Ultrasonic Washer–Dryer System for Space Habitats: Design Upgrades and Parabolic Flight Readiness

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Clothing makes up nearly 25% of all non-food supplies sent to the International Space Station (ISS). To support sustainable human missions in deep space, NASA's Life Support and Habitation Systems Focus Area looks to advance technologies to support and improve logistics. Our team is creating a compact ultrasonic clothing washer/dryer system that bypasses traditional limitations and is suitable for space. Thermal drying uses a lot of energy to evaporate water, while our ultrasonic drying method offers a quicker, more efficient alternative. It uses piezoelectric transducers to vibrate textiles at the micron scale, mechanically removing water as cold mist rather than evaporating it. This speeds up drying and reduces energy use, no matter the fabric makeup. This paper details recent upgrades to a full-scale ultrasonic washer–dryer system, readying it for parabolic flight testing. Improvements include an enhanced human–machine interface, better packaging, and optimized performance and control. We also present extensive pre-flight ground tests conducted to ensure reliability and identify potential risks. Collaborating with P&G, we report preliminary cleaning tests using various detergents. These results lay a crucial foundation for the laundry system designed specifically for space. By cutting clothing-related payload and waste by over 97%, this technology supports long-term human exploration missions on the ISS, the Moon, Mars, and beyond.

Nomenclature

ESM	=	Equivalent System Mass
ISS	=	International Space Station
UTS	=	Ultrasonic Technology Solutions

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I. Introduction

Approximately one quarter of the non-food supplies on the ISS consists of clothing for crew members. All clothing, regardless of use, is eventually soiled and ultimately discarded. This is more frequently applied to exercise clothing. For health reasons the crew must perform prolonged daily exercise. The lack of on-board laundry facilities forces them to re-use sweaty, soiled clothing for multiple days with final disposal and storage of exercise clothing after roughly one week of use. From this daily exercise arises the need for fresh clothing that is comfortable, hygienic and free from foul aromas. Addressing this issue requires developing a compact, efficient washer-dryer unit suitable for use in lunar, Martian, and microgravity environments. NASA aims to develop technologies enabling extended duration of manned missions in deep space. This paper introduces an innovative solution that meets the above requirements.

Conventional thermal evaporative drying consumes substantial energy because of the need for phase change. Theoretically, evaporating 1 kg of water requires 2,200 kJ, but the actual energy consumption is often three to four times higher due to inefficiencies in standard drying machines [1, 2]. In specialized applications like freeze-drying food and dehydrating fruits or vegetables, energy usage can be 20 to 30 times greater [3]. Under the author's leadership, researchers at Oak Ridge National Laboratory invented a novel direct contact ultrasonic drying technology, now exclusively licensed by Ultrasonic Technology Solutions (UTS), to overcome these limitations. Unlike traditional thermal drying, this approach does not rely on heat to evaporate water; instead, piezoelectric transducers generate high-frequency mechanical vibrations that displace water at the microscopic scale. The water is mechanically removed from the wet material as a cold mist jet ejected from micro-holes at the centers of piezoelectric elements. The process is shown in Fig. 1. By significantly reducing reliance on evaporation, this method enhances both energy efficiency and drying speed.

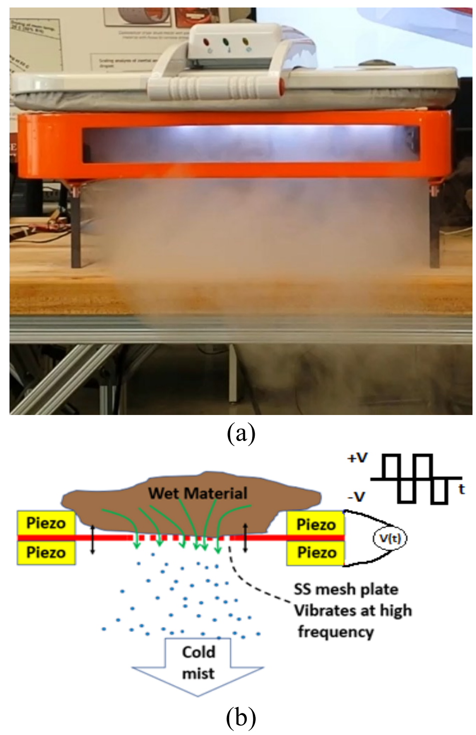


Figure 1. a) Cold mist extracted from wet fabric using a direct contact ultrasonic dryer. b) Schematics of water extraction from wet material using the bi-morph piezoelectric transducer.

In 2023, Ultrasonic Technology Solutions (UTS) demonstrated a feasibility module for the combination of ultrasonic washing and drying of textile samples. Through this study, effective removal of oils, salts, and stains was achieved while preserving fabric integrity. Optimal cleaning took place within 5–10 minutes. Ultrasonic drying was demonstrated across multi-layer fabric stacks, enabling a significant reduction in system size and providing performance data relevant to NASA’s requirements [4]. In 2024-2025, the team validated a full-scale ultrasonic washer–dryer using folded, full-sized garments, achieving >75% water removal from an eight-layer T-shirt within the first 30 minutes using an ultrasonic dryer, and demonstrating a hybrid ultrasonic-thermal drying process that outperformed evaporative-only methods. Autonomous wash-and-dry cycles were completed in 82 to 138 minutes (9–15 garments/day), with up to 99.989% microbial reduction in fabrics [5-6].

The current study presents recent design upgrades to an ultrasonic clothes washer–dryer system developed for parabolic flight testing. The work includes improvements to the human-machine interface, optimized system encasing for area efficiency, and refined performance and control strategies, along with extensive pre-flight ground testing to assess long-term reliability and identify potential risks. In collaboration with P&G, preliminary cleaning experiments using multiple detergents and conditions were conducted and are reported here. Together, these findings establish a critical foundation for the laundry system explicitly designed for space which reduces clothing-related payload and waste, in turn supporting long-duration human missions aboard the ISS, Gateway, and habitats and transit vehicles on the Moon, Mars, and beyond.

II. Technology Background

Traditional drying techniques such as heat and evaporation are energy-intensive. Instead, as shown in Fig. 1b, a novel method is used by employing piezoelectric elements to generate intense micro vibrations on the surface of the wet material [7-15]. These vibrations produce high accelerations, aiding in mobilizing water trapped in the fabric. The water then moves toward an array of micro holes located at the center of specially designed transducers, where it is expelled as a cold mist driven by vibrational energy. Figure 1a illustrates the cold mist ejected from wet fabric in prior prototypes. This micro-pumping approach has proven to be highly effective at higher moisture contents, markedly enhancing drying efficiency and speed in tests with standard textiles.

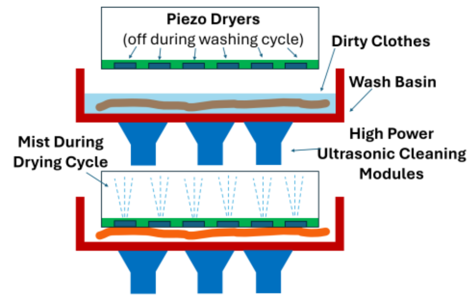


Figure 2. Schematic of the key components of the combo ultrasonic clothes washer and dryer.

III. Test Setup & Results

The schematic representation of the ultrasonic washer–dryer for space applications is shown in Fig. 2. After the crew member folds the T-shirt and places it in the machine, water is pumped into the bath. During the washing cycle, the high-powered ultrasonic elements introduce intense vibration into a thin layer of water in contact with the fabric, generating cavitation. The intense pressure waves produced through the cavitation process bombard the surface of the garment. This mechanically dislodges oils, salts, particulates, dead body cells, and microorganisms from textile fibers without relying on bulk agitation, detergents, or elevated temperatures. The disinfecting potential of the ultrasonic fabric washing was reported in a recent publication [6]. Following approximately 10 minutes of washing, the water is drained and the system transitions to an ultrasonic drying mode in which dedicated direct-contact ultrasonic dryer modules induce rapid, directional ejection of water from the fabric (as a fine mist), enabling efficient moisture removal for the bulk water. The mist is taken in by a water-capturing unit (not shown here), where the air-mist separation occurs through the centrifugal action of a spiral air passage. In the final phase, evaporative thermal drying is employed to remove the residual water from the fabric, completing the drying cycle. During the ultrasonic drying process, the water-capturing unit traps mist and small droplets, then a diaphragm pump drains the collected water. During the thermal drying phase, the water vapor passes through the water capture system and is released into the cabin after passing through a HEPA filter. By combining ultrasonic washing and drying into a single, compact architecture and relying on mechanical energy to remove the bulk of water rather than solely on thermal evaporation, this approach enables a lightweight, fast, efficient, and modular garment care system well-suited for spaceflight environments and long-duration human missions.

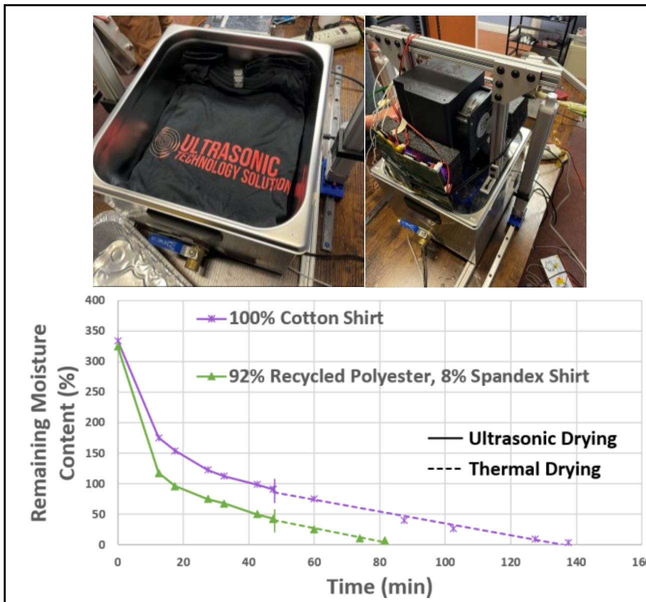


Figure 3. Completed prototype with the integrated sensors and instruments.

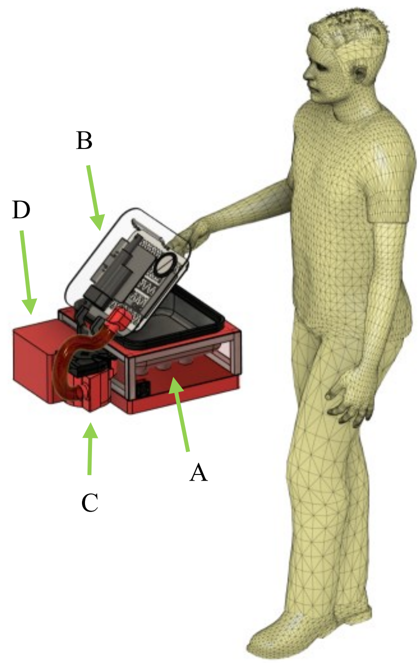
In 2025, the team demonstrated that the full-scale prototype could dry an 8-layer, folded, full-sized T-shirt. Figure 3 shows the alpha prototype along with the drying test results for two T-shirts. The ultrasonic washing cycle duration was 10 minutes, followed by hybrid ultrasonic and thermal drying. Two common T-shirt materials are compared: 100% cotton and 92% recycled polyester with 8% spandex. As shown in the graph, the spandex garment, which is widely used on ISS, had a much faster total drying time (about 83 minutes), whereas the cotton T-shirt took

135 minutes to completely dry. In other words, if the machine is used continuously, it would have the capacity to wash and dry 9 to 15 T-shirts per day.

IV. Upgraded Test Setup

More recently, several upgrades have been implemented to improve the system's compactness and efficiency. One area is the enhancement of the water capturing unit design. Figure 4a shows several versions of the centrifugal component, illustrating each modification which led to a smaller and more compact unit. All actuators, the ultrasonic bath, and the linear rails have also been substantially shrunk. Figure 4b shows the 3D rendering of the near-final system. The upgrade’s dimensions are 484 mm long x 366 mm wide x 239 mm tall, for a total volume of 44 liters. This is less than half the volume of the previous working version. Figure 4b shows the upgraded system at scale. Component A is the ultrasonic cleaning basin. B is the ultrasonic dryer module integrated into the lid. C is the water capture unit. D is the electronics box for the system. The crew member opens the lid, folds the fabric, places it in the machine, closes the lid, and presses the start button to begin the washing and drying cycles. The team successfully fabricated this system and conducted the initial evaluation. The design is primarily for a Martian environment, but by adding two balanced systems (not shown here) and low-speed rotation, it could also be used in microgravity conditions. In preparation for the parabolic flight evaluation, the team began reliability and extended-life testing. The ground testing includes 50 washing-and-drying cycles of T-shirts. As a result of this test campaign, the team will identify the potential design issues and prepare the upgraded system for parabolic flight evaluation. Also, water samples will be collected to identify the appropriate downstream water-processing requirement for the drained or captured water, which will be subject to separate studies.

(a)



(b)

Figure 4. a) Water capturing unit. From left to right, design improvement and size reduction evolution.
b) Upgraded ultrasonic combo clothes washer and dryer module with water capturing unit.

V. Preliminary ESM Analysis

A traditional Equivalent System Mass (ESM) analysis was performed on the full-scale ultrasonic washer–dryer system shown in Fig. 3 using updated coefficients from the most recent ESM model. The analysis accounts for the entire integrated system, including the washer, dryer, and water-capture components, as well as associated power, volume, cooling, and crew-time footprints. This is done both for the alpha prototype and the projected upgraded system that will be tested in parabolic flight. For simplicity, the 1.5-2 liters of recycled water used per laundry cycle is not included in this analysis because the use will be highly process-dependent. Table 1 presents the system mass breakdown and the resulting ESM calculation.

The pictures of the alpha prototype system shown in Fig. 3 include a total hardware mass of 13.29 kg, comprising the ultrasonic washer, dryer, and water capture unit, and an enclosed system volume of approximately 93 liters. The system operates in both eco and performance modes, with power consumption up to 330 W in performance mode and 260 W in eco mode. Based on the measured operating parameters and mission assumptions, the calculated ESM of the system is 63.73 kg in eco mode and 69.09 kg in performance mode. The projected ESM for the upgraded system is also shown in this table to be about 59 kg. The upgraded prototype will be evaluated in a parabolic flight. The crew time is being estimated based on the limited ground testing conducted on the Alpha prototype. A more accurate estimate of crew time will be considered after completing the 50-cycle reliability testing and the human interaction evaluation during parabolic flights. Table 1 also presents sensitivity analysis and shows that a 10% reduction in power has ~5X more impact on ESM reduction than a 10% reduction in system mass.

By enabling repeated garment reuse, the ultrasonic washer–dryer system could potentially reduce logistics mass, waste generation, and launch costs while improving crew habitability for extended missions aboard the ISS and future lunar and Mars habitats.

Table 1. a) Preliminary ESM analysis for the evaluated alpha prototype & upgraded system projection. b) ESM sensitivity analysis for 10% change in each parameter.

	Performance Mode (e.g. 330W average)		Alpha Prototype	Upgraded system /Projection
	Inputs			
M	mass kg		13.29	10.00
V	pressurized volume m^3		0.09	0.04
Veq			13.40	13.40
P	total power kWe		0.33	0.25
Peq	the mass equvalent for power generation kg/kWe		87.00	87.00
C	total cooling required	kwth	0.02	0.02
Ceq	the mass equvalent for cooling infra kg/kWe	kg/kwth	146.00	146.00
CT	Total crew time required	CM-h/y	121.67	121.67
D	duration of mission y		0.20	0.20
Cteq	the mass equvalence of crew support kg/CM-h		0.96	0.96
			Combo Washer and Dryer ESM Calculated (equivalent mass)	Combo Washer and Dryer ESM Calculated (equivalent mass)
			69.03	58.57

(a)

Variable	Value ± Uncertainty	Partial Derivative	ESM reduction for -10% change in eahc vale
P	0.33 ± 0.033	$\partial ESM1/\partial P1 = 87$	-2.87
M	13.29 ± 1.329	$\partial ESM1/\partial M1 = 1$	-1.32
C	0.02 ± 0.002	$\partial ESM1/\partial C1 = 146$	-0.29
V	0.09 ± 0.009	$\partial ESM1/\partial V1 = 13.4$	-0.124
ESM	**69.49 ± 3.179**	—	—

(b)

VI. Energy Usage Comparison to Terrestrial Technologies

Conventional household and industrial dryers rely predominantly on resistive heating to evaporate water from textiles, a process that is inherently energy-intensive, owing to the high latent heat of vaporization. As a result, most of the input energy is expended on phase change rather than on effective moisture transport, leading to relatively low drying efficiency. This is particularly true during the early stages, when fabrics have a high free-water content. Heat-pump dryers improve overall energy efficiency by leveraging ambient heat and by using vapor-compression thermodynamic cycles. However, heat-pump dryers exhibit slow moisture removal rates during initial drying and require extended cycle times to achieve acceptable dryness. Additionally, neither technology is microgravity-ready and requires significant engineering to operate under partial-gravity conditions. Their size, mass, volume, plus having moving and rotating parts also make them inappropriate for space applications.

In contrast, the ultrasonic drying approach employed in this work removes moisture primarily via mechanical ejection rather than thermal evaporation. Experimental results show that ultrasonic drying achieves significantly lower energy consumption per unit mass of water removed, particularly during the early stages of drying, with energy efficiencies several times higher than those of conventional thermal systems. Figure 5 compares alpha prototype results with the conventional residential dryers. While ultrasonic modules may draw higher instantaneous electrical power, the energy required per gram of water removed is substantially reduced (i.e., 1000 kJ/kg ultrasonically vs. 4000-5000 kJ/kg in residential dryers), enabling rapid removal of free and loosely bound moisture. The evaporative thermal drying used to remove residual moisture from the fabric consumed substantially more energy per unit mass of water removed; however, the failure to implement insulation on the heater exterior made it even less efficient than expected. In the upgraded system, we will ensure to use appropriate insulation to reduce the thermal losses during the final evaporative drying stage.

VII. Investigation of Ultrasonic Cleaning Performance with Detergent Formulations

In a previous publication [6] the cleaning performance of the combined ultrasonic washing and drying prototype was reported, demonstrating high levels of cleanliness and disinfection using water alone. Building on those results, an additional experimental campaign was conducted in collaboration with P&G to evaluate the cleaning efficacy of ultrasonic cavitation when combined with selected detergent formulations during the washing phase. The objective of this work was to investigate how detergent chemistry interacts with ultrasonic cavitation intensity and to identify dominant trends in cleaning performance across a range of fabric and soil types.

The cleaning performance of a garment in an ultrasonic cleaner depends on numerous interacting variables, including fabric composition, detergent type and concentration, ultrasonic power level, temperature, cleaning duration, and soil characteristics. Rather than attempting to explore the whole multidimensional parameter space, this initial study was designed as a screening campaign in which fabric type, detergent type, ultrasonic input voltage, and soiling agent were varied while temperature and cleaning time were held constant. This approach efficiently identified significant effects and interactions.

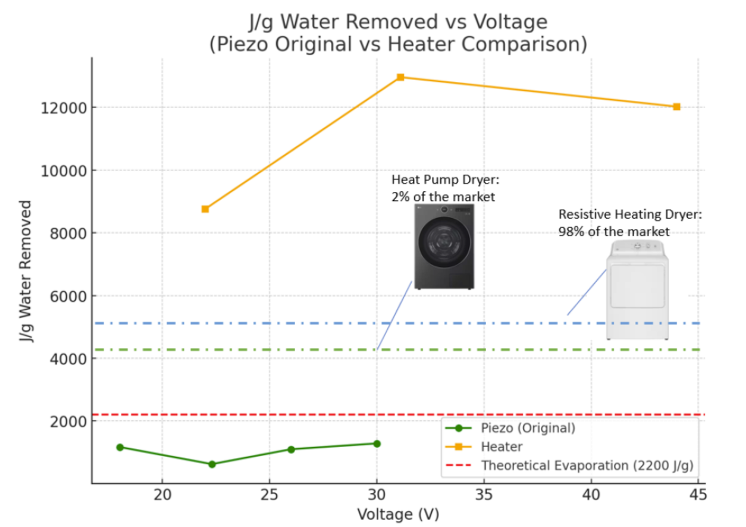


Figure 5. Comparison of the performance of different technologies.

The experimental effort was conducted in a coordinated collaboration between the UTS and P&G teams. P&G was responsible for fabric preparation, soiling protocols, detergent selection and recommended concentrations, and post-cleaning analyses. UTS prepared the ultrasonic cleaning system, developed test procedures, conducted cleaning experiments, and collaborated with P&G on interpreting the results. Three ultrasonic cleaning methods were evaluated for this study. The first consisted of water-only ultrasonic cleaning at the maximum system input voltage of 110 V. The second used a solution of water and commercial Tide Ultra Oxi Free detergent at a target concentration of 3.5 g/L, operated at a reduced ultrasonic input voltage of 50 V. The third method used a detergent solution prepared by mixing the liquid contents of Tide Stain Pens with water (approximately 30 mL detergent in 1.6 L water), also operated at 50 V. These conditions were selected to evaluate the combined influence of detergent chemistry and ultrasonic cavitation intensity.

The first set of experiments focused on cotton towel samples treated with a malodor-producing soiling agent. Small fabric specimens approximately 1 × 2 inches were prepared at two malodor levels, low and high. For each level and cleaning condition, ten replicate samples were tested. Malodor panel evaluations were conducted by P&G before cleaning, and follow-up malodor panels were undertaken after cleaning to assess odor reduction. Figure 6 shows part of the samples used in these experiments.

For traditional washing, a miniature 8-liter washing machine, designed to operate identically to a top-loading consumer washer with a center-post agitator, was used. Identical fabrics, detergents, and detergent doses as the ultrasonic cleaning were assessed. The traditional washers contained water measured to have a hardness of 7 grains per gallon and a temperature of 60F. Agitation of the test fabrics, water, and detergents was set for 17 minutes, followed by a drain and spin. Water at the same conditions was added a second time for a 2-minute rinse with agitation, drain and spin. The fabrics were then dried in a commercial dryer for 30 minutes on medium heat. These conditions mimic a traditional consumer washing machine standard cycle.

The second phase of testing examined fabrics contaminated with consumer-relevant visible soils in polyester and polycotton fabrics. The fabrics were pre-washed and then treated with a standardized soil mixture containing particulate matter, proteins, and body soils. Before cleaning, the P&G team quantified visible soil levels using colorimetric analysis. Following cleaning, color measurements were repeated, and fabric mass changes were evaluated to quantify soil removal. For each fabric type and cleaning condition, three replicate samples were included.

The final phase of the study focused on consumer-worn polycotton T-shirts post exercise and slept in for three to five days without deodorant, generating realistic malodor and soil loads. Before cleaning, malodor panel assessments were conducted, and test sections were cut from the garments based on areas that had noticeable odor. After ultrasonic cleaning, the samples underwent additional malodor panel evaluation testing performed by P&G. Ten replicate samples were tested for each cleaning method. In addition to the three cleaning methods described above, a water-only ultrasonic cleaning condition at 50 V was included to isolate the effect of ultrasonic cavitation intensity from detergent chemistry.

Figure 6. Preparation of Low Malodor Samples (Green) and High Malodor Samples (White)

Together, these three experimental approaches span a wide range of fabric types and soil challenges, including invisible soils, visible soils, and malodors generated through real consumer wear. This breadth allows trends to be evaluated across conditions that are directly relevant to consumer laundry use. Cleaning effectiveness was measured at P&G through malodor reduction, visible soil removal, and gravimetric analysis.

Malodor reduction is assessed by panelists trained to smell and identify the presence of body odor, rank ordered by odor level (none to high), odor character, and as comparisons between treatments (blind code comparisons to identify 1:1 comparison of which has more malodor).

Visible soil removal is completed using a Konica Minolta CM-3610D spectrophotometer. Before and after treatments, color reads of L, a, b, and (WI)CIE values are measured. The deltas of these values determine how close the dingy fabric, through treatment conditions, has returned to the original color values (white), from before the fabric was made to be dingy. Color change in the following table 2 is defined as delta WI(CIE) values.

Gravimetric analysis is completed through weight measurements of the fabrics on a digital scale before and after treatment conditions to determine if soils, including those that may not impact color, have been removed.

Malodor is assessend by imprinting the fabrics with artifictial soil and assessed for malodor strength. The malodor on clothing from soils is assessed following treatments through chemistry, mechanical removal, or other treatments that will reduce fabric malodor [16].

Table 2 summarizes the detergent impact on the ultrasonic garment cleaning study results. As noted previously, the overarching goal of this work is to examine how ultrasonic vibration and cavitation intensity affect cleaning performance when applied with water alone and with detergent formulations.

Testing with Tide Oxi detergent and ultrasonic cavitation at 50V show a significant malodor reduction compared to a traditional wash for the malodor panel on t-shirts in Test 1. These results suggest that detergent chemistries and ultrasonic cavitation intensity can be used together to reduce malodor.

Traditional wash testing showed strong soil removal performance for the Tide Infinity detergent. Removal of colored soils was improved with traditional washing and detergent, increased voltage and Tide Infinity were not used together in these treatments.

The second table includes measurements of malodor after cleaning on the shirts that were worn during exercise with different washing methods in the absence in detergent. These results are qualitative rather than quantitative. The studies show high malodor in a traditional wash without detergent. In a test with ultrasonic cleaning at 50V, a reduction in malodor is observed. Increasing the intensity of the ultrasonic cavitation to 110V yielded increased soil removal observed. This result further supports the conclusion that ultrasonic cleaning improves malodor reduction. This study has motivated further experimentation on high-intensity ultrasonic cleaner operation.

In summary, this screening study demonstrates that the combined effects of detergent chemistry and cavitation intensity govern cleaning performance in ultrasonic laundry systems. Ultrasonic cavitation appears to have a positive impact on malodor reduction, while detergent selection strongly influences visible and invisible soil removal and malodor reduction. Based on these findings, future work should focus on evaluating high-intensity ultrasonic cleaning in combination with advanced detergent formulations, particularly Tide Infinity, to simultaneously achieve effective soil removal and malodor control. Further studies are ongoing to leverage ultrasonic cavitation with detergent chemistries to develop an efficient laundry process for deep space missions. Results from the ongoing P&G analyses will be incorporated into future publications as they become available.

Table 2. Summary of the detergent impact on the ultrasonic garment cleaning investigation.

	Malodor Panel HIGH MO towels	Malodor Panel t-Shirts Test 1	Malodor Panel t-Shirts Test 2	Color change PE	Color change PC
Water UTS 50V	38	NA	64	0.8	-0.67
Water UTS 110V	NA	87	70	NA	NA
Water Traditional	33	99	NA	7.29	-0.72
Tide Oxi UTS 50V	51	63	NA	-0.36	-0.96
Tide Oxi Traditional	40	87	57	-12.3	-4.67
Tide Infinity Traditional	NA	NA	43	-11.3	-5.92
Tide Stain Pen UTS 50V	NA	NA	NA	0.87	-1.17
Tide Stain Pen Traditional	NA	NA	NA	6.67	-3.04
	all legs had negative comments- different intensities	Tide Oxi UTS had positive comments	Tide Infinity Traditional had positive comments		

	Malodor (Soil) Growth Measured After Cleaning on Shirts Worn During Exercise
Water UTS 50V	Medium
Water UTS 110V	None
Water Traditional	High

Color Scale	Favorable Results			Unfavorable Results

VIII. Conclusion

This study reports the performance of a novel combination clothes washer and dryer designed for space applications. The team demonstrated that the full-scale prototype could dry an 8-layer, folded full-sized T-shirt. In this process, the ultrasonic washing cycle was 10 minutes, followed by hybrid ultrasonic and thermal drying. Two different T-shirt materials, including 100% cotton vs. 92% recycled polyester and 8% spandex, were compared. The spandex garment, which is widely used on the ISS, had a much faster total drying time, about 83 minutes, whereas the cotton T-shirt took 135 minutes to completely dry. These results show that if this compact machine is used continuously, it would have the capacity to wash and dry 9 to 15 T-shirts per day. The paper also described the high-level modifications resulting in an upgraded system. The expectation is for the volume of the system to be as low as 44 liters. The ESM analysis also demonstrates ESM 69 and 58 for the alpha working prototype and the upgraded prototype. The comparison of the experimental results with the commercial drying machines demonstrates significant energy-saving potential. Energy efficiency is the most important parameter driving the ESM for the proposed technology. Lastly, in collaboration with P&G, the team investigated the impact of several detergent uses on several types of soiled fabric during the ultrasonic washing cycle. The screening results indicate that ultrasonic cavitation intensity plays a role in malodor reduction; and the combined effects of detergent chemistry and cavitation intensity govern cleaning performance in ultrasonic laundry systems. High-intensity ultrasonic operation appears to have positive impacts to achieve effective malodor suppression, while detergent selection strongly influences visible and invisible soil removal and malodor reduction.

Acknowledgments

This study was sponsored by the National Aeronautics and Space Administration (NASA) under Contract No. 80NSSC23CA166 & 80NSSC25C0446 with Ultrasonic Technology Solutions, LLC. The authors would like to acknowledge NASA for sponsoring this research.

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