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Clothes Cleaning Research for Space Exploration

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As the National Aeronautics and Space Administration (NASA) plans to establish a sustainable presence on the Moon to prepare for missions to Mars, there is an increased need to find effective and sustainable laundry solutions that are compatible with space travel and reduce the need for clothing resupply. Research and development to overcome resource constraints in space can lead to new products and practices on Earth. This paper describes a collaboration between NASA and Procter & Gamble (P&G) to advance their individual goals as well as provide additional benefits to humanity through more sustainable use of resources. In particular, the two organizations have been working together since August 2020 to advance state-of-the-art, environmentally friendly laundry solutions. Both traditional and novel approaches are being considered and held up against strict resource constraints that may exist in space missions or on Earth in the future. The results of this work are expected to contribute to NASA's strategic goal of extending human presence deeper into space and to the Moon for sustainable long-term exploration and utilization. Likewise, the collaboration will advance one of P&G's 2030 corporate sustainability goals by promoting water savings among its 5 billion consumers.

Nomenclature

BOD = Biochemical oxygen demand
CHAPEA = Crew Health and Performance Exploration Analog
ConOps = Concept of Operations
DOC = Dissolved organic carbon
ECLSS = Environmental Control and Life Support System
GCMS = Gas chromatography mass spectrometry
ISS = International Space Station
ISSNL = International Space Station National Lab
NASA = National Aeronautics and Space Administration

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P&G	=	Procter & Gamble Company, Inc.	*SRI*	=	Stain removal index
R&D	=	Research and development	*T&RH*	=	Temperature and relative humidity
RO	=	Reverse osmosis	*VOCs*	=	Volatile Organic Compounds
SAA	=	Space Act Agreement	*WRS*	=	Water recovery system

I. Introduction

THE National Aeronautics and Space Administration (NASA) and Procter & Gamble (P&G), an American multinational consumer goods corporation, began discussing mutual research and development (R&D) interests related to cleaning in 2017, which led to the signing of a non-reimbursable Space Act Agreement (SAA) in 2020. This collaboration is based on overlapping goals related to sustainability in outer space and on Earth. One of the first research and development challenges identified for joint work was laundry. Laundry has not yet been developed for the resource constrained environment of space, and finding ways to improve the environmental footprint of laundry on Earth is of great interest. By developing a laundry solution that reduces water and energy use for space, improvements can also be made on Earth.

Early efforts have been focused on defining an efficient laundry process that could eventually be used in NASA's Artemis mission to the Moon and later on human missions to Mars. At a sustainable planetary outpost, all wastewater streams (including from laundry) will have to be recycled. A leading water recycling technology that NASA has been developing for years is bioreactors to break down environmental, food, and body soils and return the water to potable standards. Thus, P&G set out to formulate a detergent that would be fully degradable in this type of biological treatment system.

Another important part of developing a successful laundry process for space is working within the resource and environmental constraints of the missions. P&G and NASA are also addressing water and energy use within washer/dryers, operational considerations for busy astronauts, and other environmental factors such as gravity and radiation that could affect detergent and ingredient stability on long missions.

II. Collaboration Goals and Mechanisms

A. NASA Goals

The Logistics Reduction project within NASA's Advanced Exploration Systems technology portfolio is working on different technologies that will reduce the logistical supplies needed to support humans on deep space exploration missions. When these supplies are not reusable or recyclable, their burden as launch mass is directly proportional to mission length. This has been the case with clothing on all missions to date as no appropriate cleaning process has been developed for space. On the International Space Station (ISS), for example, clothing is worn until it gets too dirty and then disposed with other trash.[*] The Logistics project has been searching for simple, resource-efficient cleaning methods for clothing. A goal was set to reduce the 0.21 kg/person/day of clothing launched to 0.10 or less, including accounting for the mass of other equipment and resources needed to clean clothes so that they could be reused (e.g., washing machine, extra water). Past analytical studies[1] have indicated that it takes a year or more for traditional laundry to pay off in launch mass savings of disposable clothes saved versus the equipment and other resources (e.g., energy, water) needed for laundry. This led the Logistics Reduction team to search for alternative to laundry that would use little or no water and energy. Over 20 cleaning or disinfection technologies were identified that could be applied to clothing in space, including ozone, ultraviolet light, steam, and vacuum, to name a few[2]. However, none were expected to be as effective as laundry with detergent, and it was not clear that their benefits individually or in combination would be worth the resources invested[3,4].

Then in 2020, after a period of informal discussion between NASA and P&G researchers, a formal collaboration began with the goal of improving the laundry process such that the resources required, even in space, would be worth the extra launch mass, while preserving the effectiveness of this traditional method used on Earth.

B. P&G Goals

Through this collaboration with NASA, P&G is using their more than 75 years of laundry innovation and deep technical expertise to develop innovative cleaning solutions. These cutting-edge solutions will benefit laundering on

[*] Examples of recommended wear duration are 7 days for exercise shorts and socks and 30 days for pants. However, each astronaut decides when to throw away each item of clothing based on smell, look or comfort.

Earth and the environment by enabling laundry hygiene in resource-constrained areas. This partnership was created to rethink cleaning from the ground up – unlocking new innovations to more efficiently clean clothing on Earth as well as deep space crewed missions to the Moon and Mars.

On Earth, P&G anticipates the research and findings from this program will help enable progress towards more sustainable laundry processes. The research conducted in partnership with NASA is an integral part of P&G's corporate Ambition 2030 sustainability goals – which includes reduction of greenhouse gas supply chain emissions by 40%, and ultimately net zero emission by 2040. In addition, the cleaning demands of astronauts as 'consumers' in space reflect some trends on Earth where the cleaning and removal of body soils from modern garments made from synthetic fibers (e.g., polyester athletic wear) is a formidable challenge. Given astronauts' exercise regimen, they represent a segment for which optimized cleaning is necessary.

Overall, P&G will use learnings obtained from the collaboration with NASA to develop sustainable laundry solutions with superior cleaning performance, as well as optimized cleaning cycles for the consumer around the globe (and in space).

C. Mechanisms for Collaboration

1. Space Act Agreement

The National Aeronautics and Space Act of 1958 gave NASA authority to work with any entity that enables fulfillment of the Administration's mandate through legal agreements known as Space Act Agreements (SAA's). A non-reimbursable SAA, described as a mutually beneficial activity with a partner that furthers the agency's mission, was used for the current collaboration between NASA and P&G. In this type of SAA each partner bears the cost of its participation and no funds are exchanged between the parties.

A 5-year umbrella agreement titled "Cleaning in Space" and a 2-year first annex titled "Laundry Detergent for Space" were written and signed by the parties in August 2020. The umbrella agreement was written broad enough to cover future collaborations related to various ways of cleaning people and their living spaces. The initial annex, however, focuses on working with Tide® on clothes cleaning. The agreement calls for NASA to provide goals and constraints for space laundry detergent and for P&G to deliver sample quantities of laundry detergent that meet NASA and P&G sustainability goals. In return, NASA will provide technical test results from evaluation of the detergent in NASA systems. The partners also agreed to jointly share resource saving advances with the public.

2. ISS National Lab

The ISS National Lab (ISSNL) works with corporate partners to seek solutions to challenges for Earth-based obstacles they face, which ultimately may result in the development of better or more efficient products for consumers. After the start of the SAA with NASA, P&G began to also work with the ISSNL to accelerate testing of Tide products in space. As part of P&G Telescience Investigation of Detergents Experiments (Mission PGTide) in 2022, the ISSNL is partnering with P&G/NASA to send Tide Infinity (a specialized laundry detergent formulated to meet the laundry needs of deep space), Tide to Go Wipes, and Tide to Go Pens to the ISS, where the activity and stability of the stain cleaning ingredients in microgravity will be analyzed. Experiments will be conducted on Earth in tandem with the experiments on the ISS, using the same materials to compare differences in stain removal in space versus conditions on Earth.

Collaboration between NASA/ISSNL and P&G on this project was fitting given the parallel goals of each organization. Due to the need for sustainable and stable laundry solutions for space missions, as well as the necessity of minimizing stress on laundry water reclamation systems, P&G has developed a laundry detergent that reduces the organic mass of formulated ingredients and components incompatible with NASA's closed looped systems. This detergent formulation meets the needs of constrained space environments and fits into P&G's corporate goals on reduced supply chain emissions. Further, the development of laundry products that seek to eliminate or reduce non-biodegradable components are important for on-Earth applications, both of which were necessary for a 'space compatible' detergent.

III. Development of Tide Infinity Laundry Detergent

Currently, approximately every 90 days astronauts on the ISS receive shipments of fresh clothes that are worn repeatedly until no longer sanitary, at which point they are disposed. The significant cargo costs and limited capacity make the practice of replenishing the clothing supply questionable for longer duration missions, including planned missions to the Moon (Artemis) and 3-year missions to Mars. Without laundering, it is estimated that each crew member would need approximately 210 kg (460 lbs.) of clothing for a trip to Mars, which would be extremely expensive to launch and transport for millions of kilometers. To combat these challenges, NASA and P&G set out to determine the viability of doing laundry on planetary habits in low-gravity and during micro-gravity transit on deep space missions. P&G set out to develop a fully degradable detergent that provides the outstanding stain and malodor removal performance of Tide® for use in NASA closed looped water and air systems. Additionally, major challenges for off-planet laundering include a limited amount of water available per wash load and the requirement that the wash water be purified back to drinking-quality water.

NASA set out constraints for crew garment types, quantities, water volume, laundry frequency and a total "water budget" that could be allotted for laundering. A new detergent, called Tide Infinity, was developed to meet the constraints of being fully degradable and compatible with closed loop air and water systems. Tide Infinity was also designed to use 15 liters of water per load or less to wash roughly 4.5-5.0 kg (10-11 lbs.) of clothing twice a week for a crew of 4. To this end, various technologies were utilized such as catalytic cleaning with a broad spectrum of enzymes, chelant chemistry, a soil release polymer, and specialized surfactant design. Formulation processing was utilized to make a stable formulation to clean body soils and other soils (food and drink stains, etc.) experienced in space by astronauts. Tide Infinity was specifically designed to be effective in cleaning athletic performance apparel, due to the astronauts' strict exercise regimen involving approximately two hours daily to maintain muscle strength and bodily health. Stain removal testing (Table 1)** and whiteness results (Figure 1) demonstrate the efficacy of the detergent formulation across representative soil and fabric types that astronauts are likely to encounter when on missions. A higher stain removal index (SRI) indicates better stain removal. As seen in Table 1, cleaning garments using Tide Infinity with and without enzymes both increased the SRI compared to water, indicating superior stain removal.

The efficacy of malodor removal by Tide Infinity was contrasted against that of a commercial detergent. In this study, the headspace of fabrics treated with artificial body soil and then laundered with the study detergents was measured using GSMS according to a published method.[5] Tide Infinity was tested for its propensity to prevent the oxidation of artificial body soil and squalene precursors. A significant reduction was observed where Tide Infinity yielded only 2 nmol/L of malodor markers present in the headspace versus 37 nmol/L produced from a negative control commercial detergent.

Table 1. Stain Removal Results

Representative Stain Class	Water Control SRI	Tide Infinity nil enzymes Cleaning Improvement from Control	Tide Infinity Full Formula Cleaning Improvement from Control	Tukey Honest Significant Difference
Overall Average	**32.2**	**+13.3**	**+21.2**	**5.7**
Animal Blood	81.9	+4.4	+9.0	4.2
Burnt Butter	33.0	+5.2	+7.0	3.8
Cooked Beef	31.8	+3.8	+6.7	3.8
Grape Juice	27.7	+20.6	+18.0	7.8
Spaghetti Sauce	23.4	+24.4	+50.7	7.4
ASTM Dust Sebum	7.1	+48.3	+47.1	11.2
Chocolate Soy Milk	7.8	+26.4	+28.1	7.4
Discriminating Sebum	-0.9	+3.4	+28.1	7.1
Rice Starch	34.0	+4.3	+44.3	4.6
Coffee	52.0	+6.8	+6.4	3.1
Dirty Motor Oil	22.2	+4.8	+3.8	4.2
Sriracha	58.5	+6.7	+9.8	4.4
U.S. Clay	39.7	+13.9	+16.3	5.7

** Studies utilized ASTM D4265-21 "Standard Guide for Evaluating Stain Removal Performance in Home Laundering".

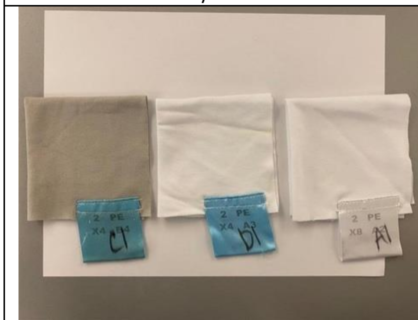
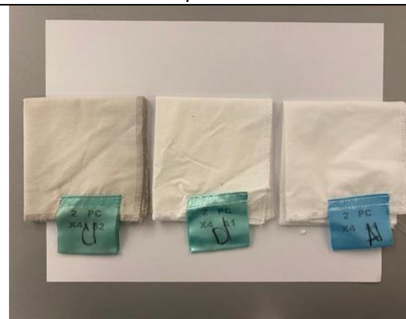
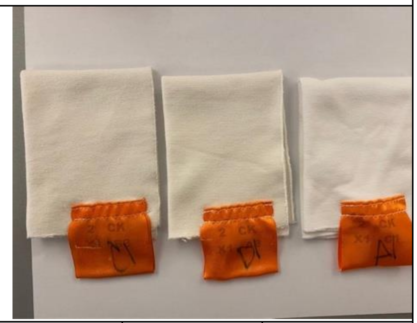
Polyester			Polycotton			Cotton Knit		
								
Water **82.3**	Tide Infinity nil-Enzyme **5.6**	Tide Infinity Full Formula **4.0**	Water **32.7**	Tide Infinity nil-Enzyme **6.0**	Tide Infinity Full Formula **0.4**	Water **34.6**	Tide Infinity nil-Enzyme **35.3**	Tide Infinity Full Formula **1.1**
Cotton Spandex			Cotton Terry					
								
Water **14.2**	Tide Infinity nil-Enzyme **9.4**	Tide Infinity Full Formula **0.0**	Water **33.8**	Tide Infinity nil-Enzyme **19.1**	Tide Infinity Full Formula **0.0**			

Figure 1. Whiteness Test Results using Tide Infinity Formulations (3 wash cycles, lower value indicates whiter)

Tide Infinity was also designed to be effective in a dual laundry machine that is used as both a washer and dryer to effectively clean clothes, recover wash solution for later reuse and capture moisture from drying. After analysis, it was found that the use of Tide Infinity and an integrated cleaning cycle design reduced laundry water usage from a typical North American consumer use range of 56-68 liters (15-18 gal) of water per load[6], to only 15 liters (4 gal).

On-Earth detergent formulations typically have a blend of surfactants, cleaning polymers, enzymes, brighteners, chelants, perfumes, pH modifiers, water control agents, solvents, processing aids, and suds control agents. However, some of these ingredients cannot be used in off-planet constrained environments. Particularly, volatile ingredients such as solvents and fragrances are incompatible with closed-loop air handling systems. Additionally, many cleaning polymers and suds control agents cannot be used. Particulates must also be mitigated or managed so as not to interfere with air purification capabilities. These limitations contributed to the need to develop a fully degradable[***] liquid laundry detergent formulation that would be of acceptable viscosity to maintain product stability (i.e., no phase or color change, yet quickly dissolves with minimal water). The Tide Infinity formulation being studied contains a suite of enzymes effective against several classes of soiling agents, as well as degradable soil release polymers to facilitate cleaning of polyester and performance apparel. Chelants and pH modifiers have also been utilized for cleaning body soils and mitigating malodor on laundered fabrics. An effective but low suds formulation and the absence of a silicone suds suppressor allows for wash water recovery without additional rinsing, which significantly reduces water consumption in the laundry cycle.

[***] The detergent components are degradable according to OECD 301B assessments. The wash water and soil load were subsequently studied in a bioreactor set-up. Additional assessments of degradation pathways such as redox methods are planned to assess alternative water recovery and soil degradation pathways.

IV. Detergent Testing in a Prototypic Wastewater Recycling System

A. NASA Wastewater Recycling Systems

Water recovery systems (WRSs) are a critical component of the Environmental Control and Life Support System (ECLSS) in space habitats, which provide a safe and reliable supply of potable water to support crew health and performance in diverse activities. Approximately 5 liters of clean water is required per crew member per day on the ISS in low Earth orbit.[7] Due to the engineering challenges of microgravity conditions on ISS, water use is limited to necessary activities. For example, clothes and towels are not currently washed and reused, so soiled clothing is converted to solid waste. As NASA transitions to more distant missions on the Lunar or Mars surfaces with partial gravity, running water for hygiene and clothes washing may become more practical. Thus, potential new wastewater streams for future missions will include both hygiene waters and laundry waters. Optimal concepts of operation (ConOps) for reusing both clothes and water in remote habitats will be required to minimize launch mass.

Details of WRS technology options can be found elsewhere[8,9] but one leading option for surface missions is the use of a bioreactor. In all cases, design of the WRS benefits from knowledge of the inlet wastewater constituents.

B. Bioreactor Testing with Laundry for Evaluation of Planetary Wastewater Architectures

A major component of integrating laundry operations with the water recovery system is the detergent composition. The laundry detergent must meet numerous goals including to effectively clean the clothes loading for a crew of four (estimated 9 to 10 kilograms of clothes and towels per week), minimize odor and gas emissions to the cabin air, minimize water required for the laundry machine, and be compatible with the upstream and downstream water treatment subsystems. Goals for the development of a partial-gravity habitat detergent included compatibility with deionized[****] water at ambient temperatures, minimization of siloxane containing compounds, and full biodegradability within the hydraulic retention time of the bioreactor.

A detergent was formulated by P&G to meet these unique space habitat goals. The detergent and optimized ConOps of the laundry machine enabled a reduction in the amount of laundry water required from the previous value of 15 liters per day to 4.3 liters per day and reduced daily total wastewater stream flow rates from 61.2 liters per day to 50.5 liters per day for the WRS, sized for a 4 person crew. The Tide Infinity detergent was provided to Texas Tech University (under contract to NASA) for inclusion and evaluation in a bioreactor-reverse osmosis-distillation system receiving humidity condensate, hygiene wastewater, and laundry wastewater. To date, in addition to the significant water savings, the detergent has met or exceeded all goals at 4 months of continuous testing in the simulated planetary WRS bioreactor system.

There has been a substantial past effort to evaluate biological treatment of space habitation wastewaters[10,11]. Most testing to date has been conducted on either ISS wastewater (microgravity) or expected partial-gravity wastewater streams. Partial-gravity habitat wastewater included a laundry component based on past proposed ratios of commercial detergent (1.2g/L of laundry water) and water use (3.75 L/person/day). This wastewater stream is a mixed wastewater that included urine, humidity condensate (HC), and hygiene waters with shower and sinks. Long term testing with about five years of operations demonstrated that >90% of the organic carbon could be removed using micro-gravity compatible bioreactors which simultaneously operated as the collection tank, receiving all wastewaters as generated. Currently envisioned missions are more focused on sustainable habitation systems. As part of the WRS down-selection process, a candidate system is being tested which includes two separate gravity dependent bioreactors. Urine is collected and treated by one bioreactor, while the other collects and treats all greywater (HC, shower, hygiene, and laundry). The treated grey water is then desalinated using reverse osmosis (RO) and the RO brine combined with treated urine and desalinated using distillation.

Testing of the new system included updating the previous laundry wastewater composition to the most current proposed composition. Laundry wastewater is produced by washing clothes (4.5 kg for a 4 person crew twice a week, for a total of 9 kg a week) using the new recommended detergent/water ratio (Tide Infinity; 34g/15L) for a total production of 30L/week laundry wastewater for a crew of four (1.1 L/crew-day). As we wanted to learn the biodegradability of the new detergent in the bioreactor and given that its concentration is 1.7 times more concentrated, we characterized and compared laundry effluent for its treatability. In this case, treatability is largely defined by the ability to remove organic matter and prevent fouling of downstream systems, specifically the RO system. Laundry effluent water quality over a 4-month operation period is presented below (Figure 2). The laundry organic carbon contributes ~50% of the total greywater organic carbon loading. Effluent quality of the bioreactor was similar for grey water made using either detergent or loading (Figure 3). Over 90% of the organic carbon was removed by the

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[****] Deionized water results from purification in current systems on ISS.

bioreactor and effluent dissolved organic carbon (DOC) was less than 20 mg/l. In addition, for both laundry formulations (old and new) the BOD/COD (biochemical oxygen demand/chemical oxygen demand) ratio of the influent (BOD/COD = 0.5) was reduced to 0.3 and 0.1, respectively, in the effluent. The new formulation demonstrated equivalent biodegradation but with a lower water usage. Absolute 5-day BOD concentrations were < 15 mg/l, which is typical of well treated municipal wastewater. Research is continuing on biological treatment of the grey water with laundry and subsequent desalination by RO to recovery water in partial gravity habitats.

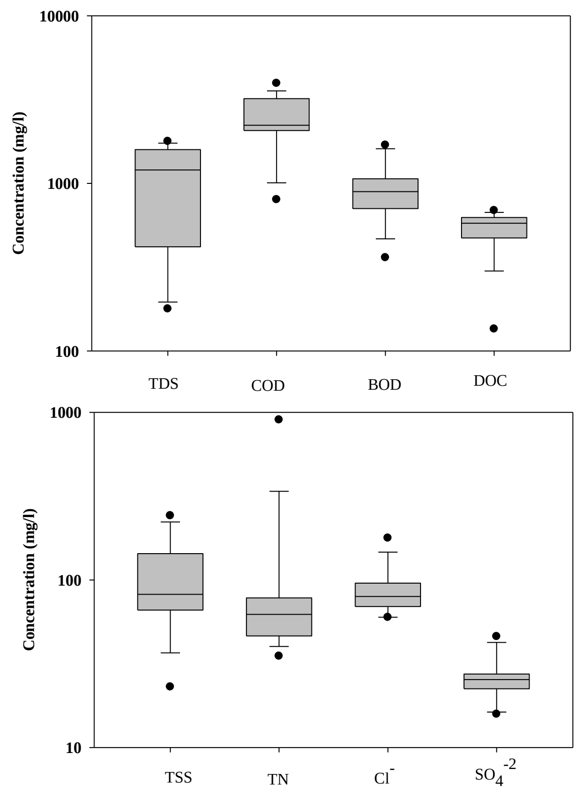

Figure 2. Laundry effluent water quality. Effluent was generated by washing 4.5 kg of soiled clothes in 15L of deionized water and using 34 g of Tide Infinity. Upper graph shows total dissolved solids (TDS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), dissolved organic carbon (DOC). Lower graph shows total suspended solids (TSS), total nitrogen (TN), chlorine ions (Cl-), sulfate (SO4-2).

C. Learning Opportunities and Reapplication on Earth

P&G is and will continually be interested in finding more efficient means to launder consumer garments, including reducing the formulated chemical resources needed for detergents as well as ensuring these detergents reduce the water and energy demands needed to achieve hygienic and clean laundry. There are several similarities with the constrained conditions associated with the ISS and Deep Space missions to those in regions on Earth with constrained water, living space, utilities, and other resources. Reapplication of current learnings include detergent design and wash conditions that may make it possible for the consumer to achieve superior cleaning with less water and utilities. Further reapplication opportunities are being considered as P&G learns more from studies on the ISS and on Earth in collaboration with NASA.

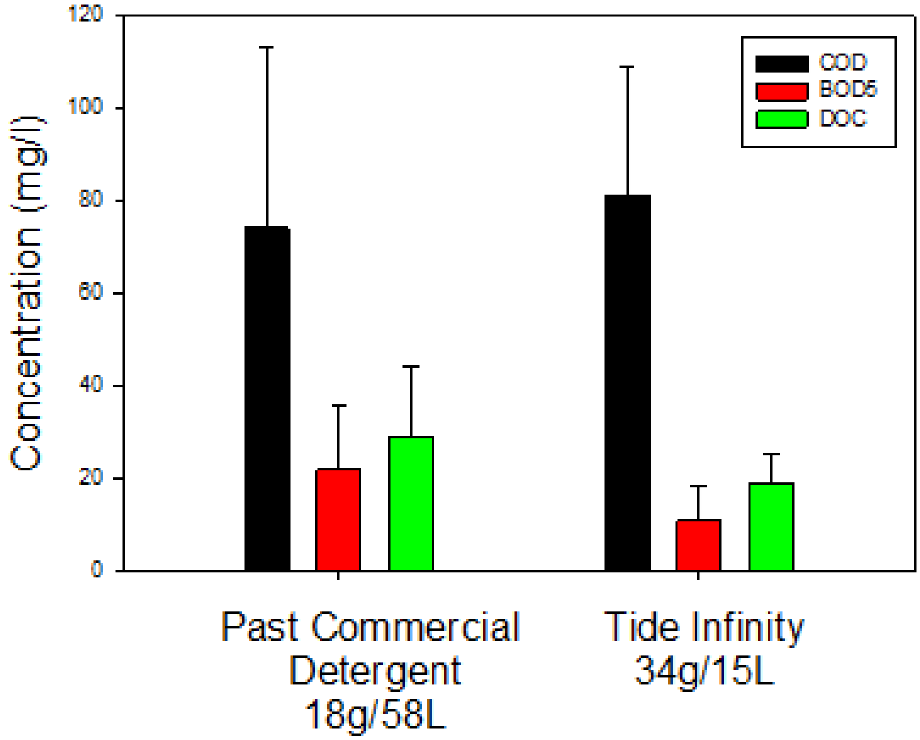

Figure 3. Concentrations of dissolved organic carbon (DOC), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) in greywater after biological treatment for both laundry loading assumptions, with standard deviation shown.

The water recovery system on ISS currently treats only humidity condensate and urine, utilizing physical and chemical processes to recover 93-98% of the influent wastewater. As more extensive hygiene and clothes laundry practices are added in future partial gravity habitats, biological processors become more attractive for treating the wastewater stream. These learnings can also be applied on Earth.

V. Doing Laundry in Space

A. Past NASA Clothes Cleaning Studies

Since Lunar and Mars Laundry is a topic of interest for long duration human missions for logistics reduction, a series of laundry studies were previously conducted at NASA's Johnson Space Center. These studies focused on the removal of malodor and stains on apparel fabrics suitable for spacecraft environments[3,4,12]

After an initial market survey of available sanitizing-cleaning/laundering technologies for apparel fabrics, NASA studies addressed the efficacy of the most promising cleaning methods such as the use of steam alone, ozone in a chamber saturated with water mist, ozone in deionized water, and detergent in deionized water. Deionized water is currently use on the ISS and planned to be used on planetary missions.

The conclusion from these independent studies was that without detergent in water, odor and stains were at best attenuated. However, key observations were made during these studies.

1. Depending on the composition of the soiling agent, the range of results with steam alone span from complete removal of stain and odor to complete persistence of the stain and residual odor.
2. Bulk deionized water alone can be an effective laundry agent if enough laundry cycles are applied. On the other side, the more a fabric is soiled, the more deionized water is required. Hence, water consumption can be high.

3. Ozone sanitation is different. Ozone was anticipated to work better than deionized water by itself since it kills microorganisms and breaks down large molecules,[13,14] making it much easier for the removal of residue. However, while ozone can be very good for killing microorganisms and removing some odors, it leaves its own persistent smell on fabrics. In our studies, results showed that the ozone smell was still present after two deionized water rinses[4].

When considering both odor acceptance and odor detection due to laundry methods in the studies mentioned above, methods with multiple deionized water washes and rinses produced consistently better acceptance and better absence of odor detection. When considering the odor acceptance of fabrics with respect to type of fiber, the two natural fabrics, cotton and wool were equivalent, the two synthetic fabrics polyester and modacrylic were equivalent, and cotton and wool were acceptable more than modacrylic. Wool was also more acceptable than polyester[15]. The varied results across the studies for odor indicated that the different fabrics have different abilities to retain odor. Therefore, each fabric needs to be considered on its own merits.

Aside from the evaluation of cleaning methods for traditional textile fibers like cotton, polyester, and blends of these fibers, NASA has been interested in evaluating the above-mentioned cleaning methods on wool and modacrylic. Wool can be worn longer periods between cleaning cycles than cotton or polyester, and modacrylic performs better than cotton in atmospheres with up to 28-32% oxygen[16].

B. Spaceflight Considerations

Astronauts have very busy daily schedules. Crew time is an expression used in the human space programs when talking about how many tasks can be scheduled each day. Regular daily or weekly activities have fixed duration allocations. Eating, sleeping, and doing housekeeping and laundry are examples of required activities in addition to those required to meet primary mission objectives. Ideally, the less crew time spent on chores like housekeeping and laundry, the more time can be spent working on research and other mission objectives in space. Since laundering will be a new activity for future planetary missions, the laundry crew time needs to be evaluated in early studies in addition to other factors such as mass, volume, power, and other resources required to do laundry. The crew time will also depend on which laundering technologies are used. Therefore, it is important to determine if technologies being considered for clothes cleaning are satisfactory with respect to crew time. Typically, laundering requires crew activities at different periods in the day: preparing the wash load, preparing the washer/dryer for the load of clothes, retrieving the dry clothes, and putting them away. Understanding how these laundering activities affect the work schedule of the astronauts is important. Collecting data on these activities can help answer technology development questions such as the benefit of a washer/dryer combo machine versus separate washer and dryer, or how much time is required for different parts of the process. In addition, the run time of the machines must be determined for the typical laundry load of crew clothing, which will include new fabrics.

This paper, while not focused on laundry hardware development, emphasizes the interconnectedness of hardware and operational factors and the value of early learnings in the development process. This was also observed in the interaction between laundry detergent and the spacecraft water recycling systems described above. The studies currently being conducted by NASA focus on the use of a washer/dryer combo machine using heat pump technology for the drying cycle. One aspect of the "operational learnings" is to determine the length of time needed to dry different loads of fabrics using a washer/dryer combo machine. This "all-in-one" type of laundry machine is attractive for space laundering because it saves mass, volume, and possibly crew time.

A typical load of fabric for planetary missions will likely be different from what a load would be today if laundry was done on ISS. Today, the astronauts wear cotton, polyester, nylon, and polyester/cotton fabric blends. These fabrics have different drying properties that affect their drying time. New flame retardant garments will be needed in exploration programs due to lower pressure, higher percent oxygen habitat environments.

These challenges will be addressed as development and integration work on space laundry continues, as discussed in the next section. Since chemistry (i.e. detergent), machine, and water use/reuse and other factors are all connected, they must be considered as a system. For example, if the fabric types and blends in use change, the composition of the detergent may need to be adjusted.

C. Future NASA Clothes Cleaning Development

One planned study consists of evaluating the mass of each garment before and immediately after wash cycles, then taking mass loss measurements as the fabrics dry until they reach a steady value in each drying condition. The drying treatments include evaporative drying in the laboratory still air, drying with forced air, drying in a washer/dryer combo with heat pump, and drying in a traditional domestic dryer to reach the bone-dry conditions for reference. These studies will start after the completion of the current exploratory study to identify the variables to optimize drying time using the washer/dryer heat pump technology.

The first laundry study using an LG® washer/dryer combo is an exploratory study of clothes drying times. Several possible variables are first listed in Table 2. The variables due to the washing machine are the preprogrammed settings and their options. All these are presented in the owners' manual of the laundry machine. Most of the options can only be used in certain programs to satisfy the hands-off characteristic of this type of machine which washes and dries clothes in the same rotating horizontal-axis drum. This characteristic brought up some questions on the relative humidity inside the drum after the final wash spin cycle. With separate washing and drying units, the initial relative humidity inside the dryer is that of the ambient air in the room when the wash load is transferred from the washer. Hence, it was important to collect relative humidity data after the final wash spin. This was done by choosing the no dry option in programs that allowed that option. Mass data before washing and at the end of the final wash spin was obtained for polyester and cotton wash loads: Marmot 100 % polyester Cocona® T-shirts initial dry mass was 4.57 kg (10.1 lbs.) and the wet mass after final spin at 1600 rpm was 5.08 kg (11.2 lbs.). Under Armour® Charged 95% Cotton/5% spandex T-shirts dry mass was 4.47 kg (9.86 lbs.), and its wet final spin mass was 5.95 kg (13.1 lbs.). The relative humidity in the drum immediately at opening of the door was 91% for the polyester and 97% for the cotton. In other words, the drying process in the tumbler starts in the high relative humidity conditions created during the wash cycles.

Table 2: Variables in the Laundering Process with the LG Washer/Dryer Combo WM3499HVA Using Deionized Water

Laboratory Conditions	Initial T&RH Final T&RH
Wash Load Composition	Composition by fabrics Composition by type of garments Number of each type of garment Initial dry mass
LG Washer/Dryer Combo Washing Programs	Soil Rinse Water Temperature Spin Dry Wet mass after final wash spin
Drying Programs	Mass after 30 min drying Mass after 60 min drying Mass after 90 min drying Mass after 120 min drying Time to reach initial mass
Drum Conditions	Drum T&RH after final wash spin Manual mode end time Programmed washing time Drum final T&RH

Using the list in Table 2, the first findings are that laboratory conditions are not affected by the drying cycle of the machine. In other words, the room did not get warmer and more humid while the machine was running the selected wash/dry cycles. Therefore, room temperature and relative humidity (T&RH) are not considered as variables for the next series of studies that will be conducted in the same laboratory. On the other hand, temperature and relative humidity inside the rotating drum will affect drying time. This is because evaporation is a surface phenomenon that depends on temperature, surface area occupied by the liquid, humidity of the surroundings, and air circulation.

In the wash load composition section of Table 2, fabric composition with respect to type and content of fibers is a variable since the more hydrophilic fabrics take longer dry. Composition by type of garments (T-shirt, pants, socks, etc.) has not been tested yet. Likewise, number of each type of garments in the wash load has not been tested yet. However, these two factors, fiber content and garment type, are important as they correspond to different surface area to mass ratios of fabrics in the wash load. The drying of a wet textile material requires an air stream to take away the water vapor from the surface. It is this surface area to mass ratio that will be the useful variable in the drying time study.

To complete research and development of laundry systems for space, the many factors and systems discussed above must be integrated into a successful operational solution. This includes the cleaning process (detergent/water), washer/dryer technology, the water recycling system, and user (astronaut) interactions. Most of these will be integrated in an upcoming Crew Health and Performance Exploration Analog (CHAPEA) ground test[17]. Tide Infinity detergent will be used in a commercially available combination washer/dryer with heat pump dryer. Simulating prototypic water recycling is beyond the scope of CHAPEA, whose focus is on testing space food systems in a Mars habitat. However, clothing and water will be limited for the crew of 4 and as prototypic as possible ConOps will be executed.

One of the biggest variables to consider for laundry machine design in outer space is gravity, or lack thereof. This part of the development process will focus first on space habitats with some gravity (1/6 Earth-G for Artemis Moon missions and 1/3 Earth-G for Mars surface missions), deferring the zero-G fluid management challenges associated with low Earth orbit and Mars transit habitats. It is anticipated that common washer/dryer designs from Earth can be adapted for lower gravity, and the Small Business Innovation Research program is being used to investigate this assumption[18].

VI. Conclusions

Under a Space Act Agreement, NASA and P&G have collaborated to identify goals and challenges for clothes cleaning in resource constrained environments such as outer space. P&G developed a new liquid laundry detergent formulation called Tide Infinity to meet those parameters. In combination with the use of optimized cleaning cycles, the use of Tide Infinity significantly reduced the water used per laundry load. NASA, through a grant with Texas Tech University, has been evaluating Tide Infinity in an experimental water recovery system using bioreactors. Results have been positive and long-term testing continues.

Additional studies are in progress for long term analysis of stability and cleaning efficacy of Tide Infinity when exposed to space travel, microgravity, and radiation. Some of these will be conducted on ISS and others on Earth for economic reasons. NASA plans to evaluate Tide Infinity in physical-chemical water recovery systems in addition to the bioreactor based systems. Further studies include realizing water reduction learnings for consumer laundering processes and treatments on Earth.

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