Final Report Document

Microgravity Medical Eyewash B

submitted to
NASA

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Executive Summary

Senior Capstone Design Team 15 has been commissioned by the National Aeronautics and Space Administration (NASA) to redesign the current microgravity eye wash station. The current design exhibits four primary limitations: single-use operation, excessive mass and volume, operational complexity requiring coordination with external systems, and dependence on frequent Earth resupply missions. Our updated eyewash design will be deployed on long-range space missions that could last multiple years.

Based on these and other requirements from our customer, we have developed our updated eyewash design. Our compact, single-eye system uses capillary-driven flow and a free-floating water ball. This design allows us to eliminate pumps and bulky tubing, decreasing the mass and volume of the overall system. The containment eyecup is held to the astronaut's face with a strap, and a silicone seal prevents leakage while improving user comfort. Contaminated water is contained within a disposal bag containing wicking material to pull it back out of the eyecup after washing the eye. This system is reusable, efficient, and easy to activate quickly.

We evaluated our design through calculations, microfluidic testing, and user try-on testing to verify our requirements. Our work demonstrated that steady-state flow was capable with our capillary framework, achieving 1.31 L/min. The prototype construction confirmed mass and volume reductions, and try-on-testing evaluated the ability to put on the system quickly. Almost all major design requirements were achieved, and water loss could be validated by testing in microgravity.

Our design went through a number of iterations to reach the final solution presented in this report. These changes were driven by our testing and collaboration from each member of the team. Updated models optimized tube placement and geometry of the eyecup to better direct flow as it pools across the eye. Changes to our tubing bends improved capillary efficiency and increased the flow rate we were capable of achieving. And improved bracket placements adjusted the fit, comfort, and seal of the eyecup to the astronaut's face.

Our capillary-based eyewash system is technically feasible and has been theoretically validated to operate effectively in microgravity conditions. Testing and analysis indicate that it can meet or exceed the required performance metrics, including flow rate and safety constraints. Overall, the design represents a viable alternative to current ISS-dependent eyewash systems for future space missions.

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1 Project Overview

During extended-duration space missions, astronaut safety requires reliable and rapid action in response to emergencies. NASA has identified the absence of a dedicated eyewash station as a critical gap in current spacecraft safety systems. While the current model has been utilized on the International Space Station (ISS), it takes up excessive space, relies on pressurized water from the Russian water dispenser, and requires frequent resupply to the ISS. Additionally, this model is reliant on the ISS platform, so it is not an option for missions beyond low orbit; however, having an eyewash is a necessary safeguard for astronauts against chemical contaminants.

The astronauts onboard these space exploration missions are the primary end-users, as they will benefit by having a safe and reliable way to clear contaminants from their eyes in case of emergency. The design team comprises Cody Haney, Charley Isham, Anish Krishnamurthy, and Andrew Van Lente. The team works under the primary advisor, Dr. Bhisham Sharma, and with the customer contacts, Dr. Jeffrey Allen and Justin Yang.

The project stakeholders are summarized as follows:

Name	Reason for Involvement / Interest or Concern in Outcome
NASA	Astronaut health and safety and long-duration mission readiness
Astronauts	Safety in case of chemical exposure and peace of mind
MTU / MAE Senior Capstone Design Program	Delivering value to all of our customers is critical to our reputation and the sustainability of the MAE SCD Program

2 The Problem

Due to the issues seen with the current system: single-use, ISS-dependent, and bulky, the team set out to create a new eye wash system. The main goal is to clear the eye of the chemical contaminant, but to understand the problem better, the team broke the design into three components: getting water from the source, directing the water to the eye and washing it, and removing and disposing of the contaminated water. Most of the design work is coming in directing the water to the eye and clearing the eye of the contaminant. To be considered a successful design, the mass and volume have to be reduced from the 2.25 kg and 12,171 cm^3 requirements over a three-year mission, and the system has to be ISS independent, capable of working in a microgravity environment ($\leq 10^{-6}$ g), and have a flow rate greater than 0.5 L/min. The flow rate relates to some of the other requirements: water pressure (< 21 mm Hg) and activation time (< 10 s).

3 The Solution

Our solution directly targets these main issues by focusing on making a reusable design that minimizes the need for long hoses and reducing mass and volume. The solution is designed for washing a single eye and utilizes capillary action and a free-floating ball of water to drive the system. A medical-grade silicone seal would help contain the contaminated water, and an elastic strap would be used to hold the system against the user's eye. As seen in Figure 1, the water ball would be attached to the end of the inflow straw.

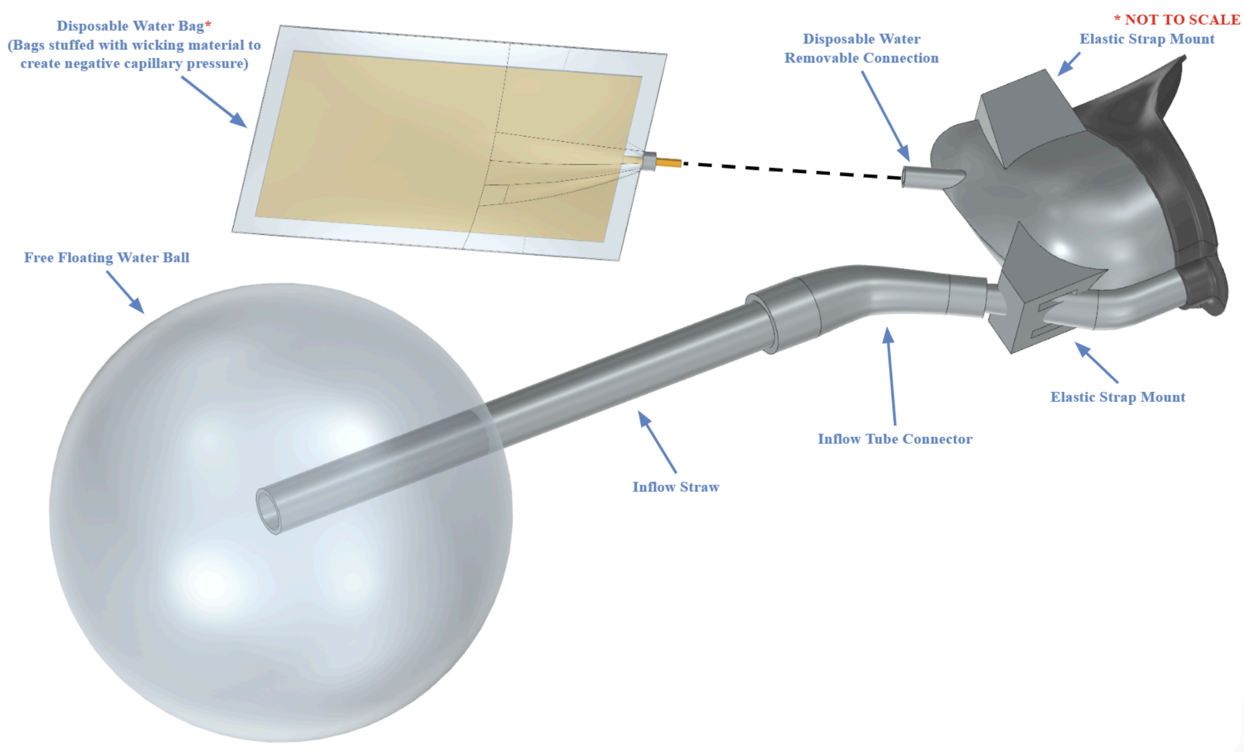

Figure 1: Overview of the Eyewash Design

When the water ball is large enough, the water will extend over the end of the inflow straw. The radius and the surface tension of the water ball create a pressure difference that then drives the water up the inflow straw towards the water containment eye cup. The inflow tube directs the water to within millimeters of the corner of the eye. The tube does not make contact with the eye to prevent any damage or pain, but gets the water close enough to bridge the gap to the eye. Since the eye is perfectly wetting, the water will flow across the eye, and due to the pressure differences, water will continue building on the eye. As the amount of water on the eye continues to grow, it will eventually make contact with the interior wall of the water containment cup. When it makes contact with the wall, it will eventually be guided to the interior wedge as shown in Figure 2.

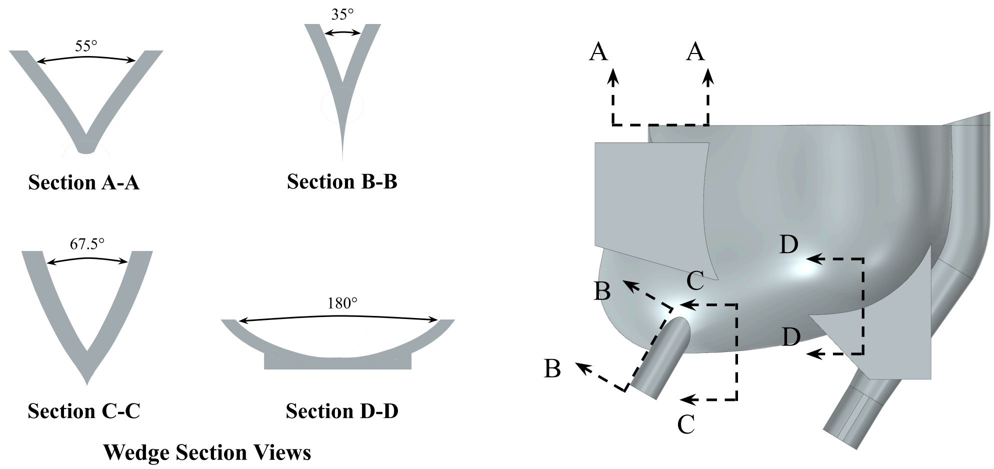

Figure 2: Cross Section of Internal Capillary Wedge

The wedge tapering towards the outflow hose creates a secondary pressure difference that drives water towards the outflow hose instead of towards the eye. At the same time, there is a second tapering wedge that guides any excess water from the main body of the containment cup towards the outflow hose as well. In the disposable bag and the outflow hose, there is a wicking material that absorbs water and creates a negative pressure that continues to draw water into the disposable bag (Figure 3).

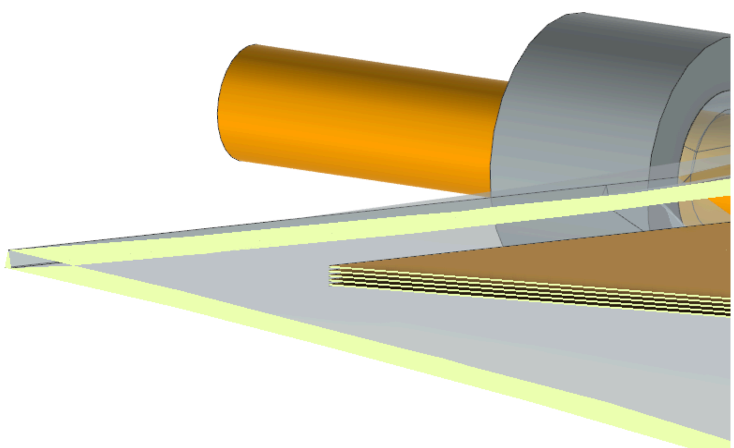

Figure 3: Wicking Material Inside Disposal Bag

When a steady state flow is created, the negative pressure from the wicking material becomes the new driving factor for the water. With a piece of 20x15x12cm of rayon, a flow rate of 1.31 L/min can be achieved. The physical prototype, shown in Figure 4, does not reflect all of the capabilities of the designed solution.

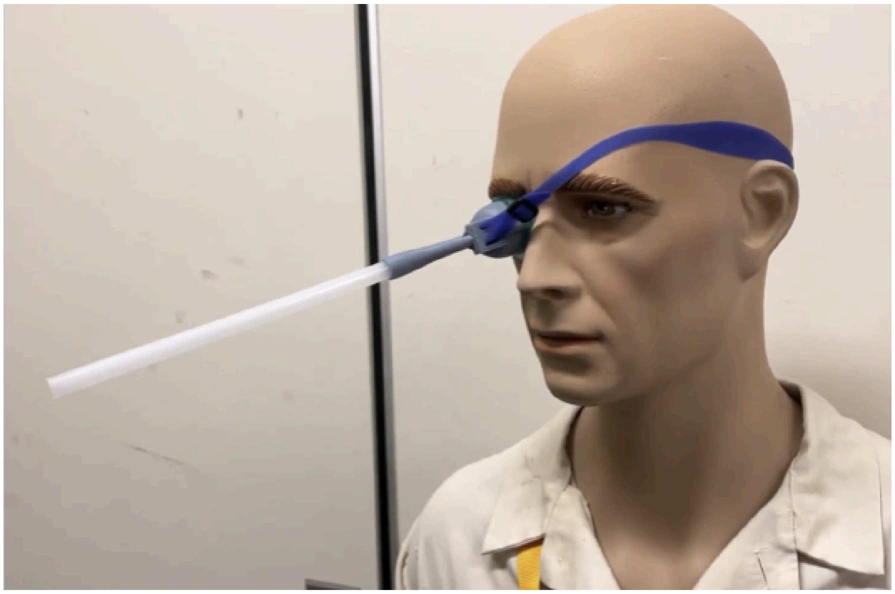

Figure 4: Physical Prototype of the Design

The physical prototype, since it would not be able to be tested as a full system in microgravity, was manufactured to the design specifications and details, but not with all of the material properties that are required. This simplification helped control the overall project cost as hydrophilic and hydrophobic agents did not have to be applied, the silicone seal did not have to be medical grade, and the resin did not have to be biocompatible and chemical resistant.

For the system to be usable in a microgravity environment, the internal components have to be perfectly wetting, as well as the outside first 9 cm of the inflow straw to hold the water ball in place. The material used would have to be biocompatible, chemically resistant, and if not perfectly wetting, it has to be able to have a wetting agent applied. For safety concerns, it was designed to limit pressure and contact with the eye. That is why the inflow hose is the closest part to the eye, and even then, it only gets close to the corner of the eye. As there are very fine details in the design, additive manufacturing is the suggested manufacturing technique. The specific process would depend on what material is chosen. If a resin-based material is selected, we would suggest a Vat Photopolymerization (VPP) process, and if more of a powder, we recommend going with a selective laser melting (SLM) process.

Based on this design, the following requirements shown in green have been met and validated by the testing and the 10D analysis conducted. The requirements shown in yellow are either considered to no longer be applicable or were not able to be verified due to time and monetary constraints (Table 1).

Table 1: Engineering Requirements

Requirement Name	Target	Actual	State of Requirement
Flow Rate	0.5 L/min	**1.31 L/min**	Pass
Fast Activation	10 sec	**1.72 sec**	Pass
Time to Put On	30 sec	**10.62 sec**	Pass
System Volume	< 12,171 cm^3	**6,830.5 cm^3**	Pass
System Mass	< 2.25 kg	**0.72 kg**	Pass
Water Temp	16 - 38 °C	NA	Not Applicable
Water Consumption	≥ 10 L	**10 L**	Pass
Voltage	≤ 120 V	NA	Not Applicable
Amperage	< 10 A	NA	Not Applicable
Water Pressure	< 21 mm Hg	**0.26 mm Hg**	Pass
Cross-Eye Contamination	≤ 1%	**0 %**	Pass
Microgravity Capable	≤ 10 E-6 g	**10 E-6 g**	Pass
Water Loss	≤ 1%	**Requires Microgravity**	Unknown

In reference to the requirement table, fast activation is the amount of time that it takes for water to reach the eye after water covers the end of the inflow straw. Water loss is the amount of water lost to the environment. It needs to be clarified with standards and microgravity testing to determine if this is only for contaminated water or if it includes clean potable water as well.

4 Prototype Verification

4.1 Verification Testing and Data Analysis

With the design of the project, the difficulty of verifying the solution was that we could not test in a microgravity environment. This meant that we had to find other ways to verify the system. To verify our system, we conducted physical microfluidic testing, try-on-testing with our prototype, and 1-dimensional analysis of the fluid flow. Although 1-D calculations were the backbone of our capillary flow justifications for major requirements, our physical microfluidic tests & try-on-testing were how we applied those equations to our system.

Microfluidic testing required scaling down different components of our design to minimize the effects of gravity. As we can’t model every component of our design, we had to focus on specific components, called transition points, and analyze the data at these locations. Our testing utilized a polydimethylsiloxane (PDMS) liquid polymer that allowed us to create points of our system. We used negatives of the geometry we wanted to model, often created using the same 3D printed resin we utilized for the eye cup. Mixing the activator and base of the PDMS polymer, we would then off-gas it in a vacuum chamber to remove all bubbles and pour it over the negative. This mold would then be left on a hot plate to cure for a day or two, after which we would remove the polymer to use for testing. Our testing employed silicon oil to model the fluid flow rather than water, since that better modeled how water would flow through our system with the hydrophilic coating. This silicon oil was dyed to improve visibility during our testing, where a camera took photos of the fluid as it moved through the tube or channel (Figure 5). Based on this flow rate, the bond number (a ratio of gravitational and capillary surface tension forces), and the radius of the tube, we could project the performance of our system. This was performed utilizing Poiseuille's Law and using the non-dimensionalized constants of each scenario: our microfluidic testing here on earth, and the eyewash operating in microgravity (Figure 5). The radius changes the plot of the system, but based on our dimensionless meniscus rise height, we can find the time constant for the eyewash and verify our hand calculations for the flow rate.

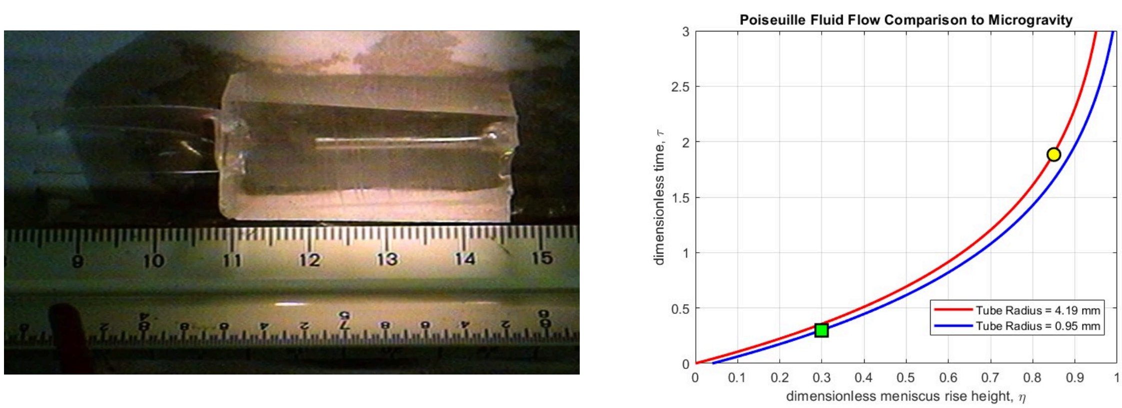

Figure 5: Microfluidic Test (Left) and Scaled Poiseuille's Flow Modelling (Right)

The try-on tests verify that the eyewash station can be put on in a timely manner. The try-on tests had individuals take the eyewash out of a box, try on the system, and the clock stops when the participants state that they have the best seal possible. On average, it took 10.62 seconds for the entire process. After the test, participants are asked about the seal and the fit. All participants stated that it was a tight seal; however, many stated that it might have been too tight. The large discrepancy in this data is that it does not include attaching the water bag or putting the eyewash on with the water bag connected. This was done so that the extra weight of the water bag and the moment that it would create would not affect how the system fit on the face.

4.2 Prototyping-Driven Refinements

The creation of the prototypes caused the need for several refinements and iterations of the design. The most significant design refinement was moving the locations of the inflow and outflow tubes, but there were also refinements involving the bracket locations and dimensions, the wedge geometry, and the size of the elastic band.

The inflow and outflow tube locations were switched after realizing that the initial orientation and locations created pinning edges for water to get trapped, created a safety concern with how close the outflow tube was to the eye, and that we were not fully utilizing the full benefits of the geometry that we are using. The relocation of the tubes also allowed the wedge geometry to be refined. We were able to modify the wedge to have a smaller angle, which increases the capillary effects. The changes can be seen in Figure 6.

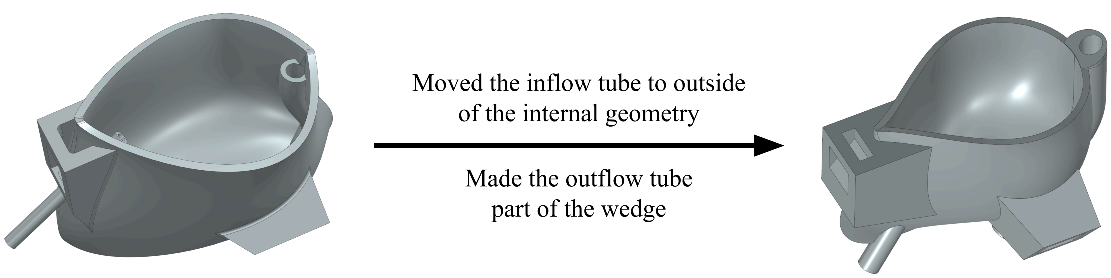

Figure 6: Iterations to Eyecup Design to Preserve Capillary Geometry

With the relocation of the inflow and outflow tubes, a new prototype was created, and it was found that the bracket locations had to be altered because the elastic band created a moment that tried to lift the bottom of the water containment cup away from the face, and in some cases, it caused a moment that forced the eyewash to fall off the wearer completely (Figure 7).

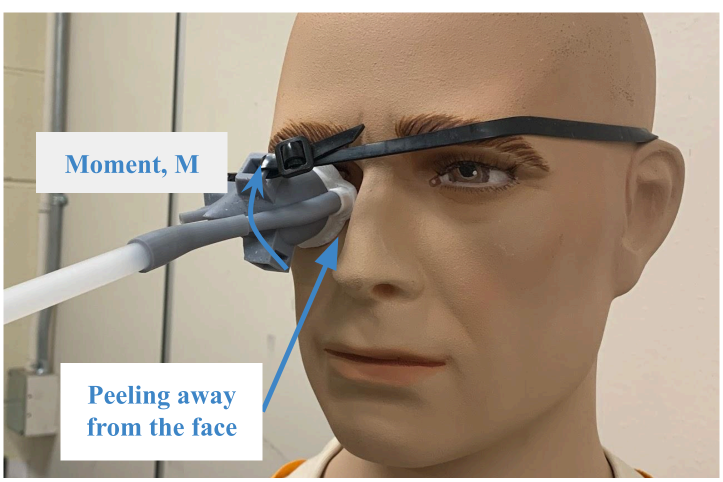

Figure 7: Moment of Bracket and Strap Location

To reduce the induced moment, the bracket was centralized, which removed the moment arm and minimized how much the lower seal pulled away from the face. With the bracket relocation, the bracket style had to be redesigned, as when it was centralized, the inflow tube went directly through the bracket. This made it so that the elastic strap had to go around either side of the inflow hose. The bracket dimensions also had to be altered to fit a larger strap. The larger strap was found to be needed during the try-on tests, where individuals stated that the fit was tight, but overly so. These changes are shown in Figure 8.

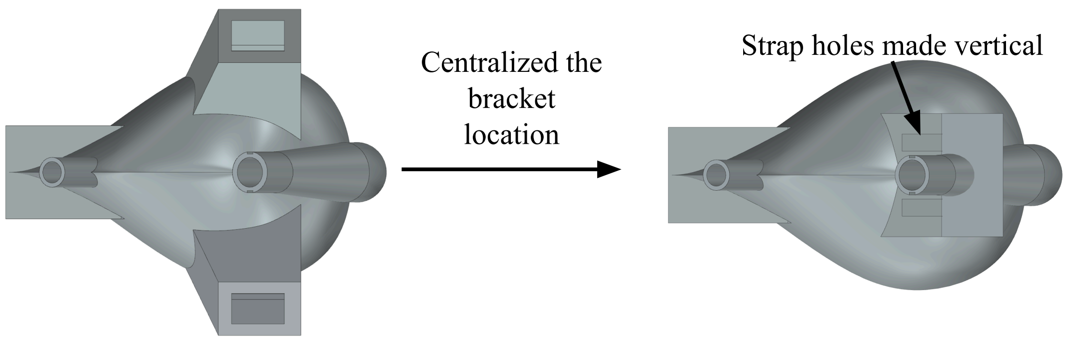

Figure 8: Iterations to Bracket Design to Eliminate Moment

4.3 Production vs. Prototyping

There were a couple of elements that ended up differing from the intended manufacturing and the actual methods or steps used, including the creation of PDMS molds for the microfluidic testing and the eye wash seal.

For the testing of our prototype through physical microfluidic testing, there were many changes from the initial designs for our testing. One of the first manufacturing changes was in the process of creating our 3D printed negatives for testing and determining how precisely we could create a small tube or channel. We employed a few resolution test prints and analyzed them with a microscope to determine how small we could print the channel and designed it accordingly.

We also implemented refinements to our testing procedure for physical testing throughout the semester. A great example of this was changing our curing process to improve the quality of our PDMS polymer channels for testing. When we first tried to create the molds with our 3D printed negatives, the surface of the molds came out very poorly (Figure 9). The surface of the polymer was tacky, almost gelatinous, and was not solid enough to use for testing. We had to go back through and evaluate what went wrong with our process and implement improvements to achieve

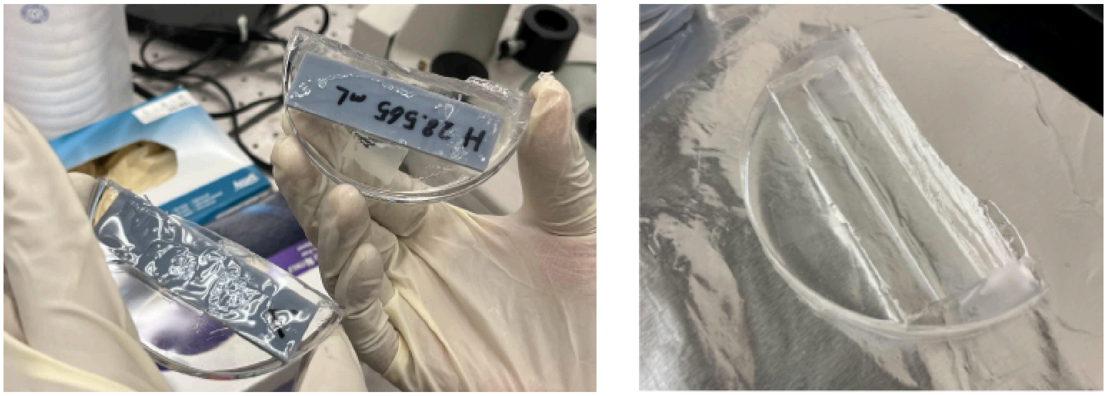

Figure 9: Poorly Cured Molds (Left) & Updated Molds after Refinements (Right)

better quality molds. First, we changed the ratio of activator and base used when we mixed and prepared the PDMS polymer before off-gassing. The recommended mix was 10% activator to 90% base, so we tried changing this to a 15/85 mix of the two. For that batch, the polymer was too solid and wouldn't come out of the negative clean enough to use for a test. Therefore, we tried 12.5% activator to 87.5% base, and this ratio worked better. We also changed some other aspects of the process, mixing the base and activator for 20 minutes instead of the original 10 to help the process. And for curing after the PDMS was poured over the negatives, we used a hot plate at a higher temperature for a shorter period of time. The original molds had been at 50℃ for 48 hours, and we tried doing 70℃ for 24 hours, which gave much better results (Figure 9). All of these refinements allowed us to achieve a well-set PDMS mold that could still be removed from the 3D printed negative, allowing us to continue forward with our testing.

The silicone seal was originally going to be 3D printed using a flexible thermoplastic polyurethane (TPU) to get a customized fit to the eye cup and the face. When it was manufactured, the TPU was not as flexible as it was thought to be, which made it so that it was uncomfortable and almost painful to wear the eyewash. This brought the recommendation of creating a customized silicone seal by creating a mold and pouring the silicone into it. The silicone was more viscous than it was originally thought to be, so it created some issues with pouring into the mold. The larger issues came with trying to remove it from the mold. The silicone had fused itself to the resin-printed mold and refused to come out. The second attempt utilized a release agent on the mold, but this made it so that the silicone did not set. The final attempt used a release agent, but used more activator to help compensate for the last attempt's issues, and again it did not set. After this, it was decided to use a goggle seal off-the-shelf and to customize it if needed.

5 Conclusions

In order to replicate this design for implementation on a long-range space mission, we have estimated that this product would cost $(removed) at a quantity of 3 units. This is based on utilizing the same materials and process we implemented for our prototype - 3D printed resin eyecup geometry, silicone molded seal to the eye, and disposal bags containing wicking material. The primary change in cost is due to the hydrophilic and hydrophobic agents, and the process that would have to be used to apply them. This replication cost could change significantly based on material selection changes from NASA.

Our testing and calculations have demonstrated that a capillary-driven flow design is capable of steady-state delivery of water to the eye in microgravity. And this method of driving flow is not only feasible, but capable of exceeding the requirement of 0.5 L/min that was our original goal. Then our method is limited only by the water source and design of the disposal bags.

6 Next Steps

Looking ahead to potential next steps for this project, we based our suggestions on the highest risks identified in our latest DFMEA: water loss, activation time, waterball adhesion, and the pressure at the eye. A lot of these concerns can be resolved or analyzed using further testing and higher-grade equipment. By utilizing high-speed cameras, we can analyze the contact angle and flow rates within the microfluidic testing with higher precision. This can create a better reference to how the model will act in true microgravity.

We can also use sensors like an accelerometer and a pressure transducer to verify that the system meets requirements and that the water bubble will stay attached to the inflow straw. The accelerometer would be placed at the end of the inflow straw to measure acceleration and see how this compares to the retention of water that the capillary straw can hold. The pressure transducer would be placed at the end of the inflow tube, where it is in close proximity to the eye. This pressure would verify the 1-D calculations that meet the engineering requirement.

Ultimately, the next steps would require testing in a microgravity environment. As the full system takes at least a minute to run a full cycle, a sub-orbital flight or low Earth orbit would be needed to get the duration needed for a full test. These tests are expensive, so a complete test plan would be needed before pursuing this method.

After the next steps, it can be expected to have a higher validated model, with more predictable outcomes. We can also evaluate the water loss for both contaminated water and the water from the free-floating potable water ball. This will also verify the conditions that are needed for the system, such as a perfectly wetting surface.

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