# Direct Contact Ultrasonic Drying Rate and Efficiency Investigation for Spacecraft Solid Waste Management

Ayyoub M. Momen[1], Jon Bigelow[2], Connor Shelander[3]
*Ultrasonic Technology Solutions, Tennessee, 37932, USA*

**The goal of our study is to investigate the drying performance of the direct contact ultrasonic drying for bagged human solid waste relevant to the current waste management system at the ISS. Unlike the conventional thermal drying methods, direct contact ultrasonic drying does not use heat nor evaporate water and therefore is not bound by the high energy input required for water vaporization. This novel method of drying mechanically removes water by shaking the object rapidly (on a micron-scale) using piezoelectric transducers. Water is removed in the form of cold mist (atomized water). By bypassing the evaporation process, the technology demonstrates a much higher efficiency and drying speed of bagged human solid waste. In this paper, we will report the ultrasonic drying performance of simulated feces on multiple piezoelectric transducers across a membrane under different configurations. The result of this study could help to design a better solid waste management system for ISS and other space missions.**

## Nomenclature

| | | |
|---|---|---|
| *Ct* | = | capacitance of the piezoelectric element |
| *Fr* | = | frequency |
| $Fr_{Res}$ | = | resonance frequency time index during navigation |
| $h_{fg}$ | = | latent heat of evaporation |
| *ISS* | = | International Space Station |
| *JSC* | = | Johnson Space Center |
| *k* | = | effective spring constant |
| *m* | = | effective mass |
| *NASA* | = | National Aeronautics and Space Administration |
| *ORNL* | = | Oak Ridge National Laboratory |
| *Qm* | = | quality factor of the piezoelectric element |
| *RF* | = | radio frequency |
| *RMC* | = | remaining moisture content |
| *UWMS* | = | universal waste management system |
| *V* | = | voltage |
| *Vref* | = | reference voltage |

## I. Introduction

There are four sources for wastewater recovery and reuse in space missions including air humidity condensate, hygiene, urine wastewater, and feces material[1]. Handling, processing, and drying of human solid waste in the International Space Station (ISS) is a major technical challenge for long-duration space flights. Human solid waste (feces) contains approximately 75% water by mass, which is currently not recovered on the ISS. This waste material is collected and stored for 1-3 months and disposed of in departing logistic vehicles. The unrecovered water for a crew of 4 can add up to as much as 480 kg for a 1000-day mission[2]. NASA Johnson Space Center (JSC) recently showed its interest in low-temperature water removal methods for human solid waste. The low operating temperature (<110

[1] Founder and CEO, Ultrasonic Technology Solutions, 10820, Murdock Dr, Ste 104, Knoxville, TN, 37932.
[2] Lead engineer, Ultrasonic Technology Solutions, 10820, Murdock Dr, Ste 104, Knoxville, TN, 37932.
[3] Engineer, Ultrasonic Technology Solutions, 10820, Murdock Dr, Ste 104, Knoxville, TN, 37932.

°C) can minimize the release of volatile organic compounds and improve human comfort and hygiene. The universal Waste Management System (UWMS) is a new system that collects waste[3]. In the modern waste collection systems, independent interfaces and air paths collect urine and feces at the same time but separately. The feces are directed into air-permeable bags, then sealed and stored in containers. In the ISS, the bags along with other trash material is burned up during the atmospheric reentry; however, for other long-duration missions, the bags need to be stored indefinitely.

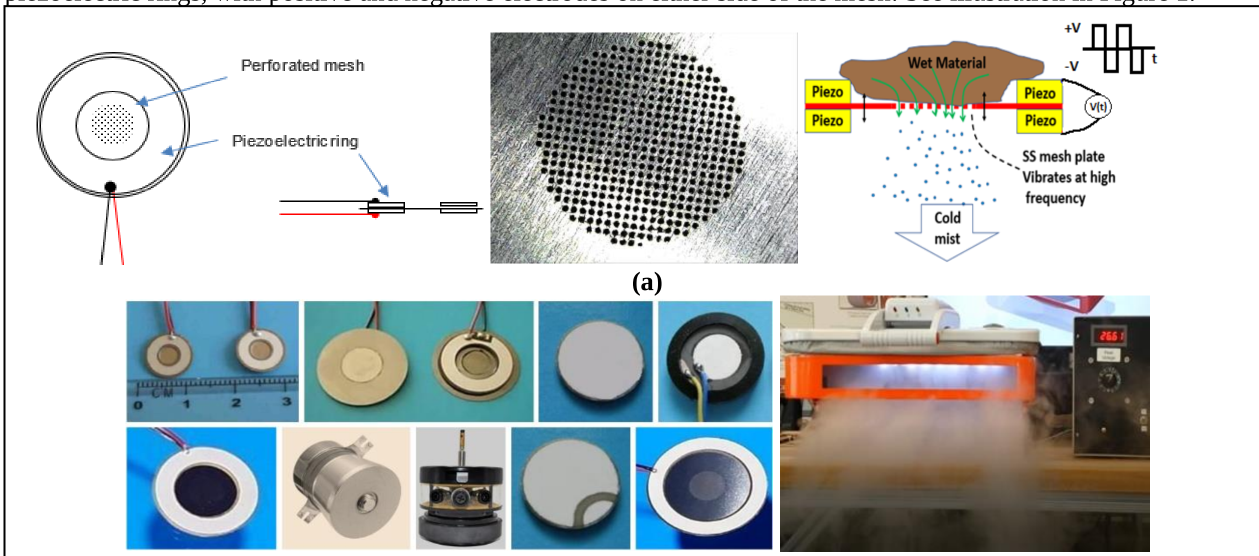
Ultrasonic Technology Solutions has recently received a NASA grant to investigate the implementation of their novel direct contact ultrasonic drying for human solid waste drying. Conventional drying methods like heat, vacuum, heat pump, infrared, radio frequency (RF), microwave, and freeze-drying all rely on evaporation to vaporize liquid water from a material. All these methods require heat to provide the enormous energy needed to evaporate the water (the minimum energy needed to evaporate water is the latent heat of evaporation, $h_{fg}$, which is ~2400 kJ/Kg @ 40 °C. The latent heat of vaporization is a thermodynamic constraint and represents the smallest theoretical energy input to vaporize water with heat. Due to practical losses and imperfect conditions, even the best drying methods that evaporate water require significantly more energy than the latent heat of vaporization.

In contrast, direct contact ultrasonic drying does not use heat nor evaporate water and therefore is not bound by the high energy input required by conventional drying methods. The direct contact ultrasonic drying technology was invented by the author of this paper and his team at the Oak Ridge National Laboratory (ORNL). The technology relies on high-frequency vibration of the piezoelectric transducers to induce significant momentum to break the surface tension force which is holding droplets in the micropores. The technology offers an alternative method for drying which relies on mechanical displacement of water, with the water removed as a mist of cold droplets rather than through evaporation. The formed mist can be captured with a filter or be carried out to the desired location using small airflow. By bypassing the evaporation process (phase change process), the technology demonstrates 5X higher efficiency and a 2X faster-drying rate on a typical fabric compared to that in the residential dryer. Detailed information about this technology can be found in Patent[4] and publications[5-8]. This paper discusses the preliminary results of direct contact ultrasonic drying of human solid waste material.

## II. Test Components

### A. Piezoelectric Transducers:

Most of the piezoelectric transducers that are drying feces efficiently are identified to be the mesh type piezos. As shown in Fig. 1, mesh piezos are generally made up of a perforated stainless-steel mesh attached to one to two piezoelectric rings, with positive and negative electrodes on either side of the mesh. See illustration in Figure 1.




(a)

(b) (c)

**Figure 1. Illustration of Perforated Stainless-Steel Mesh with PZT Ring attached (a). Various types of the vibrational elements (b). Pprototypes used to dry wet fabric consisting of a system pressing wet fabric against piezoelectric modules and the mist being ejected downward from the mesh piezoelectric elements[4] (c).**

When the piezoelectric element directly shakes the wet material at its resonance frequency, the water is mechanically displaced and ejected through the mesh holes and forms a cold mist of water droplets. These piezos are different in size and geometries. In this study, the drying performance of more than 40 piezoelectric transducers has been investigated and the results of the best performing piezoelectric transducers are reported here.

**B. Simulated Feces:**

In this work, volatile organics is not studied mainly due to smell and limited laboratory certifications. There are multiple formulations to make simulated feces for a wide variety of research applications[10-11]. Based on the technical information provided by NASA, we acquired four different types of feces formulations from SiliClone Creations (https://www.siliclonecreations.com) for our testing. These formulations of simulated feces have improved colloidal stability, shown less syneresis (water separation on standing), and improved the characteristics of wetting and adhesion with test substrates. SiliClone Creations formulations are also standardized and easy to mix, as the one-part dry mix is combined with three-parts water by weight. The formulations are specifically designed to simulate the composition of feces and standardized fatty material content with more realistic viscoelastic rheological behavior. The formulations also do not have a smell. One downside of the SiliClone formulations is that they do not simulate the bacterial load of actual feces.

**C. Membrane Material:**

The fecal material in the ISS is stored in a vapor-permeable membrane material and it is very important to demonstrate the feces material drying across the membrane. A PTFE Laminated membrane with 5-micron holes has been used in this investigation [product # 1110198, SterliTech Corporation]. This membrane closely mimics what is currently used at ISS. As shown in Fig. 2, this membrane is hydrophobic on one side and hydrophilic on the opposite side. The hydrophilic side has a good affinity to absorb water. When the membrane saturates with water, its water content to the bone-dry weight mass is about 68%. The current understanding is that if feces is stored in these membrane bags, water vapor can be slowly evaporating from feces at a very slow rate.


(a) (b) (c)

**Figure 2. The membrane used by NASA is hydrophobic on one side (a), and hydrophilic on the other side (b). The set mass of feces is sandwiched by either side of the membrane. Membrane discoloration is visible when the hydrophilic side of the membrane is touching feces (c).**

## III. Test Procedure

The experimental setup for studying the feces drying process using ultrasonics is illustrated in Figure 3. The experimental setup consisted of four major components — a modulating amplifier, an ultrasonic transducer, an analytical scale, and an oscilloscope. The custom-made modulating amplifier consisted of an amplifier driven by a microprocessor that can be adjusted to the resonant frequency of the ultrasonic transducer, and a modulator that produced a pulse-train burst-type modulation. Its output was connected to the ultrasonic transducer, and the power signal (resonant frequency and peak voltage) of the transducer and the modulating signal (duty cycle and modulating frequency) were adjusted to desired values. After the signal parameters were adjusted, a piece of wet sample material (i.e., simulated feces) was placed on the transducer and the power was turned on. The weight of the wet material was measured continuously through an RS232 interface with the computer using the open-source "Termite" data collection software. The resolution of the analytical scale is 0.1 mg (milligram).

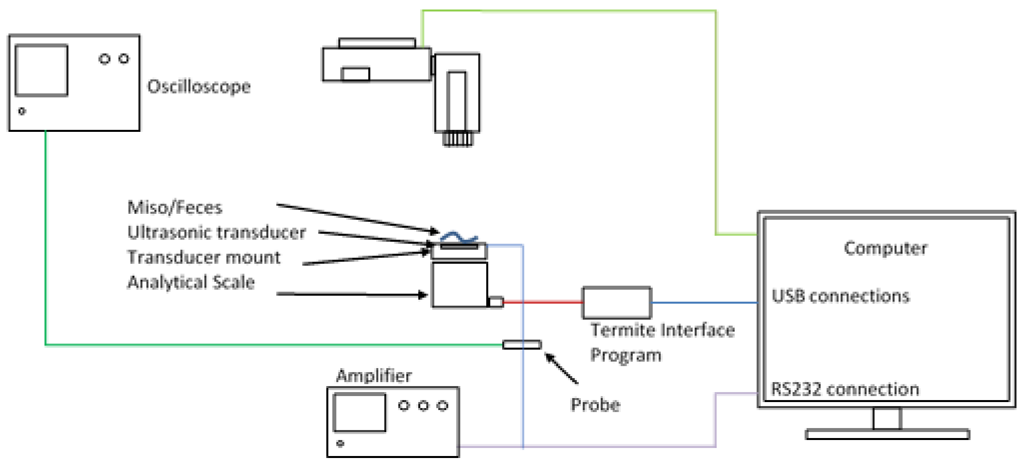



**Figure 3. Schematic representation of the experimental setup.**

The test setup design allows for simultaneous measurement and control of the feces drying process. The rate of the mass change of the wet feces, temperature, driving voltage amplitude, frequency, and power consumption of the piezoelectric transducer are all measured in real-time.

The off-the-shelf impulse sealer is used to seal the membrane bag with the hydrophobic side of the membrane on the outside. Then, the bag was filled with simulated feces and sealed as shown in Fig. 4. The thickness of the fecal material could be controlled by the amount of fecal material loading in the bag. A sealed membrane bag with simulated feces was placed on top of the piezoelectric transducer as shown in Figure 5. Then a mass was placed on top of the bag of simulated feces to add known back pressure to the bag. (In previous studies, we demonstrated that a small back pressure enhances the drying performance.) Then the piezo was powered and data could be recorded.


**Figure 4. The process of filling membrane bag (size: 1.5-2.5 cm range) with simulated feces.**

# IV. Results and Discussion

## A. Baseline Testing:

To start the testing, a baseline thermal drying of the membrane bag was performed. In these tests, a known mass of simulated feces was placed on the membrane and sandwiched between a plastic substrate and then the coupon was pressed (at a pressure of about 1400 Pa) to achieve a uniform feces thickness. On one sample, the hydrophobic side of the membrane faced the feces, wherein on the second sample the hydrophilic side of the membrane faced the feces. The baseline evaporation-based drying tests were performed at room temperature (21 °C and RH~50%) as well as at the elevated temperature of 120°C in the oven. The drying curve and the drying rate for baseline tests are shown in Figure 6. Figure 6 shows that the baseline drying curves (free air and oven, no ultrasonic drying) are approximately similar irrespective of the side of the membrane that is touching the sample. Also, as expected at elevated temperatures, the drying is faster. For instance, in the first 20 seconds, the average feces drying rate across the membrane at 120°C is 5.4 kg/m$^2$.hr, whereas at 21°C, the rate is as low as 0.18 at the beginning of the drying process.

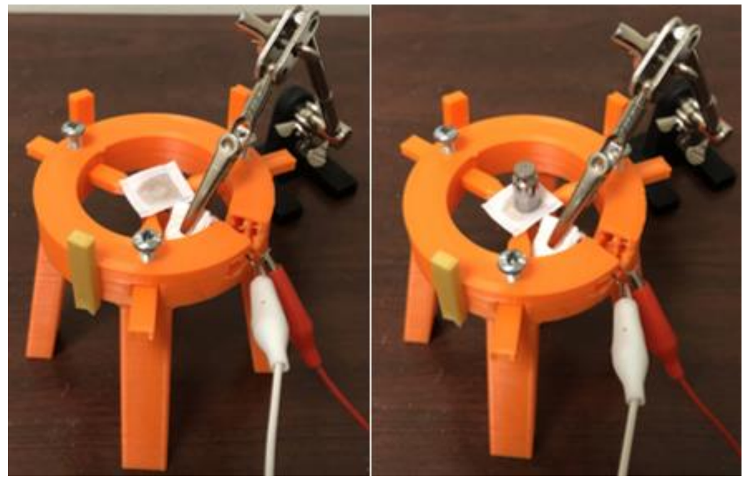


**Figure 5. Simulated feces membrane bag drying test.**

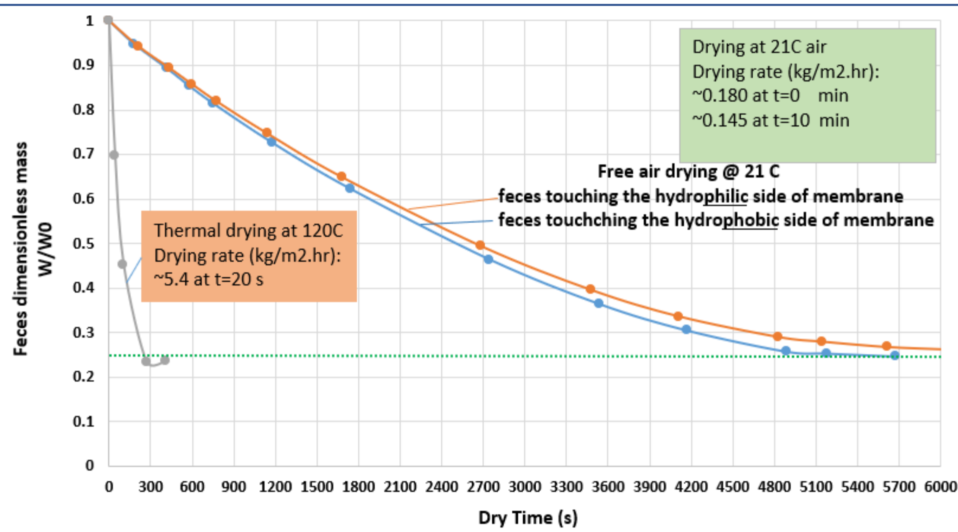



**Figure 6. Baseline thermal drying curves for feces under the membrane.**

## B. Best Piezoelectric Transducer:

Initially, more than 100 tests were performed in order to find the best type of piezoelectric transducer that can dry a membrane bag. The electrical specifications of the best-performing piezoelectric transducers have been precisely measured using the impedance analyzer. The impedance response of the best performing piezoelectric transducer is shown in Figure 7.

The resonance frequency of the best performing piezoelectric transducer is measured to be 194.3kHz and the minimum impedance was 67.19 Ω (@ resonance frequency). The quality factor (Qm) of the piezoelectric transducer was 43.13 and the capacitance (Ct) was 2.04 nF. The quality factor Qm, is the ratio of the reactance to the resistance in the series equivalent circuit representing the piezoelectric resonator.

**C. Direct Contact Ultrasonic Drying on the active area of the piezoelectric transducer:**

After identifying the best type of piezoelectric transducer, comprehensive testing was done under different configurations. The direct contact ultrasonic drying was performed on simulated feces inside the membrane bag. The feces was placed on the membrane as already shown in Fig. 5, and then placed on the best performing piezoelectric transducer.

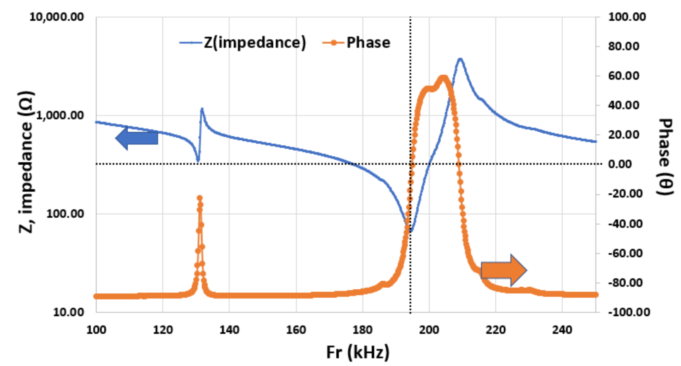



**Figure 7. The frequency response of the best performing piezoelectric element measured by an impedance analyzer.**

There are two areas of interest for a piezoelectric transducer: a) the active perforated area at the center where the water can easily escape, and b) the entire surface area of the piezoelectric transducer. A very small sample at the size of the active area of the piezoelectric mesh transducer has been evaluated and the result is illustrated in Figure 8. The drying curve for two thicknesses of the fecal material is shown in Fig. 8. Considering the fecal material has a water-to-bone dry mass ratio of 3:1, Figure 8 shows that the 290-micron thick sample drys within the first 50 seconds, whereas the 3.4X thicker sample (991 microns) dries in 240 seconds. The slope of the graph can be converted to the drying rate. Figure 8 shows that drying across the membrane yields an approximate drying rate of 25 $kg/m^2$.hr on the active area. Comparing the results shown in Fig 6, the simulated feces ultrasonic drying rate on the active area of the piezoelectric transducer and across the membrane was 5X faster than thermal drying at 120°C or 138X faster than free air-drying at 21°C.

**D. Frequency Study:** The resonance frequency ($Fr_{Res}$) of a piezoelectric transducer is measured using the impedance analyzer. When the feces membrane bag is placed on the piezoelectric transducer, due to the coupling and additional effective mass, the resonance frequency could slightly shift. Moreover, as drying takes place and the mass of the feces decreases, the resonance frequency can also slightly shift. Additional investigation is done to find the best driving frequency (Fr) that can achieve the best drying rate. Figure 9 shows the impact of the operating frequency on the drying results. This figure shows that driving the piezoelectric transducer at 94-95% of its resonance frequency will provide the best drying rate. This is in part consistent with the theory where the additional mass can shift the effective resonance frequency of the system to the lower levels (Fr~$\sqrt{k/m}$).

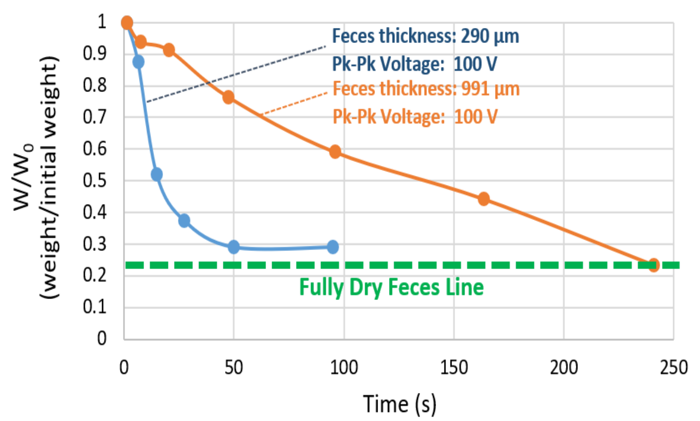



**Figure 8. Ultrasonic drying curve of simulated feces on the active area of the piezoelectric transducer for two different thicknesses. Note that the simulated feces contain 75% water (water to solid ratio of 3:1).**

**E. Voltage impact:** The vibration magnitude of the piezoelectric transducer increases at the higher peak-to-peak voltages and the trend continues until the excessive voltage breaks or damages the piezoelectric transducer. After identifying the best performing piezoelectric transducer and the best operating frequency, the impact of the peak-to-peak applied voltage on the drying of the membrane bags on the entire piezoelectric transducer was investigated. The amount of water in the material can be defined by the remaining moisture content (RMC) as described in Eq. (1) below:

$$RMC = \frac{wet\ mass - bone\ dry\ mass}{bone\ dry\ mass} \quad (1)$$

Figure 10 shows the drying rate as a function of the remaining moisture. We kept the upper limit of voltage at 115V since this specific piezo will be damaged at 130V. The maximum area average drying rate of >8 kg/(m$^2$•hr) is achieved at 115V peak-to-peak. Note that this is the average drying rate on the entire surface of the piezoelectric transducer.

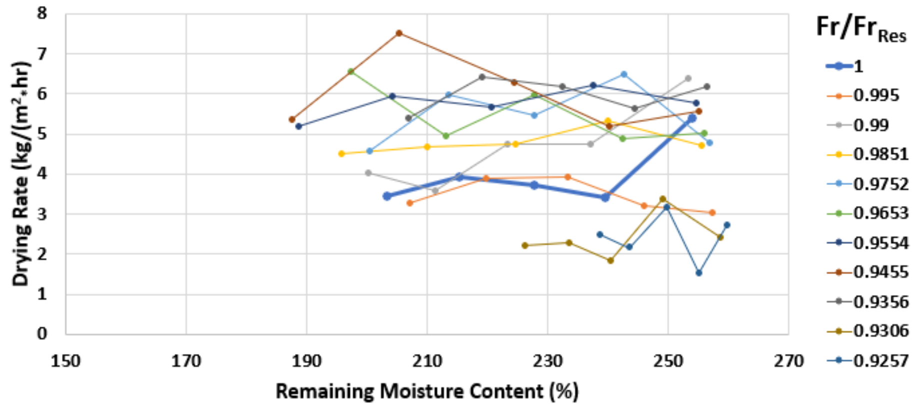



**Figure 9. Impact of the operating frequency on the drying rate of the best performing piezoelectric transducer (70V pk-pk).**

Clearly, the drying rate improves almost linearly at the higher voltage input as shown in Figure 10. However, the piezoelectric transducer power consumption is proportional to the voltage square (Power ~ V$^2$). Therefore, careful consideration needs to be taken to find the drying rate that meets the application requirements and at the same time does not reduce the drying efficiency of the piezoelectric transducers unnecessarily. Considering that the voltages above 130+V could immediately damage the piezoelectric transducer and 115V could reduce the lifespan of the piezoelectric transducer, we decided to keep the voltage below 100 Volt pk-pk for the scale-up system design.

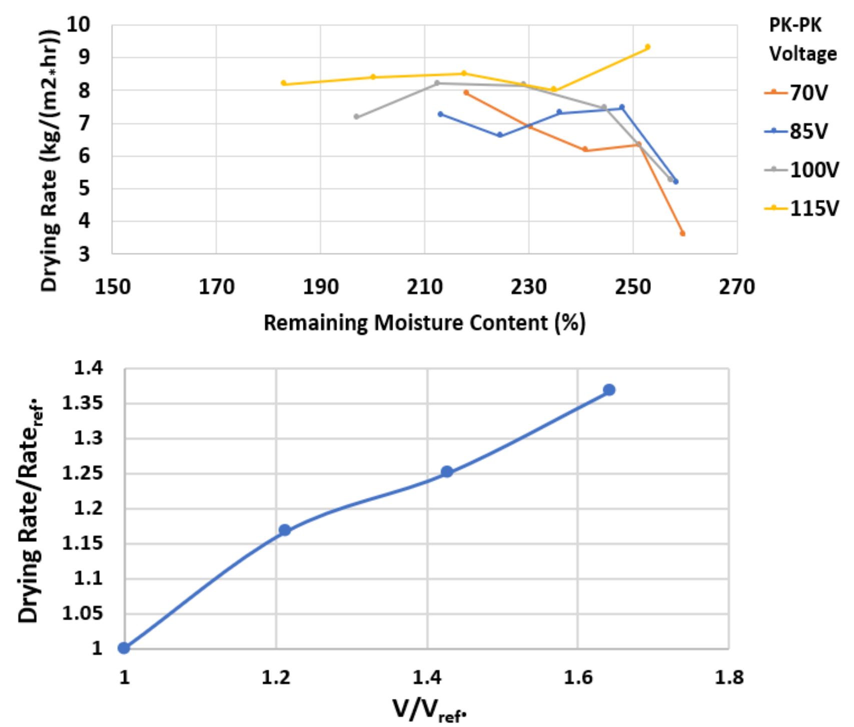



**Figure 10. Impact of the peak-to-peak voltage on the drying rate of the membrane bag covering the entire surface of the piezoelectric transducer (a). the average dimensionless drying rate as a function of the dimensionless voltage (b).**

**F. Scale-up system specifications for space applications:** Our team is currently working on developing the proof-of-concept prototype, enabling the next generation of the human solid waste dryer for the space applications to be realized. Please note that the technology is quiet during operation as the ultrasonic frequency is significantly above the human hearing range. Based on the preliminary data partially described in this paper, the large-scale system and the material handling will have the following specifications: the astronaut will put their membrane feces bag into the compact (30×20×10cm) and lightweight (<2-4kg) ultrasonic drying machine for fast drying. The machine consists of 270 piezoelectric transducers placed on two matching arrays of piezoelectric transducers. Each feces bag contains approximately 0.12 kg of fecal matter (typical daily fecal mass of a healthy human). Based on the drying rates identified, each membrane bag can be dried in about 45 minutes. The dry bag will be removed and stored in the existing storage cabinet. In this scenario, the ultrasonic dryer machine is ready to get the next feces bag. If scheduled correctly, such a system can support a crew of 4-8 people. For additional convenience, resilience, and reliability, the ISS might use two of these machines at the same time.

## V. Conclusion

This paper introduces a new method of human solid waste drying. The technology uses the high-frequency vibration of piezoelectric transducers to mechanically extract water from the fecal material stored in a membrane bag. Many experiments were conducted to identify the best-performing piezoelectric transducer that can dry fecal material. The highest drying results yielded an approximate drying rate of 25 $kg/m^2.hr$ on the active area of the piezoelectric transducer, which is about 138 times faster than drying the same membrane in the free air at 21°C and 50% relative humidity. The drying rate at different frequencies and voltages is measured to facilitate the design of the larger-scale system. The technology can open new opportunities for more effective solid waste management and more efficient water recycling in space applications, reducing the payload associated with near-Earth or deep space missions. The technology will also reduce astronaut interaction with bagged feces and could improve their overall hygiene and comfort.

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