Ultrasonic Clothes Washer/Dryer Combination for Moon, Mars, and ISS Applications

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Our study aims to investigate the effectiveness of an ultrasonic-based combo garment washing and drying system for space applications. Our system leverages our technological innovations in direct-contact ultrasonic fabric drying in combination with ultrasonic fabric washing. The main objective of this investigation is to gauge the effectiveness of washing and drying textile garments ultrasonically. In this paper, we will report the results of experiments conducted to assess the effectiveness of washing clothes ultrasonically, including ultrasonic intensity testing, stain removal testing, and fabric degradation testing. This study's outcome could lead to the production of an Ultra-Fast Ultrasonic Washer/Dryer Combination unit that would reduce clothing resupply costs for crewed missions to the moon, Mars, and the ISS.

Nomenclature

ISS = International Space Station
LEO = Low Earth Orbit
RMC = Remaining Moisture Content (%)
SBIR = Small Business Innovation Research
UTS = Ultrasonic Technology Solutions
SOA = Safe Operating Area
UV-IR = Ultraviolet- Infrared
VOC = Volatile Organic Compound

I. Introduction

If humans are to explore Mars or spend long periods of time living and working on the moon or in Earth's orbit, many life support and habitation system technologies will have to be invented or improved. Key capabilities and technology solutions to extend human presence in the solar system are already in development under various NASA programs, including the recycling of carbon dioxide, urine, and fecal waste products of crew members. Creating an efficient and sustainable habitat for these future explorers will also require lightweight, low-power, compact

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appliances to fulfill many of the functions we take for granted on Earth, such as meal preparation, waste handling, and clothes cleaning. As part of NASA's technology roadmap to improve human accommodations for exploration missions, a 2022 Small Business Innovation Research (SBIR) solicitation called for innovations in food heating, refrigeration, hygiene, and clothing washers/dryers. For clothes cleaning, a combination washer/dryer was requested that could operate at Moon or Mars gravity and clean up to 4.5 kg of cotton, polyester, and wool clothing in a timeframe of <7 hours having <50 kg machine mass, <0.3 m3 external machine volume and using <300 Watts of electrical power.

In response to the Human Accommodations SBIR call, Ultrasonic Technology Solutions (UTS) proposed a direct contact ultrasonic clothing washer/dryer. Using piezoelectric transducers, this novel method agitates the clothes in a small amount of water to remove soils using sound waves and then mechanically removes water by rapidly shaking them (on a micron-scale). By partially bypassing the evaporation process, the technology demonstrates efficiency and drying speed improvements compared to traditional laundry. UTS has now completed a Phase 1 SBIR contract to prove the concept, and the results are described here. It is believed that this technology can be used for efficient clothes washing/drying on the International Space Station (ISS) in Low-Earth Orbit (LEO), on the moon and Mars, and back home on Earth.

Currently, there are clothes laundering systems used in outer space, mainly due to water budget and mass and volume limitations. For example, astronauts must exercise for 2.5 hours each day to keep their health and bone density. Due to weight and volume restrictions, the astronauts do not place their clothes in a washing or drying machine after exercise; instead, astronauts in the ISS have to wear the same exercise clothing up to 7 times and discard them in the trash due to significant body odor.

Drying any wet material conventionally using heat and evaporation requires a tremendous amount of energy. Ideally for every 1kg of water removal, 2,200kJ/kg is required and accounting for all the inefficiencies of regular industrial or residential dryer machines, 3 to 4 times this is currently required per every 1kg of water removal. In the case of freeze-drying food, fruit and vegetable drying, 20-30 times of this energy is being used [1]. To dry wet material, our team took an entirely alternative path. In order to dry a wet material, unique piezoelectric elements are used to shake (vibrate) the material very hard at a micron-level scale. The extremely high acceleration introduced to the water trapped in the wet material moves it out. This water will migrate toward thousands of small micro-holes at the center of our uniquely designed transducers, where the immense vibration ejects it out in the form of cold mist. This micro-pumping effect is very efficient for drying materials, including fabric, drywall, pulp, and paper [2-11]. Also, the application of this novel drying method for human solid waste drying for NASA applications has been successfully demonstrated [12].

II. Machine Details

The completed Ultrasonic Combination Washer/Dryer unit will be very compact, weighing less than 5 kg and taking up less than 0.02 m^3 of volume (roughly the size of a large laptop). The overall power consumption during drying will be 100-250 W during the drying cycle and 100-150 W during the ultrasonic washing cycle (depending on if two or three ultrasonic cleaner piezo assemblies will be used). The benefit of using an ultrasonic Combination Washer/Dryer over conventional washing and drying machines is an expected reduction of lint generation and fabric degradation during normal use, and the elimination of harsh chemical or detergent use. Moreover, unlike the conventional methods, there would not be any rotational components in the system. The rendering of the proposed system is shown in Fig.1.

Figure 1. Rendering of the proposed ultrasonic Combination Wash/Dry Unit.

The heart of the system is composed of two or three high-powered ultrasonic cleaners attached to the exterior stainless-steel wall of the system. The ultrasonic drying component of the machine consists of a 150-250 piezo matrix installed on the lid. The low-density foam (or rubber mesh) is responsible for keeping water on the surface under zero-gravity conditions while not impacting the ultrasonic cleaning performance. Crew members on ISS will fold their T-shirt (or clothes) along with the towels or their socks then place them on the foam. The lid is closed, and the machine begins cleaning. During the washing cycle, only the ultrasonic cleaners will be turned on for 5-10 minutes to wash the fabric by agitation. Then the ultrasonic cleaner will be turned off, and the ultrasonic dryer on the lid will be turned on to pull all the dirty water upward through micro holes. In the back of this matrix, there are several microcapillary and micro-grooves to capture water. For capturing the vapor portion of the mist, a small thermoelectric-based heat exchanger will be used to condense water, assisting the water capture recovery performance.

Figure 2 shows the simplified diagram of the process. The use of the machine is simple: the user first folds a dirty garment 1-2 times and lays it on the blue ultra-low-density foam, as shown in Fig. 2. The foam is wet by approximately 1 liter of water. The low-density foam pores ensure water does not splash or float away, even under zero-gravity conditions. Next, the machine is closed, and the cycle is started. There are no other steps involved and when the user opens the machine and removes the garment it will be completely clean as both washing and drying occur with the same unit. The machine's use is simpler in comparison to traditional wash/dry units where clothing must be transferred between two separate cycles.

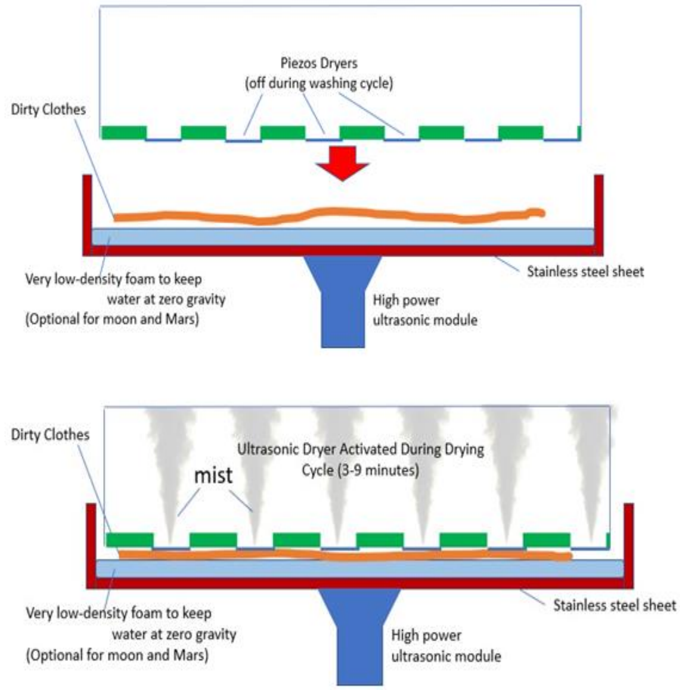

Figure 2. Diagram of ultrasonic drying system within the ultrasonic combination Washer/Drver unit

III. Ultrasonic Combination Washer/Dryer Components

A. Ultrasonic Cleaner

To prove the effectiveness and feasibility of ultrasonically washing fabric garments, a commercially available ultrasonic cleaner is used. The ultrasonic cleaner consumes 1200 W of power and has a cleaning tank volume of 30L, however as will describe later, a small portion of this machine is used for the experiments. A plastic container control volume is placed in the center of the ultrasonic cleaner's tank to isolate fluid that contacts samples. The control volume is used to reduce the amount of deionized water that is needed to be replaced between tests, and to contain the testing fluid for the analysis of dissolved contaminants, and to monitor fabric degradation. Testing verified that the control volume container did not considerably affect the intensity of the ultrasonic waves. Note that the ultrasonic cleaners and their cleaning ability are rated based on their power intensity in terms of watts per liter of fluid. Thus, the insulated plastic bottle mimics a lower power, lower volume ultrasonic dryer environment.

Conventional cleaning processes often use chemicals or detergents to remove contaminants from fabrics. Cleaning with chemicals and detergents presents a few pitfalls for use in space, such as the need for consumables, chemical safety concerns, VOC release, and storage challenges. Therefore, an Ultrasonic Washer/Dryer system is optimal for use in space because it eliminates the need for consumables and minimizes safety concerns.

B. Ultrasonic Dryer

The Ultrasonic drying component of the system will use Direct Contact Ultrasonic Drying to remove moisture from the clothing. Unlike conventional thermal drying methods, direct contact ultrasonic drying does not entirely rely on heat or water evaporation. It, therefore, is not bound by the high energy input required for water vaporization. In a high moisture level content range, water is ejected from a wet object in the form of a cold mist (atomized water). By bypassing the evaporation process, the technology demonstrates a much higher efficiency and drying speed on a wide range of fabrics [2-11]. A schematic of the dryer is shown at the bottom of Fig. 2. Here, you can see a profile view of the Direct Contact Ultrasonic Dryer where it is removing moisture from fabric and ejects it as mist upward. The mist that is generated from the drying process will be subsequently captured, filtered, and sanitized before being reused in the next wash cycle.

IV. Ultrasonic Combination Washer/Dryer Component Test Procedure

A. Ultrasonic Washer

Salt Removal Test Procedure

Salt-soaked samples are used in the experiment to simulate sweat-soaked clothing. Salt resulting from sweating is the main dirt on the crew members' clothing. The purpose of the salt removal test was to show the salt removal and cleaning performance of ultrasonic washing compared to soaking in water alone.

Oil Removal Test Procedure

The effectiveness of oily contaminant removal by the ultrasonic cleaner is tested using an oil-based sunscreen. Sunscreen is used because it closely simulates oil and grease contamination of fabric from contact with greasy or oily skin and because of its hard-to-remove nature. Most of sunscreens are highly water and sweat resistant. In the laundering industry, it is regularly used to test conventional washing machine performance. It also provides a quantitative metric for gauging laundering performance, unlike other methods that are solely qualitative such as visual evaluation. The laundering performance of sunscreen contamination is quantitatively measured by UV reflection and rejection using a commercially available UV IR rejection meter. Six samples of double-layered fabric from a 100% cotton T-shirt have been carefully cut out, and the seam was closed by three staplers. The size of the six double-layer fabrics was approximately 21.5 ×14.75 cm. The experiment involved three control samples which are soaked in 40º C water at 3, 7, and 20-minute intervals and three samples soaked in 40º C water that were ultrasonically cleaned for 3, 7, and 20-minute intervals, respectively. Considering there is no washer or dryer at ISS, there is no baseline for comparison. We selected pure water cleaning as a baseline because it is the simplest and more practical than the use of soap, chemicals, and detergents in ISS. Any chemical use will introduce challenges associated with odor, VOC, and chemical management, recycling, and also requires an additional supply of chemicals.

Dye Removal Test Procedure

The effectiveness of colored stain removal by the ultrasonic cleaner is tested qualitatively using food coloring red dye to stain fabric samples. The fabric samples are soaked in a solution of red dye and water for 16 hours, the sample is then air dried to allow the stain to set into the fabric. It was then placed in the ultrasonic cleaner and run for three minutes. A separate control sample is placed in a container of water and allowed to soak without agitation. Next, the samples are visually inspected, and the hue of fabric is compared to assess stain removal performance.

Fabric Degradation Test Procedure

For space applications, fabric wear and tear during the wash and dry cycles is not only important for increasing the lifespan of the garment but also microfiber-based pollution needs to be minimized in such a confined space.

The objective of this experiment is to ultrasonically clean fabric samples at various time intervals to observe the effects of ultrasonic washing on fabric mass and the life and quality of textile fabrics. Forty dog bone samples were prepared for this experiment. Fabric degradation is tested using two quantitative metrics and one qualitative metric. The two quantitative metrics are the mass difference of the samples before vs. after ultrasonic cleaning and the tensile strength of the fabric. The qualitative metric to assess degradation in the samples is conducted by looking at the samples under a microscope to see if there is degradation on a micro scale. Microscope images were taken of every sample before destructive testing with a magnification of 40X. The magnification allows the analysis of single strands of fabric for degradation. There is one control sample that did not undergo any ultrasonic cleaning and there are 40 numbered samples that were washed for varying amounts of time to see if fabric degradation is a function of ultrasonic wash time. The samples are weighed with an analytical scale three times before and after the samples are washed and the values are averaged.

B. Ultrasonic Dryer

Drying Performance Test Procedure

Since minimizing the mass and volume of the dryer is critical for applications in space, we determined that the only way to meet those constraints is to fold the article of clothing before placing it inside the wash/dry machine. Which leaves the question of how thick of a material can we dry without flipping the garment? The main objective of the drying performance test is to determine which piezoelectric transducer has optimal drying performance and how many layers of fabric can be dried with the integrated Direct Contact Ultrasonic Drying Unit.

The test consists of eight experiments where two different piezoelectric transducers are tested on 1, 2, 4 and 8 layers of fabric. The fabric used for the test is a synthetic polyester/spandex blend and is held constant throughout the test.

V. Results and Discussion

A. Ultrasonic Washer

Salt Removal Results

Fig. 3 shows the % of salt mass removed from the fabric sample vs. time. After one minute the results are similar, with the ultrasonic cleaner removing 27.06% of the salt from the fabric and soaking alone in deionized water removing 24.88%. However, ultrasonic cleaning begins to remove a much higher percentage of salt mass beginning at five minutes, where it is able to remove 81.92% vs. soaking only which removes 61.52%. Soaking begins to catch up to the ultrasonic cleaner around 30 minutes. Overall, what these results show is that five minutes of ultrasonic cleaning is as good as 30 minutes of soaking. We believe that initially there is a large amount of salt on the surface of a fabric, and regardless of the process, one could easily remove this surface salt; however, the salt that is trapped deep inside the fabric is difficult to remove by soaking whereas ultrasonic agitation removes it quickly. Under zero gravity conditions, however, we are expecting the solubility rate of the salt in water to be significantly diminished as the natural convections/mixing and density current may not exist under zero gravity and the process may become purely diffusion controlled. In such a situation, the ultrasonic cleaning impact may be even larger.

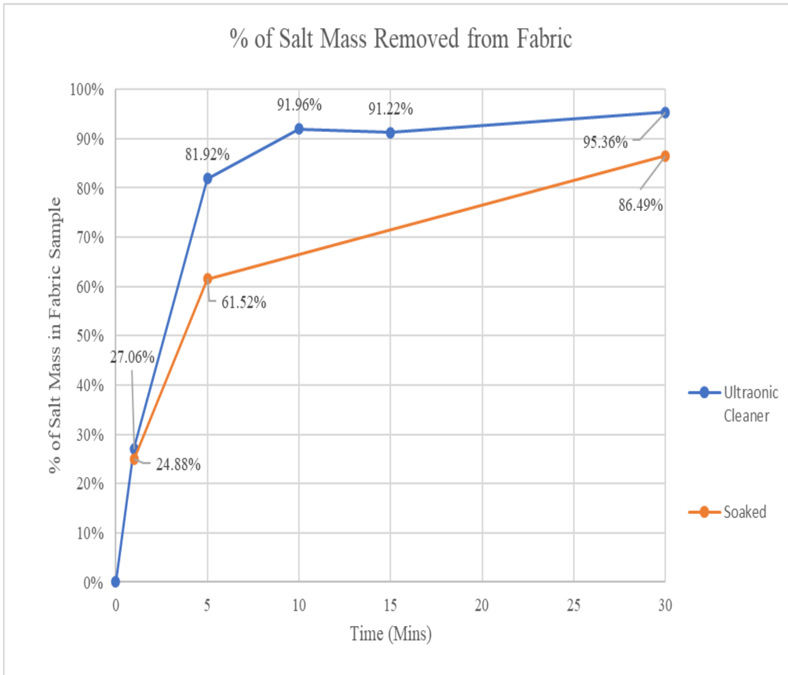

Figure 3. Percent Of Salt Mass Removed from Fabric Sample with Ultrasonic Washing vs. Soaking

Oil Removal Results

Fig. 4 shows the sunscreen removal percentage graph of the ultrasonic sunscreen removal test that compares soaked control samples to ultrasonically cleaned samples. The clearest conclusion the graph suggests is that the samples that are ultrasonically cleaned consistently lost more sunscreen mass than the control samples, which are only soaked in water. This strongly suggests that the purely mechanical, non-chemical approach of ultrasonic cleaning has a significant impact on sunscreen contamination removal rate.

The second conclusion is that we did not see a clear correlation between how long a sample is cleaned and the amount of sunscreen contamination removed. For instance, for control samples that are only soaked in water, the longer submerge time under water has almost no correlation to the stain removed. The same for ultrasonic cleaning.

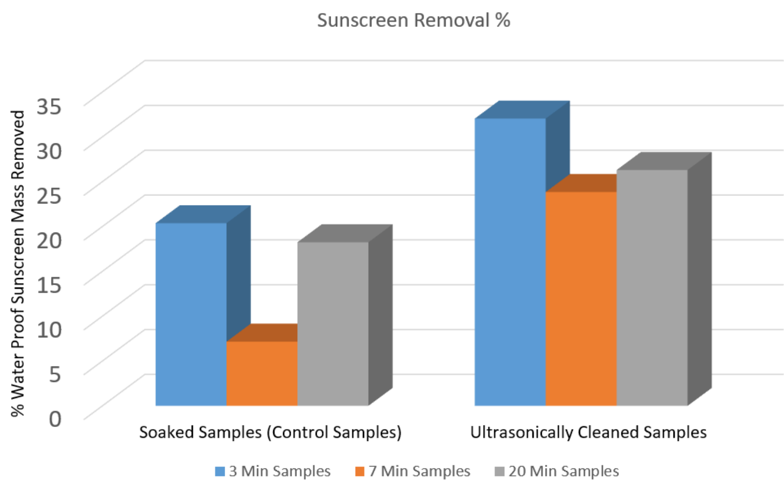

Figure 4. Percent of Sunscreen Removed from Soaked Samples vs. Ultrasonically Washed Samples

The last conclusion of the oil removal test is that ultrasonic cleaning can loosen some fraction of the sunscreen within the first few seconds, and the remainder of the sunscreen is set and difficult to remove.

Dye Removal Results

The dye removal test suggests that ultrasonic washing can remove significantly more red dye than by soaking the sample in water alone. The top half of Fig. 5 shows that all visible traces of red dye are removed from the sample that is ultrasonically cleaned, returning the fabric to its original white color. However, the control, water-soaked sample retained a visible amount of contamination from the red dye. The test suggests that the ultrasonic cleaner has an advantage in color stain removal compared to soaking it in water without agitation.

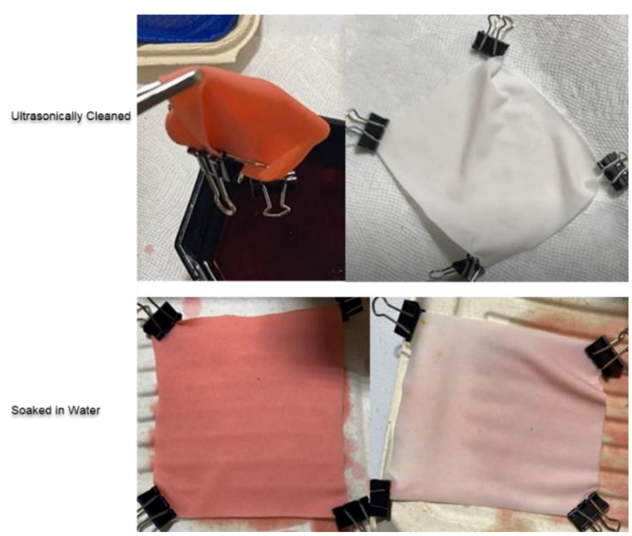

Figure 5. Dye Removal comparison of Soaked fabric vs. Ultrasonically Washed Fabric

Fabric Degradation Test Results

Regular washing and drying cycles slowly degrade the fabric quality until a point where the user discards the clothes. The number of washing and drying cycles vary greatly between the different garment types, from 11 cleaning cycles of coats and scarves to the 73 cleaning cycles of socks. A recent study by Ingun Grimstad Klepp et al [13] showed that the lint mass generation during the washing/drying process varied between households and ranged from 0.1 to 32.5 g/week, with an overall average lint mass of 6.4 ± 6.0 g/week (mean ± SD). For an average 5lb load of laundry and two loads of laundry per week, this amount of lint is about 0.06% of the garment mass per laundry cycle, suggesting the garment may lose about 1% of its mass through lint within 20 washing and drying cycles. Also, lint is a flammable material whose presence introduces the risk of fire for the user. Anything that can reduce the lint generation is valuable from the perspective of safety, air quality, and increased longevity of the ISS filtration system.

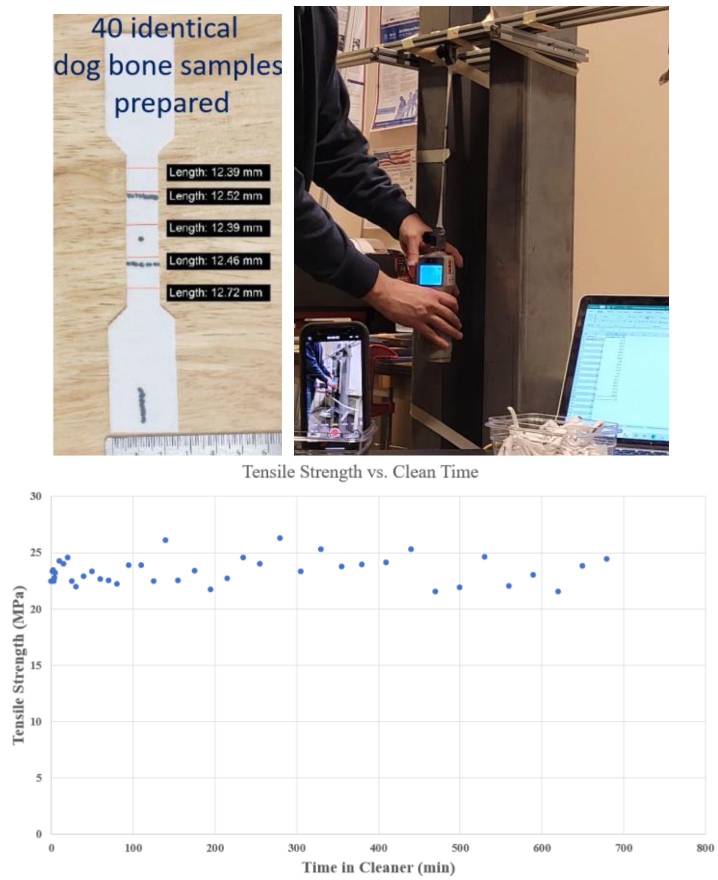

Figure 6. 40 dog bone samples are used to perform tensile strength, lint generation, and fabric quality testing for extended ultrasonic cleaning exposure of fabric.

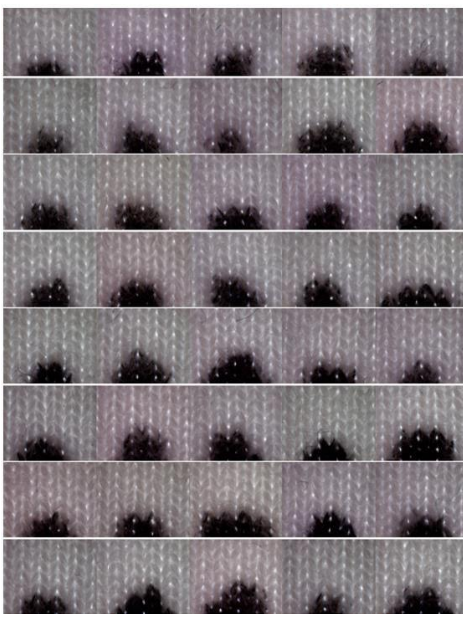

Figure 7. Fabric quality under an optical microscope near a black Sharpie dot used as the reference point. Top left is the brand new, and bottom right is the sample ultrasonically washed for 680 minutes.

The results of the fabric degradation study suggest that there is an average mass difference of 1.2 mg and an average percent reduction in mass of 0.23% before vs. after ultrasonic cleaning for 680 minutes. Assuming an ultrasonic wash cycle takes 10 minutes, this length of washing is equivalent to 68 wash cycles. These results suggest that compared to a regular washer on Earth, the lint generation is 15X less than the regular household washing machine. Tensile testing of the samples is shown in Fig. 6 and suggests there is no statistically significant reduction in the fabric strength across the samples, some of which experienced up to 680 minutes of continuous ultrasonic cleaning. Microscopy of the samples, shown in Fig. 7, suggests that there is no visible degradation of individual fabric strands as a function of ultrasonic wash time when compared to a control sample.

B. Ultrasonic Dryer

Drying Test Results

The dryness of the fabric sample is determined by the Remaining Moisture Content Percentage (RMC) of the sample. The RMC percentage is calculated by dividing the mass of the water in the sample by the dry mass of the sample (RMC= water mass / bone dry mass of sample). The mass of water in the sample is determined by subtracting the dry mass from the total sample mass. The RMC percentage is zero when there is no remaining moisture in the sample. The RMC can be more than 100% since the percentage is based on the dry mass of the sample, and since most absorbent materials can hold more than their own mass in water. For instance, at 270-300% RMC, a regular cotton fabric is saturated and can start dripping water. Figure 8 shows the % RMC vs. Time graph and a depiction of how the garments need to be folded before being inserted into the wash/dry unit. First glance at the graph suggests that as the number of layers increased, the time it takes to dry will also be increased. However, interestingly, the trend between the number of layers and the drying time is not linear. Logically, doubling the number of layers should double the drying time but this is not the case. Another way we can look at the trend seen in the data is to compare drying times at a certain % RMC value when the fabric is close to dry, in this case 45 % RMC, and divide by the number of layers being dried. At 45% RMC using the best performing piezo, one layer of fabric dried in about 300 seconds, two layers in about 425 seconds, four layers in about 750 seconds, and eight layers in about 1,525 seconds. Dividing the drying time by the amount of layers of fabric results in a quantity of seconds divided by the number of layers of fabric, which gives 300 seconds/layer for single layer, 212.5 seconds/layer for two layers, 187.5 seconds/layer for four layers, and 190.6 seconds/layer for eight layers of fabric. This comparison suggests the optimal number of layers for drying folded fabric is four layers at 187.5 seconds/layer with eight layers following closely at 190.6 seconds/layer.

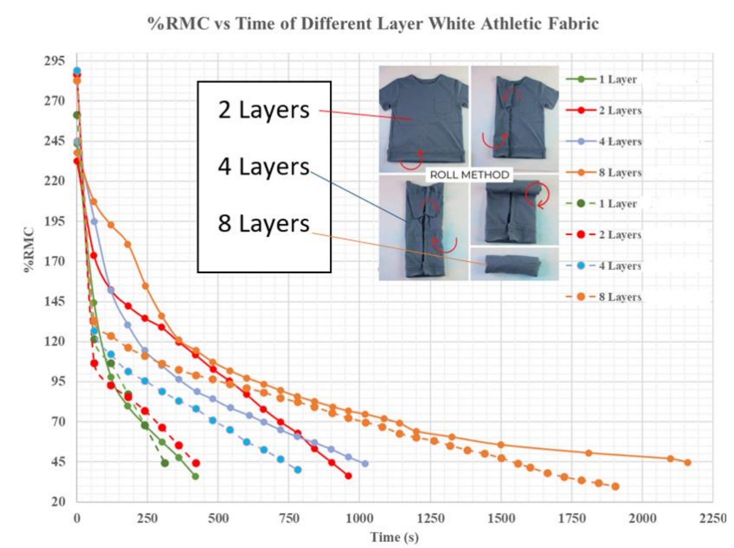

Figure 8. RMC vs. Time of Different Athletic Fabric

Previous tests have demonstrated that drying all the way down to 5%, called fully dried fabric in the industry, is possible through ultrasonic drying; however, subsequent tests revealed that drying below 20% RMC will negatively impact the lifespan of the piezos. Therefore, for a NASA combo wash/dry unit we suggest 30% RMC to be the lowest end of the drying process and the T-shirt to be air dried for the remainder of the drying. Even though fabric with a 30% RMC feels dry to the touch, small traces of heating elements could also be embedded to act as a low-temperature heater for final drying.

Interestingly, the results show that folding a garment up to four (and maybe eight) layers does not impact the drying time for one of these piezo types. The thickness effect (maximum penetration depth) shows its effect at the eight-layer fabric stage. All of these results are good compared to SOA, giving us the message that the optimum garment thickness is four-layer where both efficiency and speed are maximized.

C. Projected Cost Saving:

According to a *Forbes* magazine article, the space industry grew to a record $469 billion in 2021 [15]. In addition, according to the CSIS aerospace Security Project, the cost of launch per kg delivered to lower Earth orbit has been falling, especially with the recent SpaceX launches as shown in Fig. 9. Given the current assumptions of NASA for 0.25 kg/T-shirt and a wear length of seven days (if no laundry is available), and assuming that our combo washing/drying machine can wash and dry garments 40 times (very likely more in a high supply stressed environment) before it is discarded, the amount of savings for NASA can be estimated as follows.

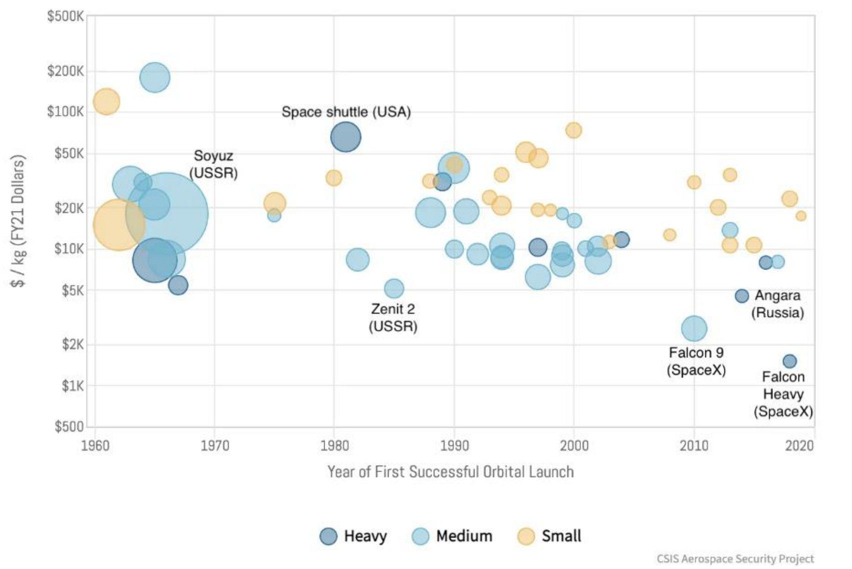

Figure 9: The cost of launching objects to LEO. Source: CSIS Aerospace Security Project [16].

Current practice for four crew members in a 1,000 day mission:

- o T-shirt supply need: 0.25 kg × 1,000 days × (1/7 coefficient of use) × 4 crew = 142 kg T-shirts
- o Assuming other clothing (socks, underwear, shorts, pants) will be 2x this, then the total weight of garment supply = 285 kg garment
- o Cost to launch:

With space shuttle: 285 ×$54k/kg = $15M
With Space-X: 428 ×~$5.4k/kg = $1.5M

Our technology can potentially save 97.5% of the costs for 40 wash and dry cycles. Please note that a more exact calculation requires insider data on launch cost, which we do not have access to.

Also note that in addition to reduced costs, the proposed technology has the potential to improve crew comfort and hygiene by eliminating the reuse of dirty clothes, and a potential reduction in odor originating from dirty garments. Additionally, potential VOC emissions that could happen with other laundering methods such as dry cleaning or traditional washing/drying with detergents, are eliminated since there are no detergents or solvents used. Finally, the system has a reduced system mass and volume compared to other traditional laundry systems. The prototype does not produce noise in the human audible range and we are expecting the scale-up machine to be a very low noise system.

VI. Conclusion

In this paper, the feasibility of ultrasonic fabric cleaning and direct contact ultrasonic drying was investigated. This study aims to better understand the potential technology performance metrics required to design an ultrasonic combo clothes washing and drying machine for space applications. The results show that ultrasonic cleaning is very effective in removing salt, color dye and oil stain from fabric. Also, the results suggest that ultrasonic cleaning is not negatively impacting the fabric strength nor quality of the fabric. The lint generation from the process could be 15X less than the regular laundry process on Earth. The ultrasonic fabric drying results suggest that the drying process is still very effective and can remove water from a multilayer fabric. The ultrasonic drying process is found to be most efficient and effective when removing water from 4 (followed by 8) layers of fabric. This suggests that the clothing can be folded before being placed inside the proposed machine to save space, mass, and power. The machine can be designed in a very compact form at less than 0.02 m^3 volume and 5 kg mass. The proposed combo fabric washing and drying machine can help to significantly reduce the crew supplies on ISS, the moon and Mars missions, enabling extended life in space and improving human life quality, safety, and hygiene beyond Earth.

Acknowledgments

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