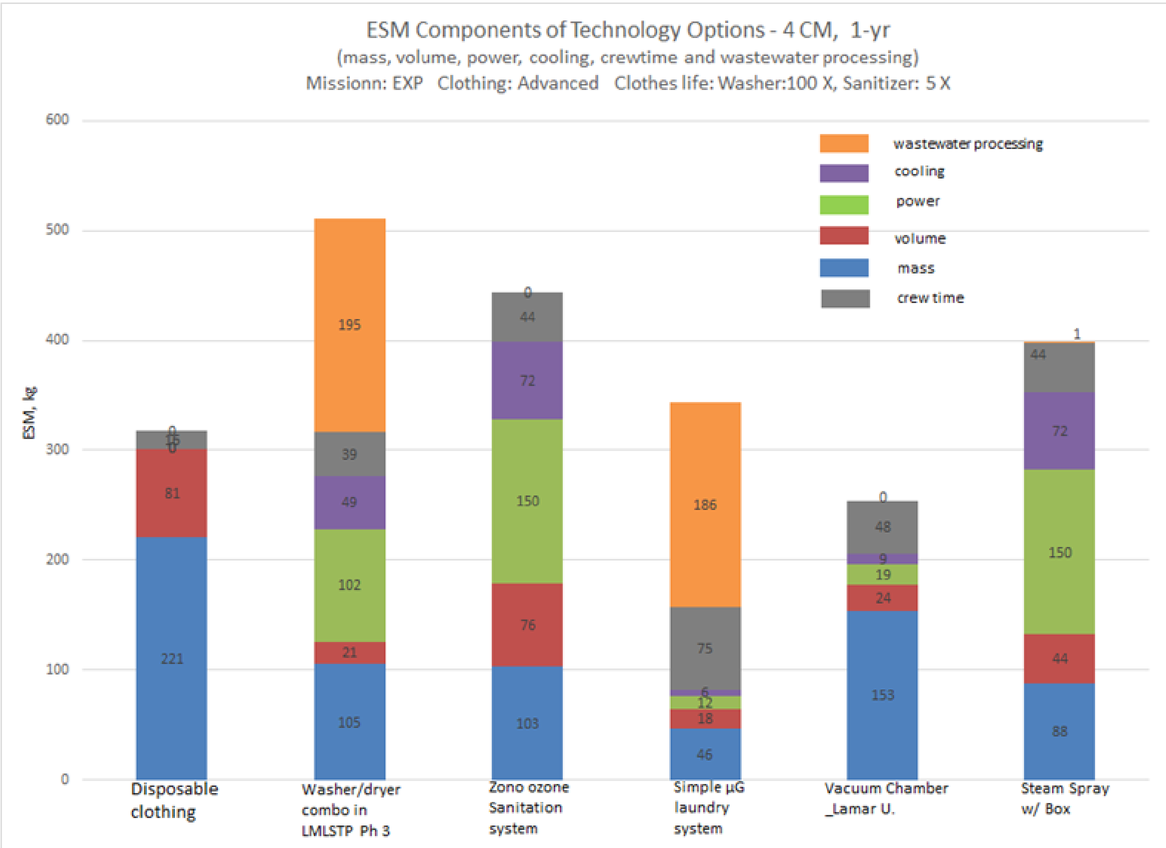

Figure 12. Relative ESM components of laundry options for a 1-year exploration mission using advanced clothing and laundry options.

C. Considering Non-Clothing Items and Exploration Missions

NASA performed a follow-on study in which clothing and non-clothing items were laundered and reused as described in section III.D. This made the break-even time for a laundry system shorter. Figure 13 shows that, for exploration missions with advanced clothing, it takes only 10.8 months for a simple µG washer to break even when it is used to wash other items in addition to clothes. Ambient air drying of the washed items is assumed in the simple laundry case. A comparison of break-even time with and without non-clothing items for the simple µG washer is as follows:

	Break-Even Time (months) – Simple µG washer	
Missions	Clothing Only	Clothing + Non-Clothing Items
ISS (baseline clothing)	12.6	10.6
Exploration (adv. clothing)	14.3	10.8

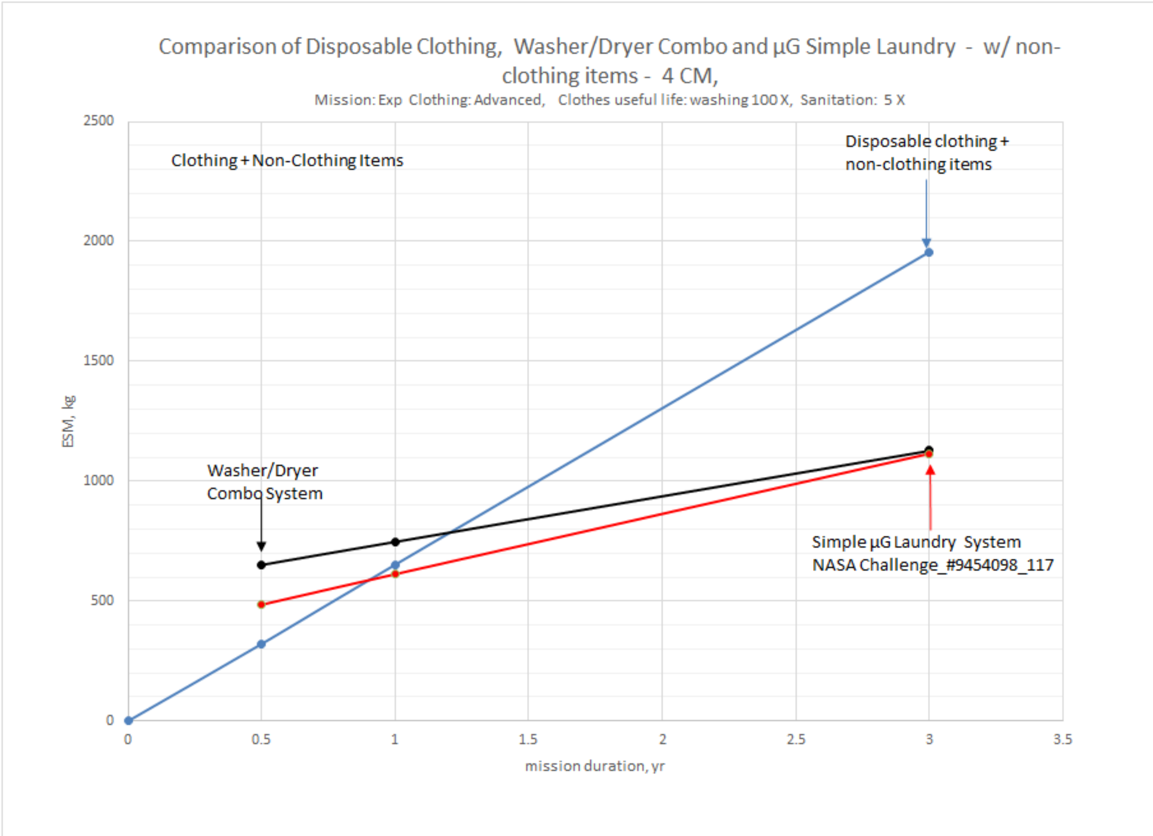

Figure 13. Break-even time with advanced clothing for simple µG washer and washer/dryer combo for exploration missions (clothing + non-clothing items).

V. Conclusions and Recommendations

The answer to whether or not astronauts will wash clothes on their way to Mars may depend on how technology progresses in clothing textiles and in clothes cleaning systems, for both water based laundry and alternative sanitation methods. Then again, especially if there is not a clear technical driver, human factors may be the deciding force. The subject of space laundry has been revisited in this study trading disposable clothing and several different types of clothes cleaning systems, some of which sanitize or freshen the clothes and others which completely wash them with soap and water. The different cases require different amounts of resources such as water, power, and human effort. The following variables were considered in this study:

Missions:	ISS and Exploration
Clothing:	Baseline and Advanced
Laundry Options:	Washer/Dryer combo, simple micro-G washer
Sanitation Options:	Ozone, Steam, and Vacuum

For ISS missions, the trade study results illustrate that with both baseline (currently used on ISS) and advanced clothing, disposable clothing has lower launch mass than any of the cleaning and clothing reuse systems, unless clothing items were to be re-worn by different astronauts on future expeditions. Even when reasonable assumptions were made to include non-clothing items such as towels into the equation, disposable clothing still had the lowest equivalent system mass.

NASA's Logistics Reduction project has already begun to reduce disposable clothing mass by introducing commercial textiles that have natural antimicrobial properties and thus can be worn longer.[18] If we assume NASA will fully extend and implement these findings, then exploration missions will only clean and reuse clothing on missions where the cost of doing so is less than this disposable option. Using ESM or launch mass as a proxy for cost, this study

found the break-even times for various clothes cleaning options compared to disposable clothing for future human space exploration missions. The lowest ESM technologies and their break-even times were as follows:

Cleaning Option	Break-Even Time (months)
Sanitation methods (low TRL)	8.4 – 19 (assuming 5X reuse)
Water based laundry (mid TRL)	14 - 26

If some non-clothing items such as wipes and towels become reusable by washing, then break-even time with a simple washing system could shorten to about 11 months. For longer missions, the study showed that, for exploration missions with advanced clothing and a simple washer with air drying, ESM savings could be up to 860 kg for a 3-year mission for a crew of four, compared with disposable clothing.

Because of the relatively high resource cost of processing laundry wastewater and the power required for a hot air dryer, the washer/dryer combo was often not as attractive as other options in this study. However, it should be pointed out that this is the tried-and-true method on Earth, and even though a washing machine has not yet been developed for space (microgravity missions in particular), the technology readiness level (TRL) and effectiveness of water washing is considered greater than all of the sanitation methods described here. Reduction of the water processing penalty would certainly help water washing trade more favorably.

Future exploration missions may also need a sterilization unit for space suits and tools. If these could do double-duty for clothes cleaning, the payoff could be significant. Steam and ozone sanitizing cabinets could be good candidates for this type of approach. Vacuum sanitation, if it is further verified to be effective in eliminating microbes and odor, seems worth developing into a higher TRL system because of simplicity and low power penalties.

The best clothing system depends on the mission and assumptions; however, as shown above, analysis results indicate that washing, or otherwise sanitizing, clothes on space missions will start to pay off as mission durations approach about 1 year. ACS work done under the AES Logistics Reduction project has contributed to extending the break-even point and thus delays the need and expense of developing a space-qualified laundry until we get closer to missions of a year or more. Hopefully, ground development work as well as commercial industry advancements will continue on these and other innovative cleaning options, and this subject will be revisited in several years.

Acknowledgments

The authors wish to express their sincere thanks for contributions and comments from Evelyne Orndoff, Darwin Poritz, Robert Trevino, James Broyan, Thilini Schlesinger, Glenn Johnson, and Vicky Byrne.

References

[1]NASA director Charles Bolden letters to Rep. Palazzo and Rep. Edwards on NASA Future Exploration Plans, http://www.nasa.gov/sites/default/files/palazzo-letter-4-2-14.pdf, April 2, 2014.

[2]Ewert, M., and Jeng, F., "Laundry Study for a Lunar Outpost", ICES paper 2009-01-2515, 2009.

[3]"Joint Crew Provisioning Catalog", SSP 50477, Revision. B, ISS, June 2012.

[4]Ewert, M. K., Broyan, J. L. "Mission Benefits Analysis of Logistics Reduction Technologies", 43rd International Conference of Environmental Systems, AIAA-2013-3383.

[5]Equator model EZ1500 washer/dryer combination unit.

[6]Solver Verification Document, "Challenge #9454098, NASA Challenge: Simple Microgravity laundry System", Submission_117, Sept., 2010.

[7]"Michalek W. F., "Advanced Microgravity Compatible, Integrated Laundry System", final report, NASA SBIR Phase I Contract: NNX12CD41P, UMPQUA Research Company, Aug. 2012.

[8]Communications with Darwin Poritz/JETS/JSC_EC2.

[9]Communication with ZONO Sanitech, http://www.zonosanitech.com/the_zono_solution/the_zono_equipment.html

[10] https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9992

[11]"Guideline for Disinfection and Sterilization in Healthcare Facilities, 2008", Center for Disease Control and Prevention, document, http://www.cdc.gov/hicpac/pdf/guidelines/disinfection_nov_2008.pdf

[12]"bacteria: The Space Colonist", http://www.panspermia.org/bacteria.htm.

[13]Daleo P., Robinson D., Petry D. and Hernandez M., "S.P.A. Sanitizing Small Pass Through Airlock", presentation from Lamar University, TX, April 15, 2013.

[14]Johnson G. and Ganske S, "ISS Clothes Cleaning machine", a presentation at Johnson Space Center/NASA, April 2010.

[15]Levri, J.A., et al., "Advanced Life Support Equivalent System Mass Guidelines Document", NASA/TM-2003-212278, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040021355.pdf

[16]Lange K., "Estimates of ISS WPA and UPA Expendables using Alternative Water Processor (AWP) Waste Water Load", personal communication, Feb., 2014.

[17]Based on ALSSAT Rev. 12 run results. ALSSAT is a NASA ECLSS system analysis tool.

[18]Orndoff, E.S., "Space Wear Vision: Development of a Wardrobe for Life in Space Vehicles and Habitats", abstract submitted to International Space Station Research Investigations and Experiments conference, Moscow, April 2015.