

Full-Scale Ultrasonic Clothes Washer/Dryer Evaluation Results

International Conference on Environmental Systems (ICES)

ICES 2025/ Prague, Czech Republic/ Submission # 59

July 13-17, 2025

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Project Goal:

- Development of the full-scale prototype ultrasonic cleaning and drying of fabric for the moon, Mars, and beyond.

Issue:

- Crew Clothing accounts for approximately 25% of crew supplies for ISS.

Technological Gap:

- **Lack of clothing washer/dryer combination for ISS, moon (1/6g) or Mars (1/3g)**

Requirements:

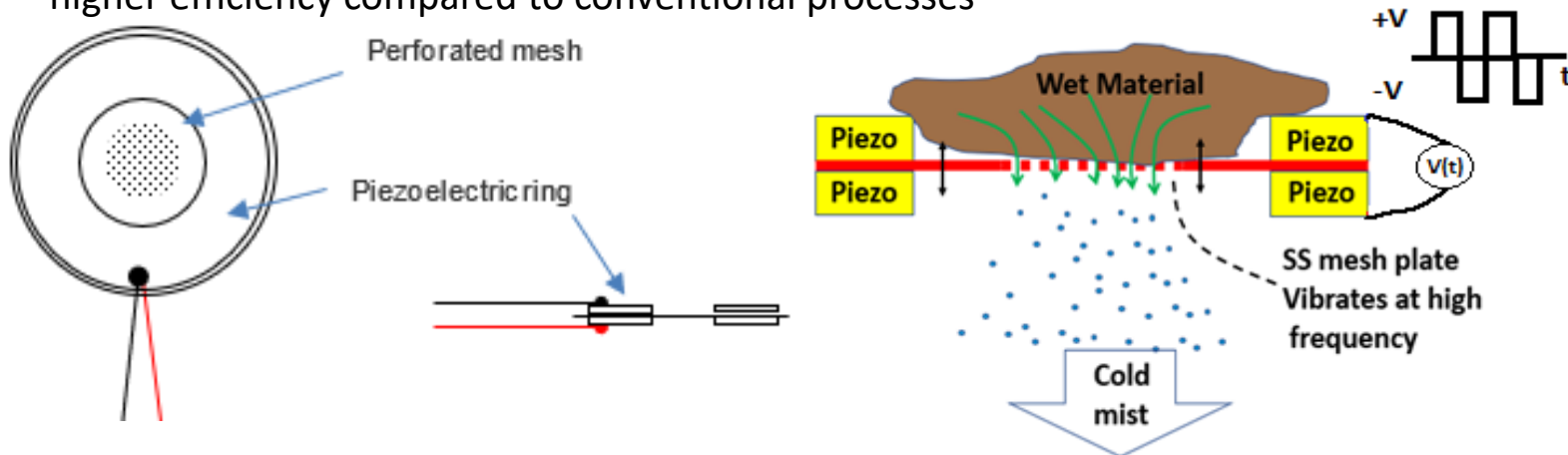
- Clean up to 4.5kg of cotton, polyester, and wool clothing
- Less than 7 hours cleaning time
- Machine mass <50kg, external volume <0.3m³
- Electrical power <300W
- Prototype development assumes 101.3kPa habitat pressure

Support missions:

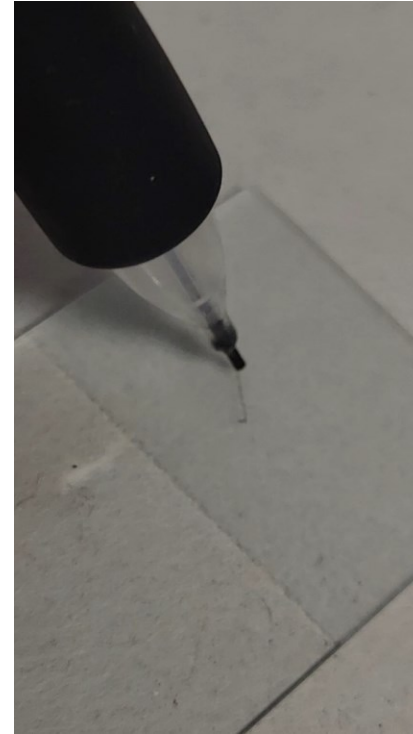
- Orion, ISS, Gateway, Artemis, and Human Landing Systems.

Background- Direct Contact Ultrasonic Drying

- Invented at Oak Ridge National Laboratory
- Inspired by nature!
- Relying on vibration rather than evaporation.
- Vibration is introduced by piezoelectric elements to wet material sitting on the piezo.
- Introduced momentum through vibration, mechanically displacing water, ejecting it through the mesh holes, and forming a cold mist of water droplets.
- The formed mist can be captured with a filter or be carried out to the desired location using small airflow.
- By bypassing evaporation, the technology demonstrated up to 5X faster and higher efficiency compared to conventional processes



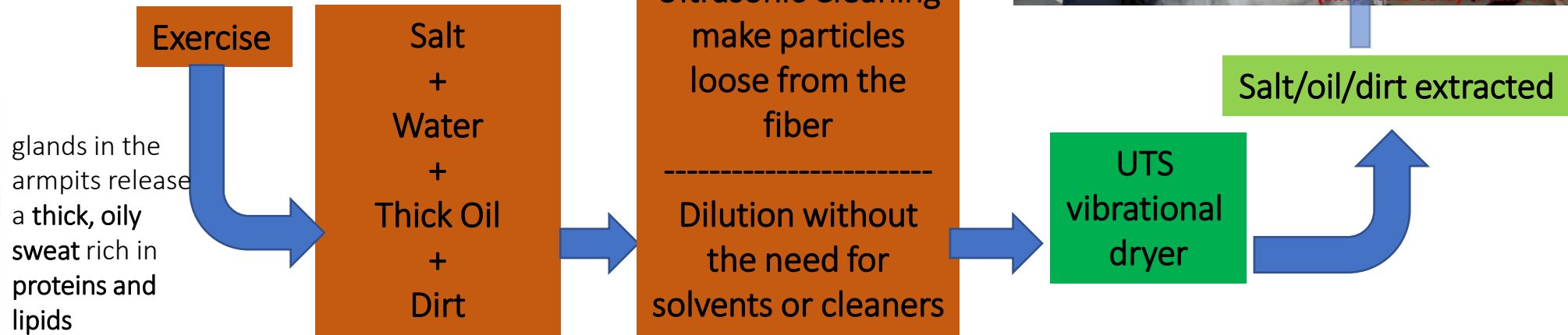
Background- Industrial Ultrasonic Cleaners



Ultrasonic cleaners are the industry standard for the **Mechanical Cleaning** of dirty/rusted parts.
Vibration → Micro cavitation → Pressure Waves → Breaking apart loose parts (dirt/rust)

Footnote: the underlying physics of the process is **not** dependent on gravity and relies on momentum and atmospheric pressure.

Big Picture Idea – Rely on fully solid-state solutions (no moving parts)



⊘ Limitations of Conventional Laundry Systems

- Slow operation
- High power consumption
- High water usage
- Dependence on consumables and chemicals; release of VOCs and gases
- Incompatible with zero or low gravity environments without full redesign (*e.g., compressor, refrigerant lines, oil management, and tumbling mechanisms*)
- Impose significant vibrational and imbalance forces on structures
- Washers generate lint, which accumulates in dryers
→ **#1 cause of residential dryer fires in the U.S. ***

🔄 Trade-Offs of Ultrasonic Washing & Drying

✓ Pros:

- Fully solid-state design — no complex mechanical systems
- Simplified, modular, and portable architecture
- Minimal moving parts → higher reliability
- Reduced weight and volume
- Eliminates need for consumables (*optional if required*)
- Operates independently of gravity
- Lower power consumption
- Significantly reduces lint generation

⚠️ Cons:

- Limited load capacity — optimal for a few garments per cycle

*<https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/home-fires-involving-clothes-dryers-and-washing-machines>

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Key Findings from Previous Demonstrations

Sunscreen Removal (Oily Soil):

- Ultrasonic cleaning produced a 12× greater change in UV reflectance (UVR%) compared to soaking alone.

Salt Removal:

- 5 minutes of ultrasonic cleaning outperformed 30 minutes of passive soaking.

Color Stain Removal:

- Stains were completely removed in under 3 minutes using ultrasonic cleaning.

Lint Generation Comparison

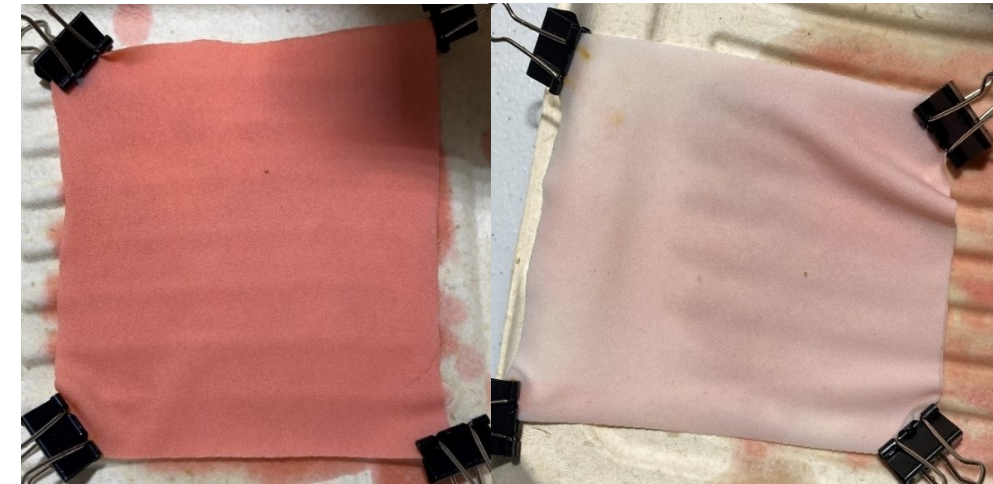
Method	Mass Loss	Duration
Ultrasonic	~0.2%	700 minutes (~200 cycles)
Conventional	~1.0%	20 residential wash cycles

Fabric Integrity:

- No statistically significant degradation in fabric strength after 700 minutes of ultrasonic cleaning
- No visible fabric damage observed after extended ultrasonic exposure

Ultrasonic Drying Insight:

- Optimal performance found with 4–8 layers of small-sized samples, leading to improved size reduction, speed, and energy efficiency



Dyed fabric after 3 min of **Soaking** before (Left) and after (Right)



Dyed fabric after 3 min of **Ultrasonic Cleaning** before (Left) and after (Right) 7

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•Stain Removal:

- Ultrasonic cleaning removed **2× more cocoa** and **11× more charcoal** than soaking

Salt Removal from Full-Size T-Shirts:

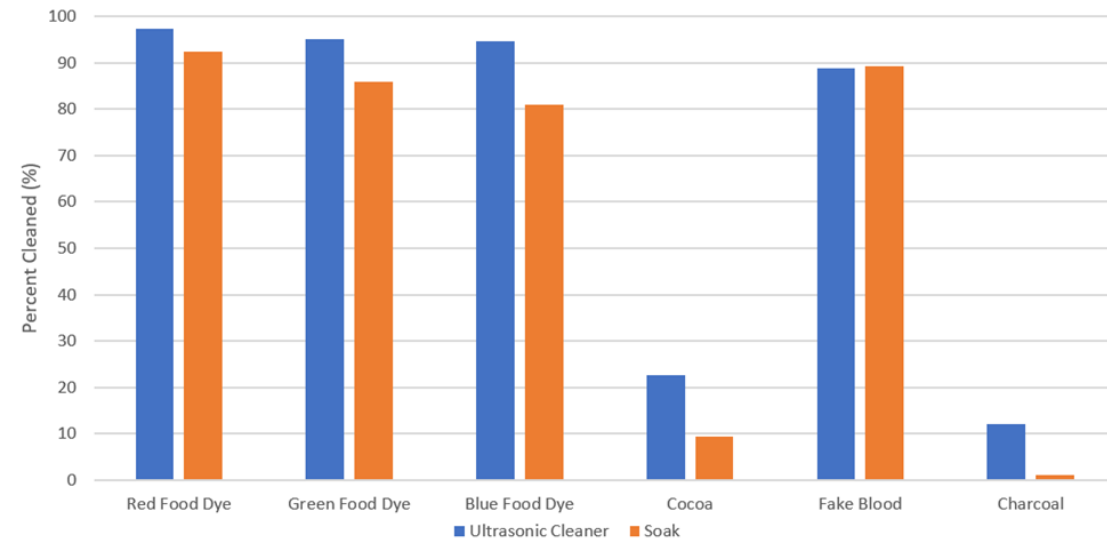
- Achieved **>86% salt removal** in just **7.5 minutes**
- Validated using both **mass tracking** and **salinity meter** (error <2.7%)

Efficiency & Performance:

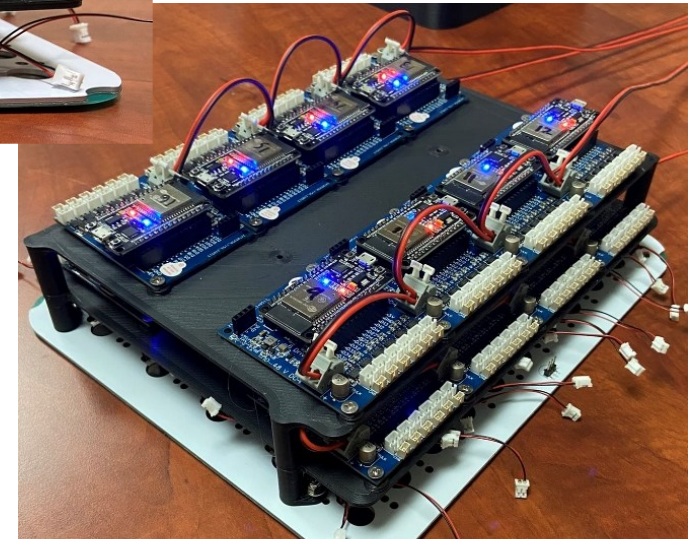
- Uses **minimal water (30 mm depth)** and **low energy**
- Avoids thermal evaporation—removes water through **mechanical vibration**

Scalability & Space Readiness:

- Technology scaled to wash and dry **full-size, folded T-shirts**
- Compact, energy-efficient design ideal for **ISS, Moon, and Mars missions**



Ultrasonic Dryer Components



Test Setup and Prototype Overview

•Integrated Washer + Dryer System

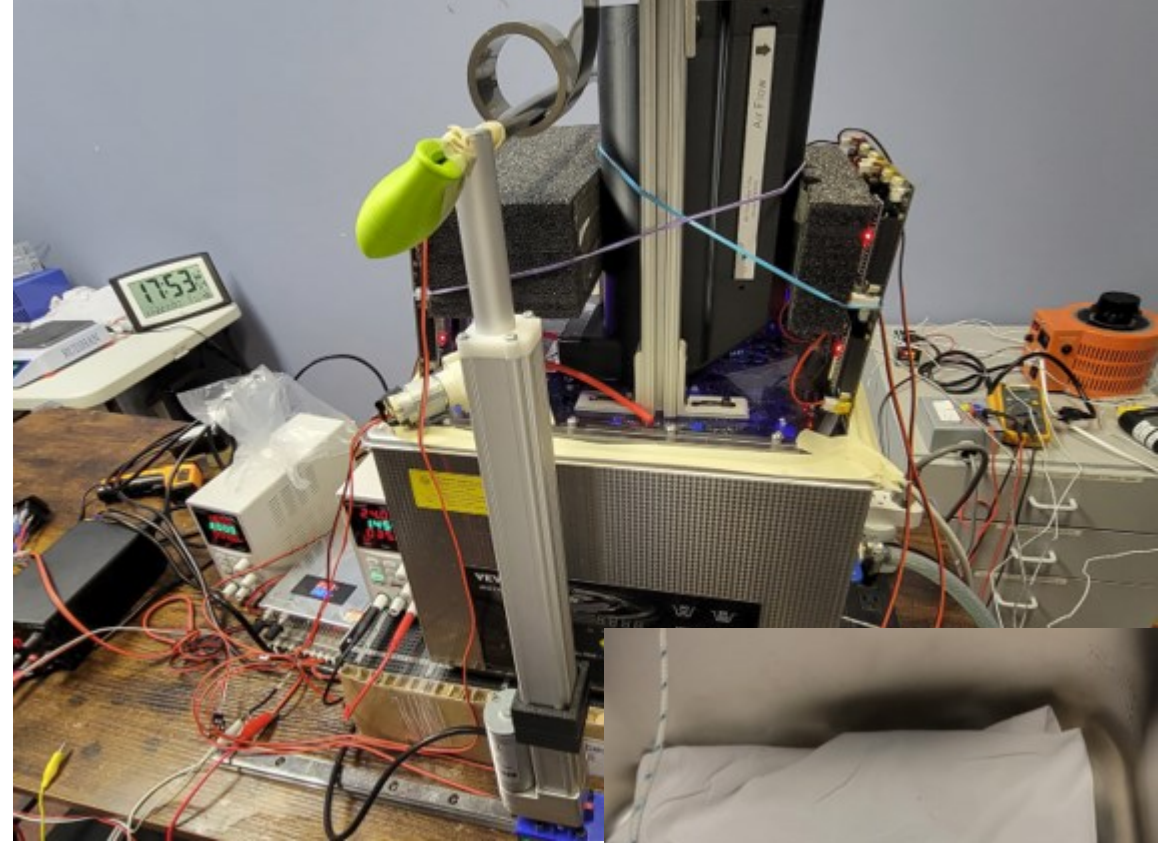
- Consecutive ultrasonic **wash and dry** cycles on medium adult T-shirts
- Garment folded in 8 layers to fit the machine

•Ultrasonic Garment Cleaner

- Optimized frequency, water level, and cleaning time
- Equipped with 16 smart piezo amplifiers, sensors, and a mist-capturing unit

•Direct Contact Dryer Details

- 96 piezo modules + constant-force backpressure system
- Final-stage heaters fill drying gaps and boost the temperature to **75–80°C** for final drying and boost disinfection



Mist Capturing Unit Design

•Purpose:

Captures micron-sized droplets generated during ultrasonic drying

•Centrifugal Separator System

- Waterproof blower + **4-stage spiral airflow path**
- Centrifugal force pushes the mist to the walls for separation

•Enhanced Water Capture

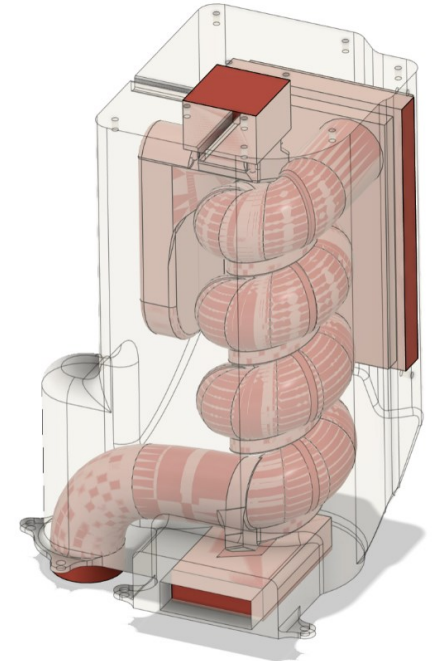
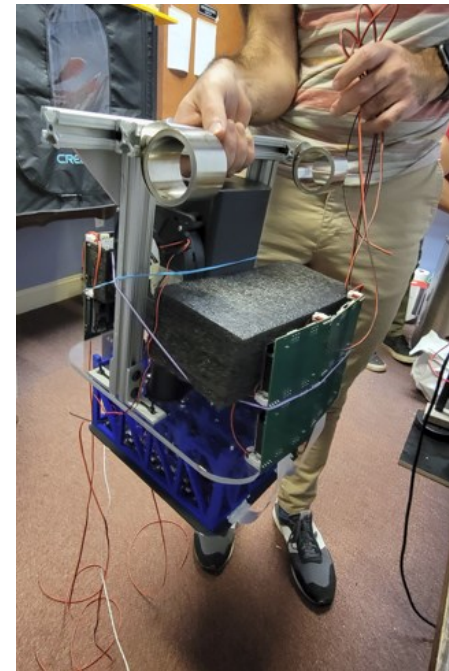
- **Grooved spiral base** isolates water from the air stream
- **Upward-beveled baffles** guide water into the groove, block re-entrainment

•Final Filtration

- **HEPA filter** removes residual particles at the air outlet
- Discharge air measured to be cleaner than the room condition

•System Integration

- Optimized for airflow, efficiency, and seamless integration with the prototype



Disinfection Evaluation Protocol (3rd Party Evaluator- Nelson Labs)

•Goal:

Assess microbial reduction during the full ultrasonic wash–dry process

•Organisms Chosen:

- **Staph** – Gram-positive skin bacteria
- **E. coli** – Gram-negative, common gut bacteria

•Test Setup:

- 2" × 2" swatches inoculated with **Staph** (Gram+) and **E. coli** (Gram–)
- Sterile USP-grade water used for cleaning

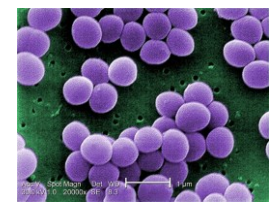
•Procedure:

- **Ultrasonic Cleaning (10 min)**
 - 4 water samples collected during the cycle
 - 1 swatch per organism tested post-wash
- **Ultrasonic Drying (30 min)**
 - Mist samples collected at 2 and 10 min
 - 1 swatch per organism tested post-dry
- **Thermal Drying (90 min)**
 - Final swatches collected for full-process analysis

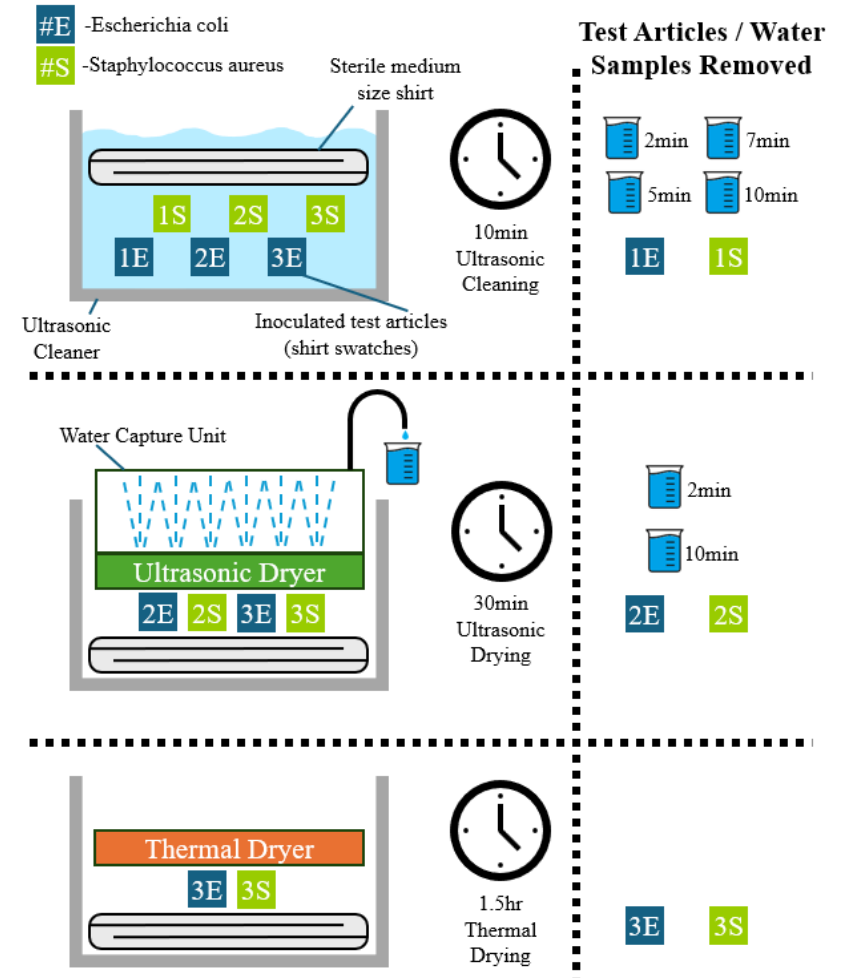


E-Coli

Commonly found in fecal contamination



Staphylococcus aureus
Very common on human skin



Disinfection Results Summary

•Staphylococcus aureus (Gram+)

- **Ultrasonic cleaning: ~50.6% reduction**
- **Ultrasonic drying: increased total kill to >99.989%**
- Achieved **LOG₁₀ 3.91** microbial reduction after wash + dry
- Thermal drying had **no measurable added effect** due to prior efficacy

• E. coli (Gram-)

- No detectable activity after exposure to **USP-grade pure water**
- Likely rapid die-off due to **hypotonic shock**

•Water Sample Results

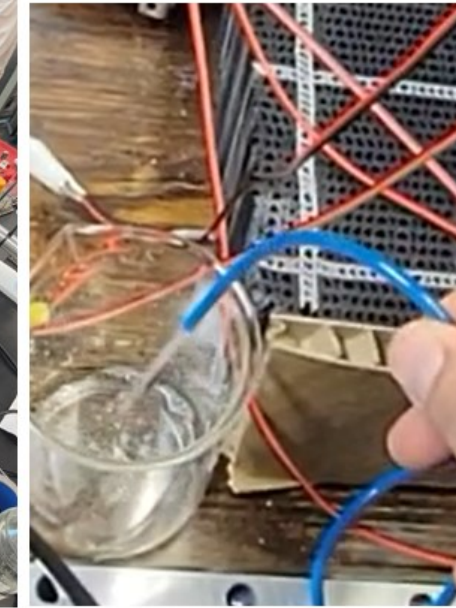
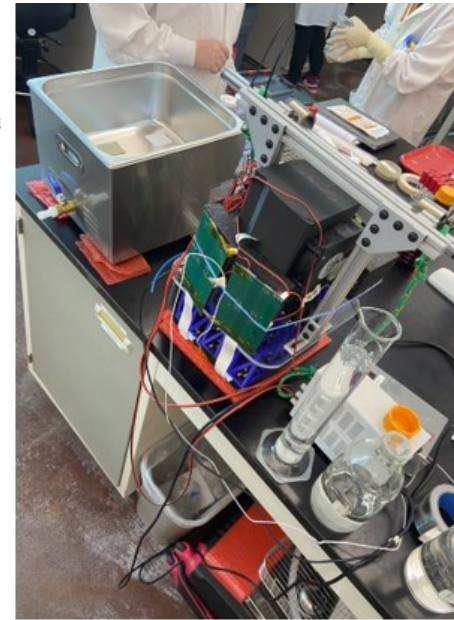
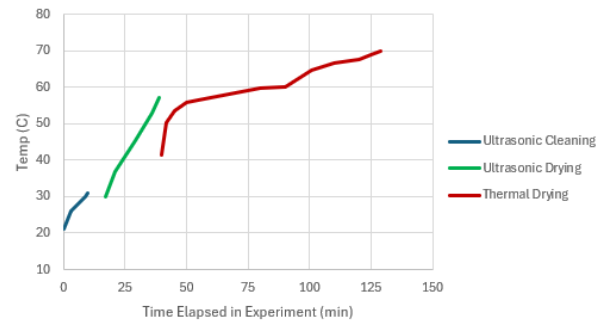
- **~98.7% CFU/mL reduction** during ultrasonic cleaning
- Final captured mist sample: **<1 CFU/mL**

•Temperature Effects

- Cleaning: **~31°C**
- Ultrasonic drying: **~57°C**
- Thermal drying: **~70°C**
- Some disinfection may be enhanced by incidental heating

•Caution:

Results are condition-specific; more testing is needed under **realistic use cases** (e.g., sweat, oils, salts)



	Symbol from Diagram	Shirt Swatch Test Article	Average Corrected Control Titer (CFU)	Corrected Test Article Recovery (CFU)	Percent Reduction (%)	LOG ₁₀ Reduction
Staphylococcus aureus, ATCC #6538	1S	1S (After Cleaning)	3.0 x 10 ⁶	1.5 x 10 ⁶	50.6	0.31
	2S	2S (After Cleaning + Ultrasonic Drying)		<3.1 x 10 ²	>99.989	>3.98
	3S	3S (After Cleanig + Ultrasonic Drying + Thermal Drying)		<3.1 x 10 ²	>99.989	>3.98
Escherichia coli, ATCC #8739	1E	1S (After Cleaning)	5.3 x 10 ⁵	<2.1 x 10 ²	>99.961	>3.41
	2E	2S (After Cleaning + Ultrasonic Drying)		<2.1 x 10 ²	>99.961	>3.41
	3E	3S (After Cleanig + Ultrasonic Drying + Thermal Drying)		<2.1 x 10 ²	>99.961	>3.41

	Staphylococcus aureus, ATCC #6538	Escherichia coli, ATCC #8739
Water Sample	Calculated Count (CFU/1mL)	Calculated Count (CFU/1mL)
Ultrasonic Cleaning - 2min	~1500	<1
Ultrasonic Cleaning - 5min	~1300	<1
Ultrasonic Cleaning - 7min	~380	<1
Ultrasonic Cleaning - 10min	20	<1
Ultrasonic Drying - 2min	<2.0	<1
Ultrasonic Drying - 10min	<1	<1

System Stress Testing – Summary & Outcomes

Drying Performance Gains:

- Increased piezo voltage from **18V to 22.3V** improved drying speed
- Further increases (to 26V, 30V) showed **diminishing returns** due to saturation
- Heater voltage increase (from **22V to 44V**) yielded **non-linear thermal gains**

Test Results Recap:

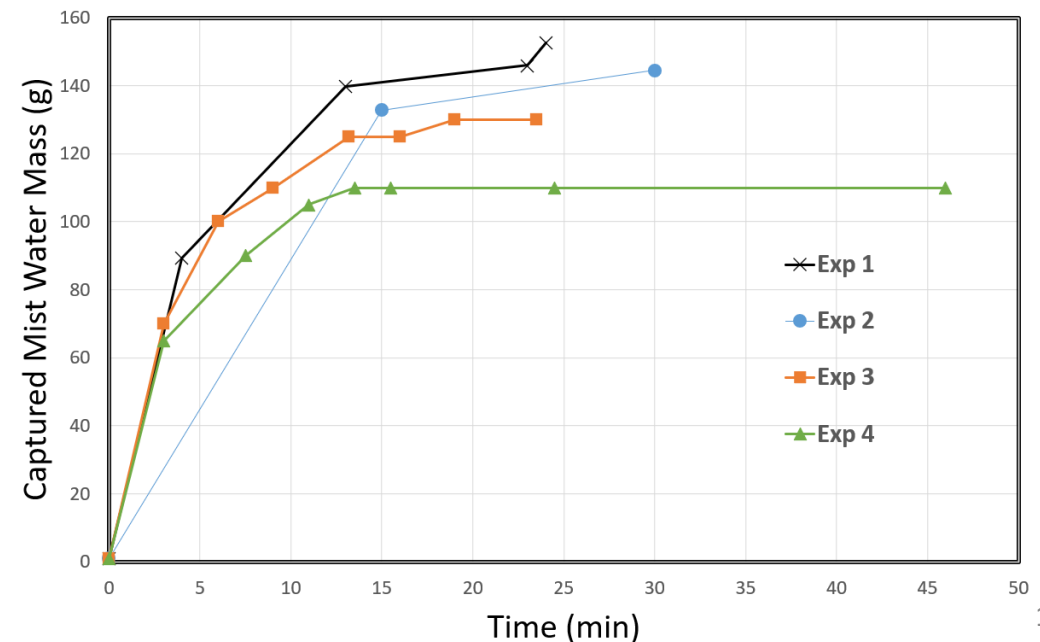
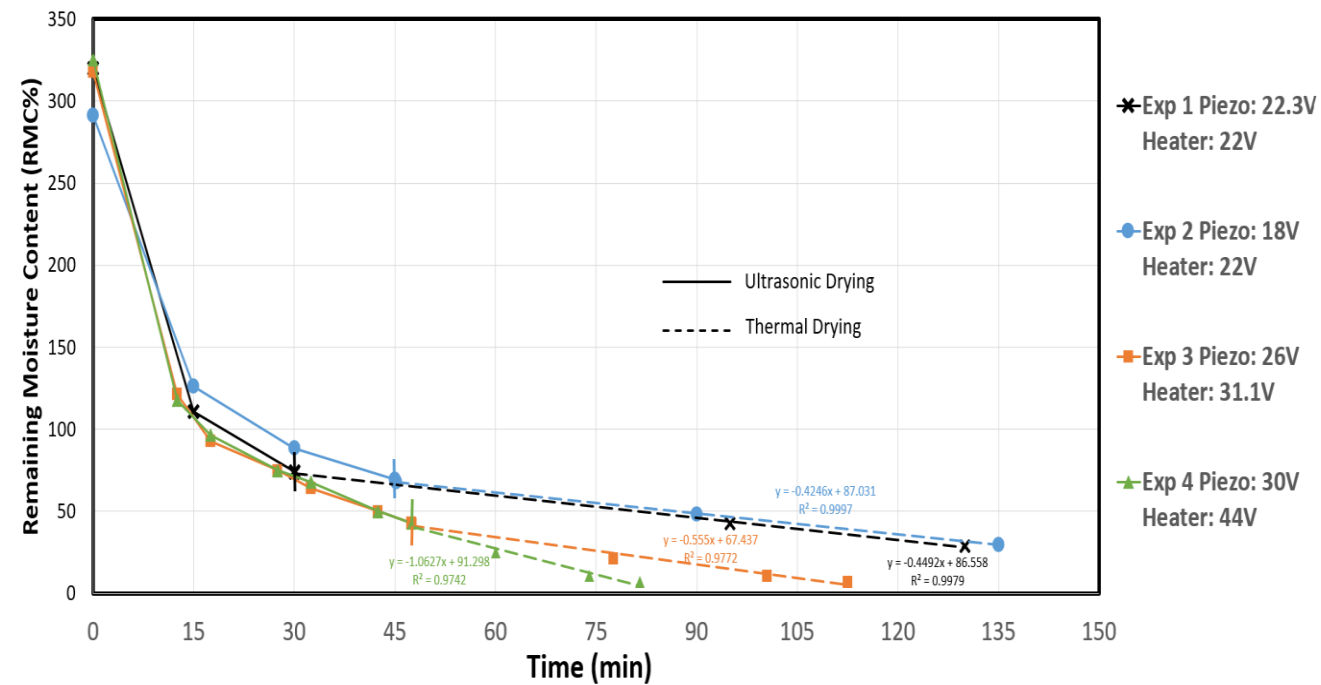
- **Test 1 & 2:** Hybrid drying (ultrasonic + thermal) reduced drying time to **~2.8 hrs**
- **Test 3 & 4:** Optimized setup achieved **full dryness in 90 min** (RMC 7% at 82 min)

Operational Potential:

- Our **Optimized hybrid Ultraosnic+Thermal cycle:** **~1.5 hrs per T-shirt**
- Output rate: **Up to 16 T-shirts/day/machine**

Supporting Insights:

- Thermal drying exhibited **high linearity** ($R^2 > 0.97$)
- **Water capture** was effective (up to **150g**, ~110% RMC)
- Higher voltages = faster drying, but **non-proportional efficiency**



Ultrasonic vs. Thermal Drying – Efficiency & Insights

Drying Efficiency Breakdown:

- ~85% of water removed via **ultrasonic drying**, only **10–15%** via thermal
- **Ultrasonic drying power input**: $\sim 2.1\times$ thermal input
- **Drying slope**: $8\text{--}14\times$ higher in **first 15 minutes**
- Indicates $4\text{--}7\times$ **greater efficiency** in early-stage moisture removal

Energy Usage Comparison (First 15 min):

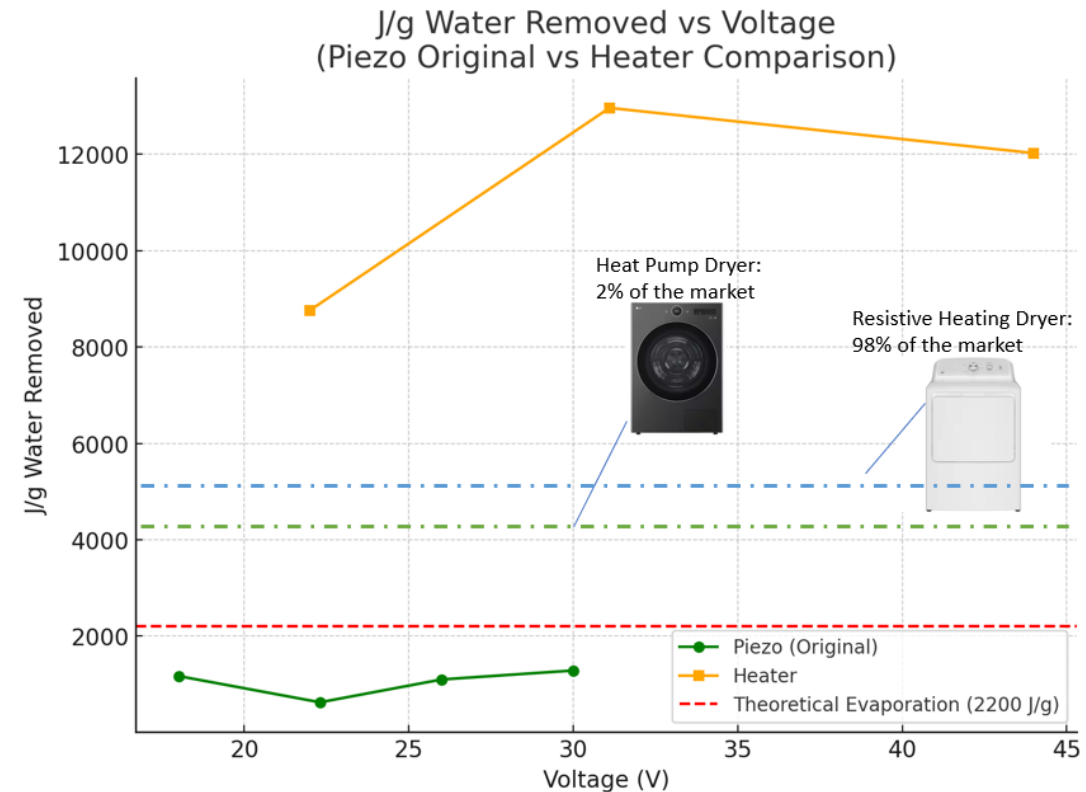
- **Thermal evaporation** requires $\sim 5\times$ latent heat of water \rightarrow **$\sim 20\%$ efficient**
- **Ultrasonic drying** uses $\sim 0.5\times$ latent heat \rightarrow **$\sim 200\text{--}300\%$ efficient**
- J/g water removed is significantly better for **piezo modules** than traditional heaters

System Optimization Point:

- Ideal: **20 min ultrasonic drying @ 22–26V**, followed by **60 min thermal drying @ 31–44V** ($T_{\max} = 90\text{--}127^{\circ}\text{C}$)

Market Context:

- Current dryers (98%) rely on **low-efficiency resistive heating**
- Ultrasonic systems offer **dramatic energy reduction potential**



Space Impact: System Mass and Clothing Logistics

Prototype ESM Analysis (Equivalent System Mass):

- Includes washer, dryer, and water capture unit
- Weight: 13.29 kg (7.52 kg cleaner + 5.77 kg dryer)
- Volume: 93 L (22.75" × 15.75" × 16")
- Power: 26V (eco) and 30V (performance)
- Cycle Time: Wash + dry 1 T-shirt every 92–120 minutes
- **ESM Results: 63.73 kg (eco mode), 69.09 kg (performance mode)**

NASA Logistics Context:

- 1,000-day mission (4 crew): 428 kg of clothing needed
- Launch cost for clothing:
 - Space Shuttle: \$23M
 - SpaceX: ~\$2.3M (at \$5.4K/kg max rate)

Impact of Ultrasonic Wash/Dry System:

- Enables 40 reuse cycles per garment
- Potential to reduce clothing mass by ~97.5% (Also trash reduction, lint reduction, flammable material reduction)
- Significant mass and cost savings for long-duration missions

Performance Mode (e.g. 330W average)			
Inputs			
M	mass kg		13.29
V	pressurized volume m3		0.09
Veq			13.40
P	total power kWe		0.33
Peq	the mass equivalent for power generation kg/kWe		87.00
C	total cooling required	kwth	0.02
Ceq	the mass equivalent for cooling infra kg/kWe	kg/kwth	146.00
CT	Total crew time required	CM-h/y	121.67
D	duration of mission y		0.20
Cteq	the mass equivalence of crew support kg/CM-h		0.96
			Combo Washer and Dryer ESM Calculated (equivalent mass)
			69.09

Conclusions

•Ultrasonic Wash–Dry System Performance

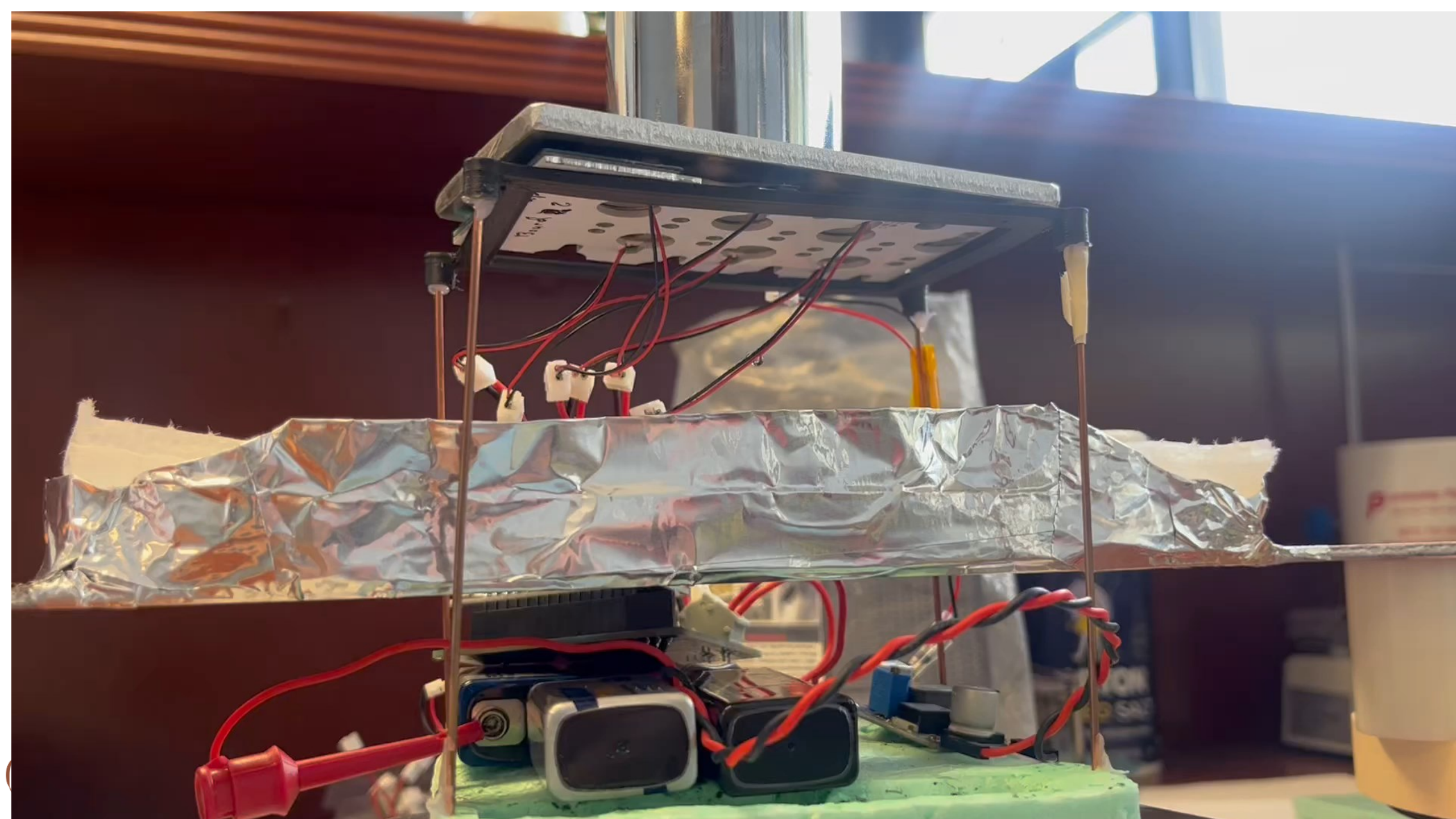
- Demonstrated effective **washing and drying of full-sized, folded T-shirts**
- Removed **>75% of water** in 30 minutes using ultrasonic drying
- Full cycle (wash + dry) completes as fast as **~90 minutes, no human intervention**

•Disinfection Efficacy

- Achieved **>99.989% bacterial reduction** on fabric (LOG_{10} 3.91)
- Water samples showed **98.7% CFU/mL reduction** during cleaning
- Final mist-captured water: **<1 CFU/mL**

•System Design Benefits

- Compact, **modular**, and **portable**
- Promising for **long-duration space missions** with minimal payload impact
- Enhances astronaut **hygiene and comfort** in microgravity environments



Clothing Payload Impact: Clothing accounts for 1/4 of the supplies sent to the ISS.

Our Combo Washer-Dryer Provides:

- > 40× reduction in clothing payload mass
- > 40X reduction in clothing trash
- > 15-50× lower lint production, reducing fire risk

- Process up to 16 T-shirts per day per machine
- Improving comfort and hygiene for crew members

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ISS026-E-011334 (18 Dec. 2010) --- NASA astronaut Catherine (Cady) Coleman, Expedition 26 flight engineer, is pictured with a stowage container and its contents in the Harmony node of the International Space Station.

Acknowledgments

This work was sponsored by the National Aeronautics and Space Administration (NASA) under Contract No. 80NSSC22PB238 & 80NSSC23CA166 with Ultrasonic Technology Solutions, LLC. The authors would like to acknowledge NASA JSC for sponsoring this research.

