NASA Zero-Gravity Space Flight Experiment
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Rotational Filtration Systems: Investigating the Effect of Microgravity on Concentration Polarization and Membrane Fouling

Om Sanan
3 Hanover Road
Scarsdale, New York 10583
om.sanan007@gmail.com
914-282-7737
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Abstract

This proposal outlines an advanced experimental plan to investigate the influence of microgravity on concentration polarization and membrane fouling in rotational filtration systems. This experiment, set to be conducted aboard a Zero-G parabolic aircraft in April 2025, will utilize 25-30 parabolas of approximately 22 seconds of microgravity each. The primary objective is to evaluate how varying levels of artificial gravity, induced through rotational motion, affect filtration efficiency and fouling mechanisms in comparison to normal and inverted gravitational conditions on Earth. The experiment is meticulously designed to not only test the fundamental physics underlying filtration processes in microgravity but also to apply rigorous statistical methods to ensure the robustness and significance of the results. The outcomes are expected to provide critical insights for the development of more reliable water recycling systems in space and advanced filtration technologies on Earth, with a particular focus on energy-efficient methods suitable for large-scale water treatment in future space habitats.

1 Purpose

The central purpose of this experiment is to systematically analyze the effects of microgravity on the processes of concentration polarization and membrane fouling within water filtration systems, with a specific focus on rotational filtration methods. These phenomena are of particular concern in space missions, where efficient water recycling is essential for long-term sustainability. By employing a rotational filtration system, this experiment seeks to quantify the impact of artificial gravity on mitigating fouling, providing a comparative analysis across different gravitational environments—microgravity, normal gravity, and inverted gravity.

The findings from this study are anticipated to guide the design of filtration systems optimized for both space and terrestrial applications, particularly where traditional methods are challenged by the absence or inversion of gravitational forces. Moreover, this research aims to address the critical need for energy-efficient water treatment methods in future space habitats, such as potential Moon or Mars bases, where resource conservation is paramount.

2 Background and Significance

Water filtration in space presents unique challenges due to the altered fluid dynamics caused by the absence of gravity. On Earth, gravitational forces assist in particle sedimentation, which can reduce the buildup of solutes near the membrane surface—a key factor in concentration polarization and subsequent membrane fouling. In microgravity, however, these natural sedimentation processes are absent, leading to an enhanced risk of fouling, which can significantly reduce filtration efficiency (Naillon et al., 2019).

Traditional Earth-based water treatment methods, particularly those relying on gravity for sedimentation (e.g., coagulation-flocculation processes), are ineffective or highly inefficient in microgravity environments. For instance, Altinkaya (2024) demonstrated that the settling time for particles in a typical coagulation-flocculation process could increase significantly in microgravity, rendering such methods impractical for space applications.

Rotational filtration systems offer a novel approach by using centrifugal force to create artificial gravity. This force acts radially outward, mimicking the effects of gravity and potentially reducing the thickness of the concentration polarization layer. Recent studies by Basu and Sharma (1997) have shown that rotational systems can enhance mixing and reduce concentration polarization in terrestrial applications, suggesting potential benefits in microgravity environments.

The scientific importance of this research lies in its potential to improve the reliability and efficiency of water filtration systems, which are critical for long-duration space missions. Furthermore, the insights gained could also enhance terrestrial filtration technologies, particularly in applications where gravity is not a reliable factor, such as in zero-gravity industrial processes or underwater environments.

2.1 Rotational Systems vs. Traditional Methods

Rotational filtration systems offer several advantages over traditional linear filtration methods, both on Earth and in space:

1. Even Pressure Distribution: In rotational systems, the centrifugal force creates a more uniform pressure distribution across the membrane surface. This even

distribution can lead to more consistent filtration performance and potentially reduce localized fouling (Jaffrin, 2011).

2. Enhanced Turbulence: The rotational motion generates increased turbulence near the membrane surface, which can help mitigate concentration polarization by disrupting the formation of stagnant boundary layers (Basu & Sharma, 1997).
3. Energy Efficiency: In space environments, where energy conservation is crucial, rotational systems may offer a more energy-efficient alternative to high-pressure driven filtration methods. The energy required to rotate the system may be less than that needed to generate high pressures in traditional reverse osmosis systems (Villafan˜a- L´opez et al., 2019).
4. Scalability: Rotational systems have the potential to be more easily scaled for larger applications, such as water treatment for a Moon base, compared to linear filtration systems which may require complex manifolds for even distribution.

2.2 Microgravity Considerations

The microgravity environment presents both challenges and opportunities for filtration processes:

Pros of Microgravity for Filtration:

1. Absence of Sedimentation: The lack of particle settling can prevent the formation of cake layers on membrane surfaces, potentially reducing certain types of fouling (Naillon et al., 2019).
2. Uniform Fluid Distribution: Without gravity-induced convection, fluid distribution can be more uniform, potentially leading to more consistent filtration across the

membrane surface (Altinkaya, 2024).

Cons of Microgravity for Filtration:

1. Enhanced Concentration Polarization: The absence of natural convection can exacerbate concentration polarization, leading to increased fouling and reduced efficiency (Basu & Sharma, 1997).
2. Bubble Formation: In microgravity, gas bubbles do not naturally rise and can accumulate in the system, potentially disrupting flow patterns and reducing effective filtration area (Jaffrin, 2011).
3. Altered Fluid Dynamics: The lack of buoyancy-driven flows can affect the transport of foulants to and from the membrane surface, potentially leading to unpredictable fouling patterns (Altinkaya, 2024).

3 Hypotheses

Based on the current understanding of filtration processes in various gravitational conditions, we propose the following hypotheses:

Hypothesis 1: The rotational filtration system will significantly reduce concentration polarization and membrane fouling in microgravity compared to non-rotating systems.

Justification: In microgravity, the lack of natural convection leads to enhanced concentration polarization. By introducing centrifugal forces through rotation, we hypothesize that solute accumulation near the membrane will be mitigated, reducing fouling. The increased turbulence generated by rotation is expected to disrupt the formation of stagnant boundary layers, promoting better mixing and reducing the thickness of the concentration polarization layer (Basu & Sharma, 1997).

Hypothesis 2: The filtration performance in an inverted gravity condition will exhibit different fouling characteristics compared to both normal and microgravity conditions, due to altered pressure distributions and flow patterns.

Justification: In an inverted gravity setup, the hydrostatic pressure distribution across the membrane will be reversed compared to normal gravity. This alteration is expected to affect the water flux and solute transport mechanisms differently than in normal gravity or microgravity conditions. The inverted setup may lead to unique flow patterns that could either enhance or hinder the filtration process, depending on how these patterns interact with the membrane surface and the rotational forces (Devaisy et al., 2023).

4 Experiment Design: Setup and Materials

The experimental design involves a controlled, highly detailed setup to ensure precise measurements and reproducible results (Figure 1). The design also includes rigorous statistical analysis to validate the findings.

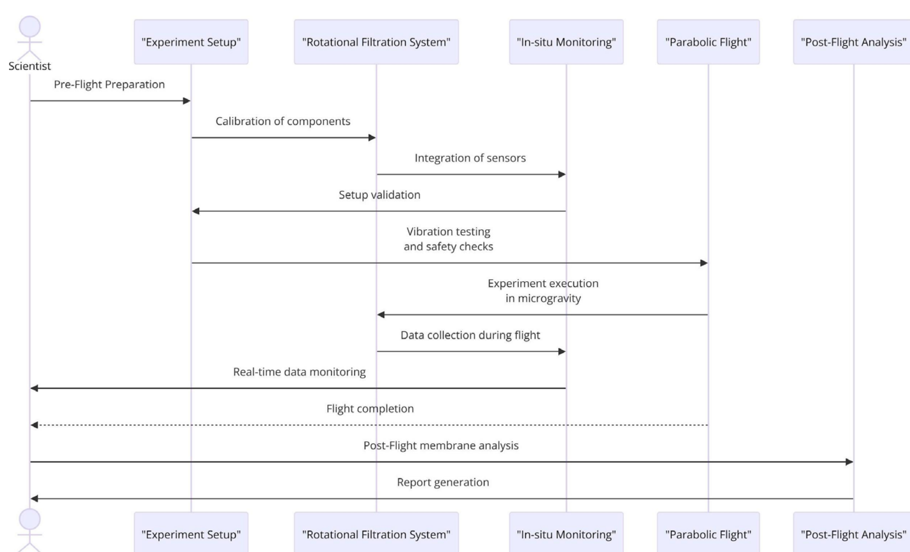

Figure 1: *Experiment Design for Rotational Filtration System. This sequence diagram illustrates the key stages of the experiment designed to investigate the effects of microgravity on concentration polarization and membrane fouling within a rotational filtration system. The process begins with pre-flight preparations, including the calibration of components and safety checks. During the parabolic flight, the rotational filtration system operates in microgravity, with real-time data collection and monitoring through integrated sensors. Post- flight, detailed analysis of the filtration membranes is conducted to generate comprehensive reports on the experiment's findings. The diagram highlights the interactions between the experimental setup, data collection, and subsequent analysis phases.*

- **Rotation Chamber:** The chamber is fabricated from aerospace-grade carbon fiber, selected for its high strength-to-weight ratio. The chamber will house a cylindrical filtration membrane, which will rotate at speeds from 0 to 3,000 RPM, controlled by a precision servo motor. The carbon fiber construction ensures minimal deformation under high rotational speeds and varying gravitational conditions.
- **RPM Range Selection:** The range of 0 to 3,000 RPM was carefully chosen for this experiment based on several factors:
  - **Sufficient Centrifugal Force:** At 3,000 RPM, the system generates enough centrifugal force to create a significant artificial gravity effect, allowing us to study its impact on concentration polarization and membrane fouling.
  - **Safety Considerations:** This range keeps rotational speeds within safe limits for the parabolic flight environment, reducing risks associated with extremely high speeds.
  - **Energy Efficiency:** The selected range balances the need for artificial gravity with energy consumption, which is crucial for potential space applications.
  - **Equipment Limitations:** The chosen range is compatible with commercially available high-speed motors and bearings, ensuring reliable operation throughout the experiment.
  - **Scalability:** This range allows for potential scaling of the technology for larger

applications without requiring extreme rotational speeds.

- **Filtration Membrane:** A 0.1-micrometer pore size membrane, made from a hydrophilic polyethersulfone (PES) material, known for its resistance to fouling and mechanical robustness. The membrane's surface will be modified with a nano-structured coating to further enhance its anti-fouling properties, ensuring minimal interaction with particulate matter. The membrane is designed to withstand the shear forces induced by high rotational speeds.
- **Circulating Pump:** An industrial-grade peristaltic pump, capable of maintaining a consistent flow rate of 1 L/min, is integrated into the system. This ensures uniform water delivery to the membrane across all experimental conditions. The pump's flow rate can be precisely controlled to simulate varying operational conditions that may be encountered during space missions. The pump is equipped with a variable frequency drive to adjust its performance under different gravitational loads.
- **In-Situ Monitoring Systems:** High-resolution pressure sensors, flow meters, and solute concentration sensors will be installed within the chamber to continuously record data throughout the experiment. Data will be logged at a frequency of 1 Hz, allowing for detailed temporal analysis. The sensors will be connected to a real-time data acquisition system that allows for on-the-fly adjustments and monitoring during the microgravity phases. Specific sensors include:
  - Pressure Transducers: Capable of measuring pressures from 0 to 10 bar with an accuracy of ±0.1%.
  - Electromagnetic Flow Meters: Measuring flow rates from 0.1 to 10 L/min with an accuracy of ±0.5%.

- Conductivity Sensors: To measure solute concentration with an accuracy of ±1% across a range of 0 to 100,000 microseconds/cm.

- **Safety Enclosures:** The entire assembly will be enclosed in a polycarbonate shell with rounded edges to ensure safety in the microgravity environment. The system is designed to be fail-safe, with all sharp components shielded and liquids securely contained within double-walled chambers. The outer shell is also designed to withstand the rigors of parabolic flight, ensuring the structural integrity of the experiment under dynamic flight conditions.

4.1 Statistical Design

- **Sample Size Determination:** Based on a preliminary power analysis, a minimum of 10 replicates per condition (microgravity, normal gravity, inverted gravity) will be required to detect a statistically significant difference in filtration efficiency with a power of 0.8 and an alpha level of 0.05. The effect size is estimated based on prior studies in similar filtration systems, where a medium effect size (Cohen's d = 0.5) was observed.

- **Hypothesis Testing:** The primary statistical test will be a one-way ANOVA, comparing the mean filtration efficiency across the three gravitational conditions. Post-hoc comparisons will be conducted using the Tukey-Kramer method to control for Type I errors across multiple comparisons.

  - **Null and Alternative Hypotheses:**
    - Null Hypothesis (H0): There is no significant difference in filtration efficiency and membrane fouling between the three gravitational conditions.

- Alternative Hypothesis (H1): At least one gravitational condition results in significantly different filtration efficiency and membrane fouling compared to the others.

- **Data Analysis and Interpretation:** Data will be analyzed using statistical software (e.g., R or SPSS). In addition to ANOVA, regression analysis will be used to assess the relationship between rotation speed and fouling rate. Statistical significance will be determined at the alpha level of 0.05, with power analysis guiding sample size to ensure sufficient sensitivity.
- **Power Analysis:** Given the expected medium effect size and desired power of 0.8, the total sample size for the experiment is calculated to be 30 experimental runs, distributed evenly across the three conditions. This sample size ensures a high probability of detecting true differences, if they exist.

4.2 Operational Procedure

1. **Pre-Flight Preparation:** Calibration of sensors, integrity testing of the rotation chamber, and validation of the double containment system for fluids. The system will undergo vibration testing to simulate conditions during flight and to ensure robustness. Additionally, the rotational system will be tested under simulated microgravity conditions using a neutral buoyancy facility to predict system behavior during the flight.
2. **During Flight:** The experiment will be conducted during the microgravity phases of the flight, with data collection focused on the filtration performance during these brief periods. Each 22-second microgravity segment will be used to test the system under both static and rotating conditions. High-speed cameras will be

used to capture any transient phenomena that occur during the rapid transitions into and out of microgravity, allowing for a detailed analysis of dynamic effects on fouling.

3. **Post-Flight Analysis:** Upon return, the filtration membranes will be analyzed using a comprehensive approach that combines multiple accessible methods:
   - **Optical Microscopy:** Using a standard light microscope with magnifications ranging from 40x to 400x, commonly available in high school and undergraduate laboratories, to visually assess fouling patterns. This method provides a broad field of view and the ability to observe color changes associated with fouling.
   - **Contact Angle Measurements:** To assess the surface properties of fouled membranes using a simple setup involving a dropper, a camera or smartphone, and image analysis software. This technique is accessible to students at various educational levels and provides information about the hydrophobicity or hydrophilicity of the membrane surface.
   - **Colorimetric Analysis:** Using dye adsorption tests to quantify the degree of fouling. This method involves exposing the membrane to a standardized dye solution and measuring the intensity of color adsorbed, which correlates with the extent of fouling.
   - **Weight Analysis:** Precise weighing of the membrane before and after fouling to determine the mass of accumulated foulants. This simple yet effective method can provide quantitative data on fouling levels.

Data from the in-situ sensors will be analyzed to compare the filtration efficiency and fouling behavior across the three gravitational conditions. These combined accessible techniques ensure comprehensive analysis while providing opportunities for engagement at various educational levels.

5 Safety Considerations

Safety considerations are integral to the design and execution of this experiment, particularly given the microgravity environment. The following measures will be implemented:

- **Mechanical Safety:** The rotation chamber and all moving parts are designed with a high safety factor, ensuring they can withstand the stresses of high-speed rotation. All mechanical components are enclosed within a polycarbonate shell to prevent accidental contact and injury. The rotational components have been engineered to operate smoothly under variable gravitational forces, with stress analysis performed using finite element modeling to predict performance under flight conditions.
- **Electrical Safety:** The system operates on a low-voltage DC supply to minimize electrical hazards. All wiring is secured and insulated, with redundancy built into critical systems to ensure continuous operation during the experiment. Additionally, the system includes surge protection to guard against any electrical spikes that may occur during the dynamic flight environment.
- **Fluid Containment:** The experiment involves handling fluids under microgravity conditions, necessitating robust containment strategies. All fluids are housed within

double-walled containment systems, with additional seals to prevent leaks. Any potential breaches will be contained within the outer shell, preventing spillage into the aircraft cabin. Fluid integrity will be continuously monitored using pressure sensors that can detect even minor leaks, triggering an automatic shutdown of the experiment if necessary.

- **Emergency Protocols:** The system is equipped with an emergency shutdown mechanism, which can be triggered manually or automatically in response to sensor data. This ensures that the rotation can be halted immediately if any anomalies are detected. Pre-flight training for the team will include emergency procedures, ensuring all personnel are prepared to respond to any situation that may arise during the experiment. Emergency drills will be conducted to simulate various failure scenarios, including fluid leaks, mechanical malfunctions, and electrical failures.
- **Pre-Flight Testing:** Comprehensive pre-flight testing will be conducted, including vibration tests to simulate flight conditions, leak tests for fluid containment, and electrical integrity checks. These tests are designed to identify and mitigate any potential issues before the experiment is conducted in microgravity. Additional tests will include a full-scale mockup of the experimental procedure under controlled conditions, ensuring that all systems perform as expected.

6 Engineering and Physics Principles

The rotational filtration system in this experiment relies on several key engineering and physics principles:

6.1 Centrifugal Force

The primary mechanism driving the filtration process in our rotational system is centrifugal force. In a rotating reference frame, an object experiences an apparent force directed away from the axis of rotation. This force is given by:

$$F_c = m\omega^2 r$$

where m is the mass of the object, ω is the angular velocity, and r is the distance from the axis of rotation.

In our filtration system, this force serves two purposes:

1. It creates a pressure gradient across the membrane, driving the filtration process.
2. It aids in the separation of particles from the fluid, potentially reducing fouling.

6.2 Concentration Polarization

Concentration polarization is a phenomenon where solutes accumulate near the membrane surface, creating a concentration gradient. This can be described by the film theory model (Jaffrin, 2011):

$$J = k \ln \frac{c_m - c_p}{c_b - c_p}$$

where J is the solvent flux, k is the mass transfer coefficient, c_m is the concentration at the membrane surface, c_b is the bulk concentration, and c_p is the permeate concentration.

In microgravity, the absence of buoyancy-driven convection can exacerbate this effect.

Our rotational system aims to mitigate this by inducing mixing through rotation.

6.3 Fluid Dynamics in Rotating Systems

Behavior of fluids in the system is governed by the Navier-Stokes equations in a rotating fr

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} + 2\boldsymbol{\Omega} \times \mathbf{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} - \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r})$$

where **u** is the velocity vector, **Ω** is the angular velocity vector, *p* is pressure, *ρ* is density, *v* is kinematic viscosity, and **r** is the position vector. The Coriolis term (2**Ω**×**u**) and the centrifugal term (−**Ω**×(**Ω**×**r**)) are unique to rotating systems and play a crucial role in the fluid behavior in our experiment.

6.4 Membrane Transport Phenomena

The transport of solutes and solvents through the membrane is described by the Kedem- Katchalsky equations (Altinkaya, 2024):

$$J_v = L_p(\Delta P - \sigma \Delta \pi)$$

$$J_s = P\,\Delta c + (1 - \sigma) c_{av} J_v$$

where J_v is the volumetric flux, J_s is the solute flux, L_p is the hydraulic permeability, ΔP

is the pressure difference, σ is the reflection coefficient, $\Delta \pi$ is the osmotic pressure difference, P is the solute permeability, Δc is the concentration difference, and c_{av} is the average concentration.

In our rotational system, the pressure difference ΔP is primarily generated by the centrifugal force, which varies with radial position and rotation speed.

7 Final Remarks and Outlook

The proposed experiment represents a pioneering effort to investigate the effects of micro- gravity on water filtration processes, with a specific focus on concentration polarization and membrane fouling within rotational filtration systems. By exploring these phenomena across varying gravitational conditions—microgravity, normal gravity, and inverted gravity—this research aims to provide critical insights that could revolutionize water recycling technologies, both in space and on Earth.

The outcomes of this study are anticipated to contribute significantly to the optimization of filtration systems used in space missions, where the challenges of microgravity demand innovative solutions. The knowledge gained from understanding how artificial gravity, generated through rotational forces, can mitigate fouling will not only enhance the reliability and efficiency of life support systems in space but could also lead to breakthroughs in terrestrial filtration technologies, particularly in environments where traditional gravity-dependent methods are less effective.

The integration of multiple accessible analysis techniques in this study serves multiple purposes. First, it ensures a comprehensive and multi-scale analysis of membrane fouling phenomena. Second, it bridges the gap between advanced research and educational outreach, providing opportunities for students at various levels to engage with and contribute to space- related research. By using methods such as optical microscopy, contact angle measurements, colorimetric analysis, and weight analysis, we not only gather valuable scientific data but also make the research process more inclusive and educational.

This approach not only enhances the depth of our scientific understanding but also promotes STEM education and inspires the next generation of researchers and engineers. The use of these accessible techniques demonstrates that meaningful scientific contributions can be made with relatively simple tools, encouraging wider participation in space-related re- search and fostering innovation at all levels of education.

Looking forward, the findings from this experiment could pave the way for more advanced studies, such as:

- Long-duration tests of rotational filtration systems in microgravity environments, potentially aboard the International Space Station or future lunar bases.
- Development of computational models to simulate the complex fluid dynamics involved in these systems, incorporating data from this experiment to improve predictive capabilities.
- Investigation of novel membrane materials and surface modifications specifically designed to combat fouling in microgravity conditions.
- Exploration of the potential applications of rotational filtration systems in other

challenging environments on Earth, such as deep-sea operations or in highly viscous industrial processes.

- Further refinement of accessible analysis techniques for space-based experiments, potentially leading to the development of new, compact instruments suitable for use in space missions.

Furthermore, the methodologies developed for this experiment, particularly the combination of parabolic flight testing with multi-scale analysis techniques, could serve as a template for future microgravity research in other areas of fluid dynamics and materials science. The emphasis on accessible tools and techniques opens up new possibilities for collaborative re- search between space agencies, universities, and even high schools, fostering a more inclusive approach to space science.

The proposed research represents a crucial step towards addressing the unique challenges of water filtration in space, with broader implications for improving water treatment technologies on Earth. The integration of advanced experimental design, rigorous statistical analysis, and comprehensive safety measures ensures that this study will provide reliable, actionable data that can drive future innovations in the field of filtration science.

As we continue to push the boundaries of human space exploration, experiments like this one are essential in developing the technologies that will sustain life beyond Earth. By tackling the fundamental challenges of water recycling in space, we not only enable longer and more distant space missions but also contribute to solving pressing issues of water scarcity and purification here on our home planet.

The proposed experiment stands at the intersection of space technology, environmental science, and educational outreach. Its potential impacts extend far beyond the immediate results, promising to inspire scientific curiosity, drive technological innovation, and contribute to our broader understanding of fluid dynamics in extreme environments. By making space research more accessible and engaging for students and early-career scientists, we are nurturing the next generation of innovators who will continue to push the boundaries of our understanding and capabilities in space exploration.

As we look to the stars, the insights gained from this research will help ensure that our journey into space is sustainable, efficient, and beneficial to all of humanity. Moreover, the emphasis on accessible research methods sets a new standard for inclusive science, demonstrating that the quest for knowledge in space exploration can and should involve diverse participants from various educational backgrounds. This inclusive approach not only enriches our scientific endeavors but also ensures that the benefits of space research are widely shared, inspiring and educating future generations of scientists and engineers.

8 Outreach and Collaboration

Outreach: The primary objective of our outreach is to enhance public understanding of water treatment and desalination technologies, especially its potential for space flights, long-term space missions, and eventual space settlements. We aim to engage a broad audience, including high school students, industry professionals and NASA researchers interested in environmental sustainability. Outreach in the form of publication, video, social media campaign involvement, and news can excite the broader public about the prospect and challenges of water treatment in the constrained environment of space.

Collaboration: Jonathan Bessette, graduate PhD student at MIT and researcher at MIT Global Engineering and Research (GEAR) center will leverage their expertise in membrane technology and fluid dynamics to provide critical insights into the experimental design and data analysis, contributing to the success of this experiment.

Jonathan Bessette obtained his B.S. in Mechanical Engineering with a minor in Studio Art at SUNY Buffalo. While there, he constructed high payload unmanned aerial vehicles for emergencies, researched traditional water treatment methods in India, and studied ice-penetrating radar – a technique that enhances models for sea-level rise. Bessette has led trips abroad to teach English, taught undergraduate courses, and is a volunteer EMT. His focus in the GEAR center is on developing deployable desalination and water treatment systems for humanitarian emergencies and highly constrained, remote scenarios. Bessette is a former Fulbright SI Scholar, Marshall Scholar Finalist, NSF GRFP awardee, Morningside Fellow, and current JWAFS Fellow.

Om Sanan is a senior at Scarsdale High School in Scarsdale, New York and a water treatment researcher and computer/AI/ML programmer for 7 years. Since Fall 2022, he has been interning with The National Renewable Energy Laboratory writing research on decarbonization of the water desalination process, water security and reuse, and energy independence. Om interned with NASA SEES Space Research during summer 2024 working with the GRACE - Weighing Where the Water Goes team. He is also working on research on community water desalination with MIT and publishing research on digital twins and large language models with Colorado State

University. Om is also the founder and CEO of Day Zero Water (https://dzwater.org), a student-led non-profit, which he founded in 2018 to implement water filtration projects in schools locally in the U.S. and water-stressed areas in India and Africa and help raise water conservation awareness.

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