Initial Testing of a Full-Scale Ultrasonic Clothes Washer/Dryer for Moon, Mars, ISS and Beyond

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This study investigates the effectiveness of an ultrasonic-based combo garment washing and drying system for space applications. The 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 medium-size T-shirts ultrasonically. This paper 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. The outcome of this study could lead to the design and development of the first ultrasonic clothes washer and dryer for space applications that would reduce clothing resupply costs for crewed missions to the moon, Mars, and micro-gravity space stations.

Nomenclature

ISS	=	International Space Station
LEO	=	Low Earth Orbit
RMC	=	Remaining Moisture Content (%)
SBIR	=	Small Business Innovation Research
UTS	=	Ultrasonic Technology Solutions
VOC	=	Volatile Organic Compound

I. Introduction

NASA's Life Support and Habitation Systems Focus Area seeks key capabilities and technology solutions to support extended human presence in deep space. Considering that the crew clothing accounts for ~1/4 of crew supplies for ISS, there is a critical technological gap that involves developing a clothing washer/dryer combination unit suitable for lunar or Martian conditions. Ideally, this device could also be portable and usable in micro-gravity conditions, making it truly versatile. Such an innovation is described here.

Drying wet material using heat and evaporation requires a significant amount of energy. Theoretically, for every 1kg of water removal, 2,200kJ/kg energy is required, and practically, when accounting for all the inefficiencies of regular dryer machines, 3 to 4 times this is required. In the cases of freeze-drying food, fruit, and vegetable drying, 20-30 times this energy is being used [1]. Initially invented at Oak Ridge National Laboratory, in contrast to conventional thermal drying methods, our team's direct contact ultrasonic drying innovation eliminates the need for

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substantial heat to evaporate water. Consequently, it is not constrained by the high energy input required for water vaporization. Employing piezoelectric transducers, this novel drying method mechanically removes water by rapidly shaking the object on a micron scale [2-12]. By partially bypassing the evaporation process, the technology exhibits significantly higher efficiency and drying speed when applied to various wet materials.

Under the SBIR Phase II contract with NASA, UTS is developing a transformative combo clothes-washing and drying machine for space applications where the ultrasonic components are the backbone of the technology. The basic components of this technology have been reported in the previous ICES paper [17]. Unlike traditional agitation washing methods that may introduce unwanted gyroscopic effects and generate a substantial amount of lint, we also explored the potential of cleaning fabric with solid-state ultrasonic cleaners. An integrated crew clothing washing/drying system approach can realize significant mission mass and volume reductions. UTS's efforts to wash and dry clothes with very little energy and water can help achieve this goal by making clothing reusable. This paper will present a comprehensive study of the ultrasonic cleaning potential for fabric and its unique design at scale, including the matching system design for ultrasonic drying. These ultrasonic processes will not be significantly affected by gravity. The results of this study could pave the way for the development of the first garment washing and drying system for use on the ISS, Moon, Mars, and other space applications, contributing to the prolonged presence of humans in space.

II. Stain Removal Testing

A. Stain Removal Testing with Ultrasonic Cleaner

1. *Stain Testing Setup*

This initial test was to find the potential stain removal ability of the ultrasonic cleaner from fabrics. The team used a 360W 15L off-the-shelf cleaner and 92% polyester/8 % spandex fabric, where fourteen 35mm diameter circle samples were cut. They were then stained with red, blue, and green food coloring, charcoal powder, cocoa powder, and fake blood, leaving 1 true unstained control sample. To do this, 100ml of water was used to saturate the fabrics, and 1ml (or 1g) of dye was added, allowing the samples to sit for 4 hours. They were then removed to dry overnight, allowing the staining to set into the fabric. At this point, the first stain measurements were read with the color meter.

Then, seven samples were ultrasonically cleaned for 10 minutes while the other 7 were soaked for 10 minutes as a comparison. The samples were then allowed to dry overnight and then remeasured. Figure 1 shows the image of the samples after they were dried. The top image is of the samples after they were stained. The bottom image is of the samples after they had been ultrasonically cleaned and soaked. Where the top row is the ultrasonically cleaned samples and the bottom row are the samples that were soaked.

The original fabric's white color is also measured with a color meter. The color was measured at five points and averaged to get a clean starting point.

Figure 1: Dried Stained Samples (top), Dried Ultrasonic Cleaned and Soaked Samples (bottom)

2. *Results from Stain Testing*

During the different stages of the stain testing, a color meter was used to measure the color of the fabric samples. This device reports color as a point in the CIELAB color space for any given measurement. This color space is designed to represent the entire range of human color perception, and it does so using three coordinates in a spherical space to define a color. The visualization of the color space is shown in Fig. 2. More information can be found in the references [13,14,15,16].

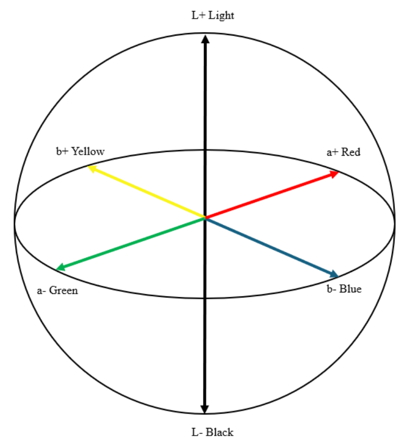

Figure 2: Visualizations of the color space.

As can be seen, there are three coordinates used in this system: L, a, and b. "L" is used to describe lightness and ranges from 0 to 100 where 0 is black and 100 is white. The next coordinate, "a" is used to describe the spectrum from red to green and ranges from -50 to 50 representing green and red, respectively. Finally, the "b" coordinate describes the spectrum from yellow to blue and also ranges from -50 to 50, with the minimum value representing blue and the maximum representing yellow.

Each measurement during this experiment produced a set of coordinates in the form [L, a, b]. These measurements were then compared to each other using different methods to evaluate the performance of the ultrasonic cleaner and the soaking alternative. The first set of measurements was on the white fabric material before any wetting, dying, or cleaning occurred. These measurements acted as a baseline against which to compare the others. The team measured 15 points (5 locations, three measurements each) on the base white fabric and averaged the results to produce the coordinates of the baseline white fabric. The white fabric's coordinates after averaging were $[L, a, b]_{white}$ = [90.13, 0.79, 1.04]. This will be referred to as the baseline color or the white fabric color.

Next, the samples soaked in the dye and then dried. Three measurements were taken of each sample. These results were averaged to produce a set of color space coordinates for every dyed sample. These will be referred to as the dyed data points. After this, the samples were cleaned either by being soaked or by being put in the ultrasonic cleaner. After cleaning and drying, the samples were measured again in the same way with the color meter. Three measurements were taken and averaged. These will be referred to as the washed data points.

To analyze the collected data, the team calculated the distances from the white fabric's color to the sample's color both on a component-by-component basis and on an overall length basis. Any distance calculated in the CIELab color space represents some color difference, whereas a larger distance represents a greater color difference. Then, the team compared the color differences between the dyed and washed samples to measure how much washing occurred in each process.

First, the team calculated the distances from the dyed sample measurements to the baseline's measurement on a component-by-component basis. The team did the same for the washed sample measurements. After this, the percent of the dying process's change to a component that was removed by the washing process was calculated and graphed below. The equations for this are also shown below.

$$Percent\ Cleaned\ for\ L\ component = \frac{(L_{dyed}-L_{baseline})-(L_{washed}-L_{baseline})}{(L_{dyed}-L_{baseline})} * 100 \quad (1)$$

$$= \frac{(L_{dyed}-L_{washed})}{(L_{dyed}-L_{baseline})} * 100$$

$$Percent\ Cleaned\ for\ a\ component = \frac{(a_{dyed}-a_{washed})}{(a_{dyed}-a_{baseline})} * 100 \quad (2)$$

$$Percent\ Cleaned\ for\ b\ component = \frac{(b_{dyed}-b_{washed})}{(b_{dyed}-b_{baseline})} * 100 \quad (3)$$

Where:
$[L, a, b]_{dyed}$ is the set of coordinates for the samples after dyeing.
$[L, a, b]_{washed}$ is the set of coordinates for the samples after washing, either with the ultrasonic cleaner or the soaking method.
$[L, a, b]_{baseline}$ is the set of coordinates for the baseline measurement on white fabric.

The results are combined into a single data point by calculating the distance in the CIELab color space between colors. This distance between two colors is referred to as "Delta E" and is the length of the vector between the two points. The Delta E between the white baseline color and the dyed color measurement is calculated. Then the Delta E between the white baseline color and the washed color measurement also calculated. By calculating Delta E as a difference between some sample and the baseline, the magnitude of Delta E effectively represents the amount of discoloration due to the dyeing material or in other words, the "dirtiness" of the sample at the time of measurement. Shown below are the equations for finding Delta E and the plot comparing them.

$$Delta\ E_{Dyed} = \sqrt{\left(L_{baseline} - L_{Dyed}\right)^2 + \left(a_{baseline} - a_{Dyed}\right)^2 \left(b_{baseline} - b_{Dyed}\right)^2} \quad (4)$$

$$Delta\ E_{Washed} = \sqrt{(L_{baseline} - L_{Washed})^2 + (a_{baseline} - a_{Washed})^2 (b_{baseline} - b_{Washed})^2} \quad (5)$$

Where:
$[L, a, b]_{dyed}$ is the set of coordinates for the samples after dyeing.
$[L, a, b]_{washed}$ is the set of coordinates for the samples after washing, either with the ultrasonic cleaner or the soaking method.
$[L, a, b]_{baseline}$ is the set of coordinates for the baseline measurement on white fabric.

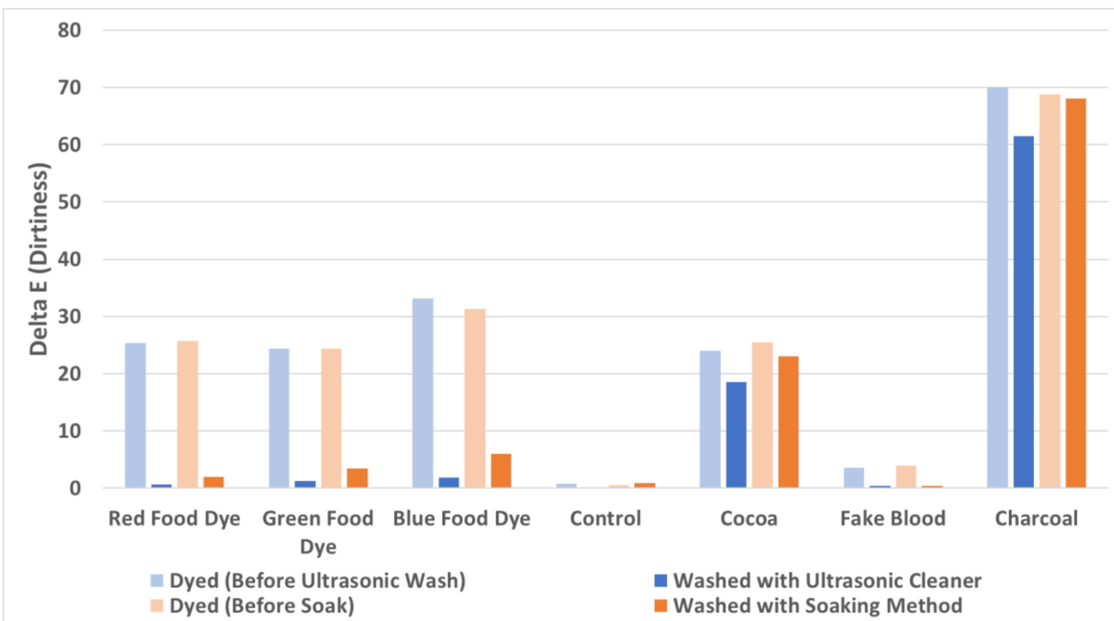

***Figure 3*:** Overall Dirtiness Before and After Washing for Each Dyeing Material (a value of 0 is fully clean).

Fig. 3 compares the overall dirtiness (color distance from baseline white fabric) before and after washing for each dyeing material and cleaning method. Also shown on this graph is the control sample, which was treated the same as the other samples except that no dyeing material was introduced to it. The slight variations in the Delta E for this sample give some insight into the amount of uncertainty in these measurements, which is relatively small.

For each dyeing material, the two lighter-colored bars represent the dyed color difference from the baseline. These should be roughly equal since no cleaning had yet been introduced, and the dyeing process was the same for each sample. This is shown in the graph, with each set of light bars having similar magnitudes. The dark set of bars for each sample represents the washed color difference from the baseline. What can be seen is that in all of the samples except for the fake blood and the control that, the ultrasonic cleaner removed more of the discoloration than soaking did. For fake blood, the washed delta E values are so close to zero that they are hard to quantify from the plot alone. The values were nearly equal and near zero, 0.39 and 0.43 for ultrasonic cleaning and the soaking method, respectively.

This plot puts into perspective the overall amount of change that each dyeing material made to the samples and the amount of cleaning that followed the dyeing process. The most significant change in color came from the charcoal powder. Below are the food dyes and the cocoa powder, which were roughly equal in discoloration. Finally, the fake blood sits at the bottom of the list, with a small amount of discoloration.

In order to normalize the results, the delta E values are shown above, and the percent difference between dyeing and washing for each dyeing material and cleaning method is calculated. By doing this, the team effectively asked, "How much of the discoloration that was added by the dye was removed by the cleaning process?".

$$Percent\ Cleaned = \frac{Delta\ E_{Dyed} - Delta\ E_{Washed}}{Delta\ E_{Dyed}} * 100 \tag{6}$$

Where:
Delta E_{Dyed} is the distance in CIELab color space between the dyed color point and the baseline color.
Delta E_{Washed} is the distance in CIELab color space between the washed color point and the baseline color.

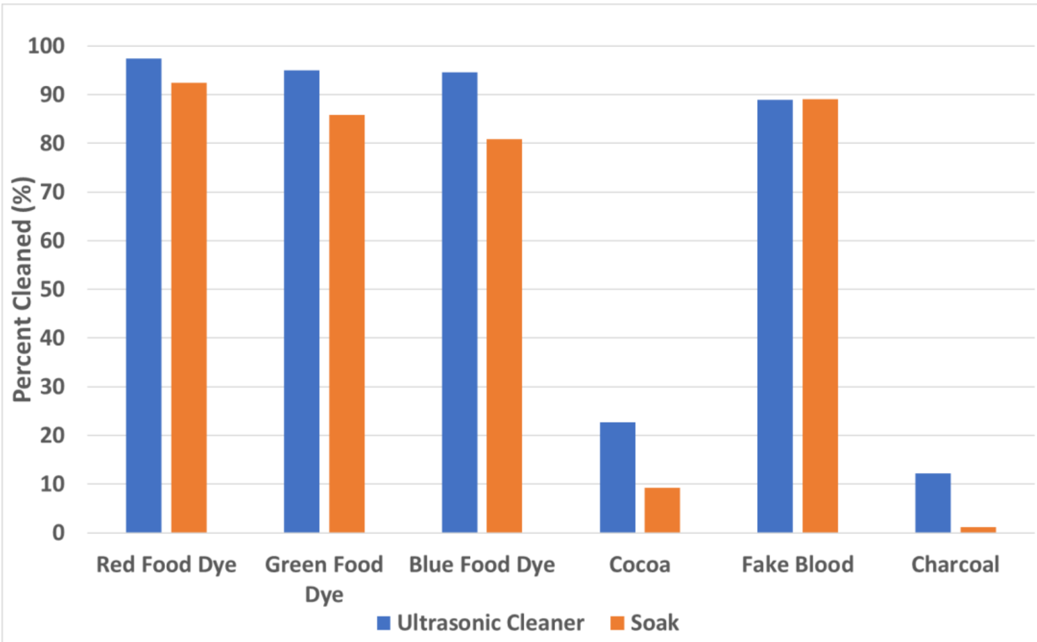

Figure 4: Overall Cleaning Achieved by Each Method.

Fig. 4 shows the results boiled down to a simple comparison of the overall cleaning achieved by each method. Here, a value of 100% would mean that all of the discoloration that was added by the dyeing material was removed by the cleaning process. In every dyeing material except for the fake blood, the ultrasonic cleaner removed the stain more than the soaking process. As mentioned above, the fake blood was almost fully cleaned by both methods, but it also did not have much discoloration. This plot shows that both methods nearly entirely removed the food dye, while the cocoa powder and charcoal were not much removed from the sample. Still, the ultrasonic cleaner removed more than twice the amount of cocoa discoloration than the soaking method and nearly 11 times the amount of charcoal discoloration than the soaking method. Overall, these data show the promising nature of ultrasonic cleaning technology and the difference between the two methods, with ultrasonic cleaning being superior.

III. Ultrasonic Washer Full-Scale Salinity Testing

Considering salt accumulated from sweating during exercise is one of the most significant contaminants in the crew members' exercise clothing, the cleaning method needs to consider the effectiveness of salt removal. The preliminary investigation on ultrasonic salt removal on the small fabric samples showed a good cleaning potential [17]. In this study, the focus will be on investigating the impact of ultrasonic cleaning on four full-size T-shirts.

A. Sensor Calibration

Salinity Sensor Calibration

To gain confidence in the salinity sensor accuracy and crosscheck the salt mass removal measurement, a calibration was performed on the salinity meter. Figure 5, shows the calibration curve for the salt meter up to 11,000 PPM level.

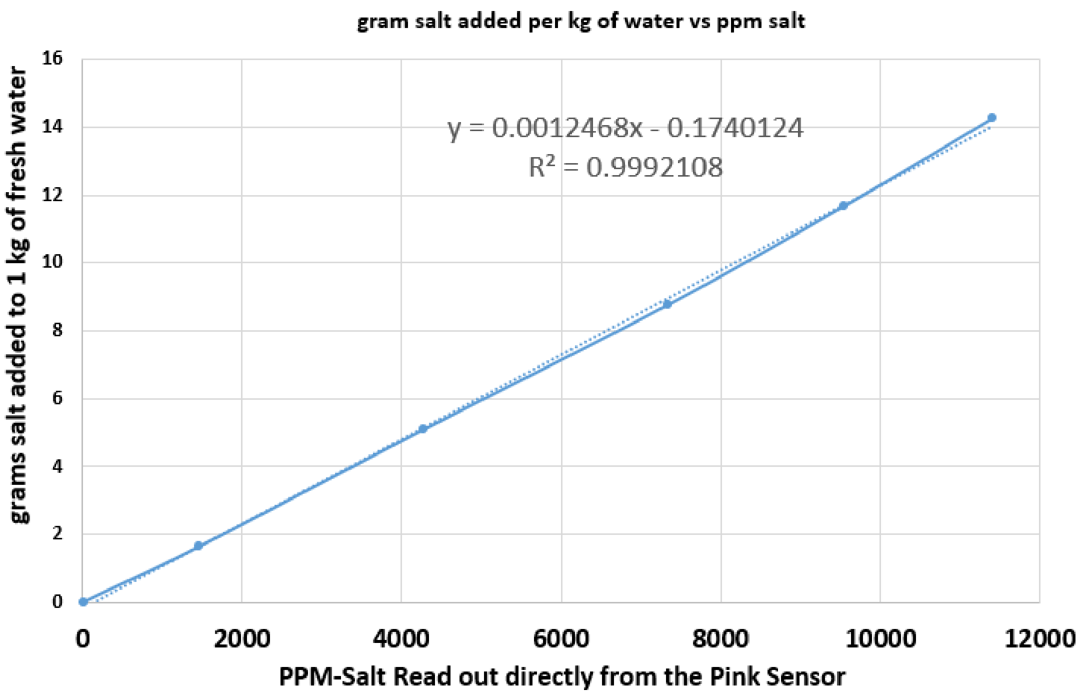

Figure 5. Calibration curve for salt meter.

Cavitation meter testing setting 30mm water height.

Another parameter the team needed to calibrate before testing began was the water depth at which the ultrasonic cleaner cavitation was most intense. The goal was to optimize the tank volume to the lowest amount while still achieving high enough cavitation to accomplish cleaning. The Cavins meter is used for this purpose. Cavins measures the unit of cavitation energy per unit area.

A Cavins meter was held at varying depths to find cavitation intensity at the given water level. Figure 6 shows the data associated with this testing when the tip of the Cavin meter sensor rod is 10 mm above the bottom of the bath. As the water level increases, the maximum and minimum intensity points are repeated, which is associated with tie points and wavelength of the vibration in the water. Since the goal in the space applications is to minimize the weight and water usage for the clothes-washing process, the water depth associated with the first peak has been selected. The data shows that the first peak occurs at the water level of approximately 30mm, which is used in the subsequent tests.

Shaft Following Water Height / Fixed Depth Marker		
Shaft Marker (mm)	Water Level (mm)	Cavins (Center Position)
10	99	58-62
10	90.1	42-48
10	78.9	42-46
10	70.2	50-54
10	59.2	30-32
10	49.5	48-52
10	39.8	40-44
10	30.6	50-54
10	19.9	36-40

Figure 6. Measuring the ultrasonic cleaner cavitation intensity for different bath depths.

Test Procedure: Ultrasonic Cleaner Salt Removal Test

Pre- Cleaning Preparation:
Before cleaning could begin, the team took a full, medium-sized t-shirt and recorded its bone-dry mass using the analytical balance.

Salt Solution Preparation:
Considering the salinity levels associated with experiments, the error introduced by a unit of error in salt mass measurement magnifies and impacts the results approximately 300 times more than a unit of error in water mass measurement. For this reason, extra care needs to be taken for salt mass measurements during the entire experiment.

Salt naturally absorbs ambient moisture and gains some mass over time. To dry the salt, it is heated at 60 C for several hours and stored in a sealed container for later use.

Before initiating the ultrasonic cleaning process, a salt solution is prepared by weighing out 20g of salt and dissolving it in 130g of water, where the salinity measurements of the solution are taken. Twenty grams of salt merely mimic the condition of the exercise T-shirts after 5 uses and right before their disposal at ISS based on anecdotal evidence.

The prepared salt solution is evenly applied to the T-shirt, resulting in the "Salted Shirt." During this process, a small amount of salt is being lost from the mass tracking process, as it contaminates the tray and operator's hands. The shirt is then left to dry on the drying rack and then its bone-dry mass is measured. The drying rack temperature set at 45C. The lower temperature will results in partial drying, which impacts the accuracy of salt estimate, and excessively higher temperatures could promote the VOC and release of gases and lost mass from the T-shirt. It is found that 45°C is a safe tradeoff temperature for this intermediate drying step.

Next, the ultrasonic cleaner tank filled with 2.45 L (30mm water depth) of tap water is passed through a reverse osmosis filtration system. The tap water in Knoxville, TN, has an average salinity of 70 ppm, and after passing it through a reverse osmosis filter, its salinity drops to 7-8 ppm. The full-size salted T-shirt is folded and then placed in the ultrasonic cleaner, ensuring it is fully submerged.

The Salted Shirt is then subjected to ultrasonic cleaning for intervals of 0, 0.5 minutes, 2.5 minutes, 5 minutes, 7.5 minutes, and 10 minutes as shown in Fig. 7. The ultrasonic cleaner is activated for each specified duration, with continuous monitoring to ensure optimal exposure of the fabric to ultrasonic waves. Following each ultrasonic cleaning interval, the T-shirt is removed, let drip into a collection tray, and hung on the drying rack.

After multiple weeks of experimentation, the team found a large discrepancy in the postprocess data. After carefully examining the process, we realized vertically hanging T-shirts are a large source of error, and the wet T-shirt will experience small and slow water dripping overnight. This is naturally caused by gravity, where the top of the T-shirt is drying first and the bottom of T-shirt may still be dripping for the first several hours. The process improved by ensuring that the T-shirts are drying out horizontally (minimizing the static pressure [ρgh] due to gravity). Thus, large hole wire meshes are used to dry out T-shirts as shown in Fig. 7 (right). This eliminated the drip and also minimized the contact area of mesh wires and T-shirt.   The experiments were repeated after this correction.

Figure 7. The experimental procedure.

The collection tray ensures no residual salt removal occurs in the cleaning tank and its water is then measured with the salinity meter to gauge the salt lost into that tank caused by initial dripping. The ultrasonic cleaning tank water is also measured to collect the salt removed by the cleaner. The team collected measurements by circulating the water in the tank with a small pump, encouraging thorough mixing of the salt in the water. Measurements are taken at 10-minute intervals until the solution has reached a steady state. The water is then drained out of the tank and weighed to calculate salt content during post-processing.

Results of Salt Removal:

The bone-dry mass of cleaned T-shirts was measured using the analytical scale. Then, the team prepares the fresh water tank, also called the infinity soak tank by filling it with 10kg of distilled water. This tank's intention is to allow the remaining salt left in the t-shirt to dissolve into this tank, where the team can measure the remaining salt concentration left after the cleaning step. This is achieved similarly by using a small pump to circulate the water, and measurements are taken at 15-minute intervals until the measurements reach a steady state. The results are shown in Fig. 8. The results is being reported from both data collected from mass losses measured by analytical balance and also the calculated mass of salt gained by water measured by salinity meter. The maximum difference between these two methods of measurement was less than 2.7%, showing a high certainty in the measured value. The uncertainty around the mean data is also shown as standard deviation in these graphs which are associated with sensory data fluctuations along with the manual process associated with the time tracking and sample movement/removals.

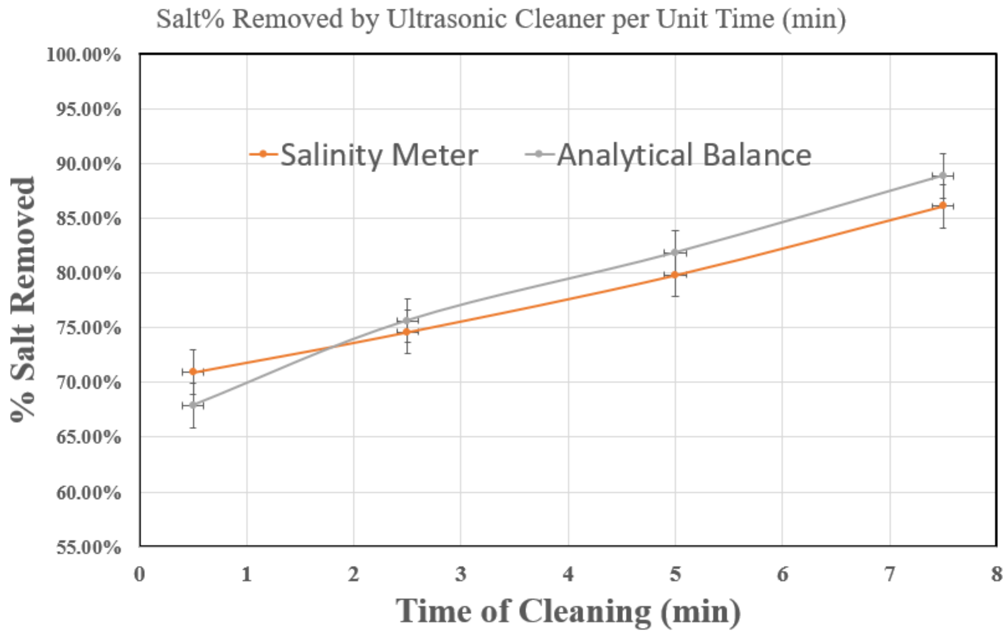

Figure 8. Ultrasonic cleaning salt removal from a T-shirt.

The initial salt removal at 0.5 minutes of cleaning is 70.94%, which indicates that a substantial amount of salt has been removed in this short time frame. The salt removal increases further as the cleaning duration increases. At 2.5 minutes, the salt removed climbs to 74.62%, an increase of 3.68%, showing continued improvement in salt removal efficiency. This incremental improvement suggests that the ultrasonic cleaner's effectiveness benefits from extended cleaning times. A notable increase in salt removal efficiency is observed at the 5-minute mark, with the salt removed increasing to 79.82%, a growth of 5.2% over the 2.5-minute test. More improvement happens at 7.5 minutes with 86.13% of salt removed, an increase of 6.31% over the 5-minute test. This trend is in line with our previous study [17] for small-scale samples, suggesting the presence of a large amount of surface salt that can be removed from folded T-shirts in the presence of water. The salt trapped inside the fabric pores is harder to remove, and fast extraction requires an active cleaning technology.

To optimize the cleaning process, a balance needs to be struck between achieving the desired salt removal and minimizing unnecessary energy consumption or wear on the fabric. Further experimentation or analysis might help determine the optimal cleaning duration for achieving the desired level of salt removal without unnecessary extended cleaning times. This data indicates that the ultrasonic cleaner effectively removes salt from the T-shirt, and there's a positive correlation between cleaning time and salt removal efficiency.

IV. Conclusion

In this paper, the feasibility of salt removal from full-size folded T-shirt using ultrasonic cleaning has been investigated. Also, the potential of the ultrasonic cleaner stain removal ability was examined. The results suggest that the ultrasonic cleaner removed more than twice the amount of cocoa discoloration than the soaking method and nearly 11 times the amount of charcoal discoloration than the soaking method. Also, the salt removal study on full-size T-shirts showed that more than 85% of salt can be removed from the garment within 7.5 minutes. This study will help to better understand the potential technology performance metrics required to design an ultrasonic combo clothes-washing and drying machine for space applications.

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