AAE 418 Microgravity Plant Watering

Final Report Fall 2023

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Introduction

Microgravity plant watering is a new project started in Fall 2023 to figure out a way to water plants in a microgravity environment with minimal artificial gravity. As this project was new, much of the semester was spent researching and designing rather than constructing. The goal of the project was to design and build a laboratory to use in microgravity to test different combinations of soils, drainage designs, and watering methods to find the best approach at testing and that will ultimately be able to water plants the best. The difficulties in plant watering that are presented due to microgravity are countless, but some notable ones were: lack of proper drainage causing oversaturation, hypoxia, and soil aeration. Because of these obstacles, we would need to find a way to test different approaches that would help find a method that would best overcome all these disadvantages that are present in microgravity.

Project Goal and Future

The goal of this project is to create a plant growing apparatus that will function in microgravity. This plant growing apparatus will fly in space on a satellite, but we want to make sure our system works well first so we will test its functionality on the zero-gravity plane. The reason why we need to fly this payload into space is because there is no current way to simulate microgravity for extended periods of time on Earth, and in order for a plant to grow we need weeks of sustained microgravity. This is why we can't test plant growth on the zero-gravity plane, but what we can test on the plane is if our growing apparatus watering and respiration system works. With this in mind, we can break the entire project's future into three steps. It is important to have a good understanding of where the project is in this timeline and not lose focus on the end goal or any of the steps in between. It is also necessary to understand all the steps in order to understand the first step. The steps are listed below.

1. Step 1: Fly payload on zero-gravity parabola plane and conduct tests.
2. Step 2: Fly payload into space on centrifuge satellite and conduct research.
3. Step 3: Future Application - Grow food for astronauts on their journey to Mars.

Step 1: Zero-Gravity Plane Soil Tests

This semester we worked on designing the zero-gravity plane payload. <u>The purpose of this payload is to find the best watering and respiration methods for our soil samples in microgravity.</u> The zero-gravity plane will give us roughly a 20 second interval of test time to experiment in, and then repeat that interval 20 times by entering and recovering from flight parabolas. Typically, the zero-gravity plane will only fly three categories of parabolas: Zero Gravity (0.0g), Lunar Gravity (0.16g), and Martian Gravity (0.3g). It is important that future AAE418 groups find a way to have our payload tested in microgravity rather than zero gravity because it has been proven that plants cannot grow properly in zero gravity; this issue will be discussed more in detail further in this report. The reason why this payload must be tested in microgravity is because our payload will experience a specified amount of microgravity during **Step 2** while growing plants on the satellite, as well as **Step 3** on its way to Mars. The goal of **Step 1** is to optimize our system and pick the best watering and respiration method for soil quality, thus why we are testing four watering methods and four respiration methods on the zero-gravity plane. Once this payload flies, the best watering and respiration methods will be selected and integrated into **Step 2's** payload.

Step 2: Growing Plants on the Centrifuge Satellite

Once **Step 1** is complete, **Step 2** will utilize our optimal soil watering and respiration methods to actually grow plants on a satellite. The satellite that our payload will fly on can rotate at different rates in orbit, thus creating precise microgravity for extended periods of time. This satellite will be answering one main question: What is the minimum amount of gravity that a plant needs in order to grow properly? The ISS has already proven that plants need at least some gravity to grow properly due to gravity-sensitive cells in their seeds that use the direction of gravity to determine which direction to grow their roots, and which direction to sprout. <u>The goal of this step is to find the minimum amount of gravity a plant needs in order to grow properly.</u>

Step 3: Growing Food on the way to Mars

This step is a visionary step of what all this work is for. Astronauts will need food on the long journey to Mars, and growing plants is an obvious choice if available. By rotating the spaceship on its way to Mars, a microgravity environment can be created that would allow the astronauts to be more comfortable, as well as grow plants. The issue is that it takes fuel and delta V to initiate a spin, and the same amount to stop the spin. This is why **Step 2** will find the minimum amount of microgravity needed for plants to grow properly in space. The gravity level found in **Step 2** could dictate the rotation rate of the spaceships that will fly to Mars with humans on board in the future. The findings and the plant growing apparatus from **Step 2** could one day be the foundation of how we grow plants on spaceships, but first we must find the optimal way to water and respirate the soil on these payloads by finishing **Step 1**.

Plant Growth and Gravity

Throughout their growth cycle, plants use various tropisms (turning in response to external stimuli) to guarantee survival in their environment. Gravitropism, the ability for plants to perceive and respond to gravity, can be divided into three components: perception, biochemical signaling, and differential growth (Vanderbrink & Kiss, 2019). This process dictates upward shoot growth, and downward root growth, in order to ensure the proper positioning of leaves for efficient photosynthesis and gas exchange, as well as the proper positioning of roots for optimal water and nutrient exchange from the soil. Gravity also affects other physical phenomena related to plant growth, such as buoyance, convection, and sedimentation.

Gravity also affects the watering of plants. Soil is naturally filled with air pockets and space between soil particles. Conventional watering from above allows gravity to pull the water downward, filling these gaps and saturating the soil. Capillary watering, commonly known as watering from below, involves sub irrigation or other systems that rely on wicking action (Gracian). There are multiple designs of this watering method that have been thoroughly researched, with Ebb and Flow method being one of the most common (Semananda et al., 2018). This method is promising in its applications to watering in-space, however capillary flow watering will not be explored in this experiment.

Issues with Watering Plants in Zero Gravity

The main problem with watering plants in zero gravity is the surface tension of the water, where the water tends to stick to any surface it contacts. (astrobotany.com, hudsonalpha.org). Water would clump up within the soil, either drowning the roots by clumping around the roots, or dehydrating the roots by forming bubbles around the roots. The plants require a 'Goldilocks zone', where the plant receives the necessary ratio of water and air for growth. In regular gravity, pots usually have a drainage hole, where water drains down into the roots and the excess drains out the hole. However, this is reliant on gravity. Therefore, we decided to figure out how water drains in microgravity as compared to normal gravity and how cycling air through the soil would alleviate these problems.

Other problems we found that arise in zero gravity are listed here:

- **Air Bubble Formation**: Without the influence of gravity, air bubbles can become trapped in the water supply lines or around plant roots. These air bubbles can obstruct water flow and deprive plants of essential nutrients.

• **Moisture Control**: Maintaining the right moisture level around plant roots is crucial. In microgravity, excess moisture can linger around the roots, increasing the risk of root rot, while insufficient moisture can lead to dehydration.

• **Nutrient Uptake**: Nutrient uptake by plants depends on the movement of water and ions through the soil or growth medium. Microgravity can affect the diffusion of nutrients, making it challenging to ensure plants receive the necessary elements for growth.

• **Microbial Growth**: Microgravity can promote the growth of bacteria and fungi, which can be detrimental to plant health. Additionally, the closed and controlled environment of a space habitat can make it difficult to manage microbial populations effectively.

• **Water Recycling**: Water is a precious resource in space environments, so efficient water recycling systems are essential. Ensuring that excess water used for plant growth is captured, purified, and made available for future use presents a technological challenge.

• **Root Growth:** In prior projects, researchers found that providing adequate hydration and aeration to the root zone of the plant in zero gravity is an issue as roots grow differently in space.

Zero-Gravity Plane Experiments Breakdown

Two experiments will be conducted simultaneously during the zero-gravity plane experiment. One will be focused on *watering the soil,* and the other will be to *respirate and drain the soil*. The breakdown of each experiment is below. Although these two processes (watering and draining) happen naturally one after the other, it is necessary to break these into two processes due to the short test periods of around 20 seconds aboard the zero-gravity plane.

The Watering Experiment

For the watering experiment, the goal is to see how well different watering methods are at diffusing water into the soil while experiencing microgravity. This experiment will start with *dry, unsaturated soil.* We have chosen 4 watering methods (Figure 1):

1. Misting: a small misting apparatus will spray the soil from above.

2. Dripping: a tube will drip water into the center of the soil from above

3. Coil: a perforated tube in the shape of a coil will run around the inside edge of the soil pot.

4. Root Injection: a tube will inject water directly into the center of the soil (where the roots would be if a plant was growing)

The primary data we are searching for during this experiment is *soil moisture vs position vs time*. To accomplish this, we will use moisture sensors positioned in various places in the soil container that will record the change in moisture during the duration of the parabola. This way we can measure how well and how long it takes for water to diffuse in microgravity with different watering methods.

The Drainage Experiment

The drainage experiment will test how well water drains out of the soil while experiencing micro gravity. Since water draining out of soil mainly relies on gravity, there will also be varying amounts of air flow circulation that will assist the water drainage. This experiment will start with *fully water saturated* *soil*. The reason for starting with saturated soil (instead of dry soil like in the watering experiment) is to immediately start testing drainage rates for a fully saturated soil due to only having 20 seconds per parabola to measure. Soil respiration is a key part of plant growth so the goal with this experiment is to flow air through the soil to help the soil breathe and drain. The experiment will start by opening a valve at the bottom of the saturated soil container right as the plane begins its zero-gravity parabola, then close once the parabola concludes. The total amount of water drained will be measured in a container and collected as data. The outputs of this experiment should be *total water drained*, and *drainage rate vs time*. We currently do not know how to measure drainage rate vs time and it is a problem to solve for the next group. Optionally, the drainage experiment could also have soil moisture sensors to measure how the soil changes in saturation in time; the output for this optional component would be *soil moisture vs position vs time.*

How the Plane Works

The zero-gravity plane will use a zero-gravity parabolic flight (ZGPF) to create around 20 seconds of experimental test time. The plane will do around 5 parabolas then turn around, do 5 more parabolas, turn around, and so on. It will repeat this process until it completes 4 turns and 5 parabolas for a total of 20 parabolas. To simplify this, we will call each group of 5 parabolas a *phase* of the test. For each parabola, we will conduct one trial of each experiment (watering and drainage) and each experiment will have its own soil container. For 20 parabolas, and 2 experiments per parabola, which makes a total of 40 soil containers for the ZGPF.

Theory

Flow rate moving through a porous medium is not an easy thing to calculate, it is recommended to perform an experiment because of how much it varies with small changes. To accomplish this, an infiltrometer is used. The problem with this is an infiltrometer cannot be used on the ground to design our system because gravity will be much different on the Zero G plane. Another very important note is that infiltrometers have never been used in a microgravity environment, at least there is no information online about them being used in microgravity or space. So, how are we supposed to size the experiment on the ground such that it functions in space? How do we design our system such that we do not have too much drainage or too much retention? There is a set of equations that can be applied to traditional porous mediums on the ground, and also with modifications for more intense environments like space. This section will lay the groundwork for traditional Darcy equations, so they can be expanded upon in the future. Darcy's law can be used to determine the velocity of a fluid flowing through soil, among other important values like drainage rate and pressure gradient (Billen, 2021). To apply these equations, Darcy flow is necessary, which is flow with Reynolds numbers between 1-10 (Billen, 2021).

To calculate fluid flow through a porous medium, the equation is $v = \frac{q}{\varphi}$ where q is Darcy flux and φ is the porosity, the ratio between void space and volume of the soil (Billen, 2021). Darcy flux, q, is defined as $\frac{Q}{A} = -\frac{Kdh}{dx}$ where K is hydraulic conductivity, $\frac{dh}{dx}$ is the hydraulic gradient, A is the cross-sectional area, Q is the discharge rate. Hydraulic conductivity, K, is equal to $\frac{k\gamma}{\eta}$ where k is the intrinsic permeability, γ is the specific weight of the fluid, which is density times gravitational acceleration: $\gamma = \rho g$, and η is the dynamic viscosity of the fluid.

Another important parameter is the volume of voids. We need this because we can find DOS (degree of saturation) to find out how long it takes for the soil to become fully saturated. Our porosity which we used earlier, can be used in the void ratio calculation, which we can use to find DOS. Void ratio is not the same as porosity. Porosity (φ) is defined as the ratio of the volume of voids to the total soil volume. We can use our approximated porosity values with our known soil volumes to find volume of voids (Chapter 5 soil classification and laboratory testing, 2019). DOS is the ratio of the volume of water to the volume of voids, $\frac{volume\ of water}{volume\ of\ voids}$, and using Darcy equations we can use our volumetric flow of water to the soil to determine the DOS at various points in time. Using the porosity definition, $\varphi = \frac{volume\ of\ voids}{volume\ of\ soil}$, volume of voids is equal to $\varphi * volume\ of\ soil$. Using this, DOS is $\frac{\varphi * volume\ of soil}{volumeof\ water}$.

Standardized Units

The following table is a table with units of important Darcy parameters to perform dimensional analysis and prove calculations that will lead to usable values (see Figure 2).

Dimensional Analysis

Beginning with γ, its metrics units are $\frac{kg}{m^3} * \frac{m}{s^2} = \frac{kg}{m^2 s^2}$. We also start with μ having units of $\frac{kg}{m*s}$, and k having units of m^2. Plugging in γ, k, and μ in to find K, the units of $K = \frac{k\gamma}{\eta} = \frac{\frac{kg}{m^2 * s^2} * m^2}{\frac{kg}{m*s}} = \frac{m}{s}$. Moving forward we need to find the discharge rate using $Q = -KA\frac{dh}{dx}$and obtain units of $\frac{m*m^2*m}{s*m} = \frac{m^3}{s}$ which satisfies units of volumetric flow. Next, we can use Q to find Darcy Flux with $q = \frac{Q}{A}$ which is simply volumetric flow divided by area, so it has units of $\frac{m}{s}$. Fluid velocity is the darcy flux divided by porosity where porosity is a unitless constant, so the fluid velocity units remain as $\frac{m}{s}$. The last very important value to obtain units for is time to reach 100% saturation. This is the void volume divided by the volumetric flow, so units are $\frac{m^3}{\frac{m^3}{s}} = s$.

Example Calculations

Assumptions:

1. Laminar Flow
2. The hydraulic gradient is 1.

Givens:

1. The area for our soil sample is one inch squared.
2. Depth for our soil sample is two inches.
3. The dynamic viscosity is used at 25 degrees Celsius, being 8.90e-4$\frac{kg}{m*s}$
4. The intrinsic permeability is 10e-9 m^2
5. The porosity of the sample is 0.43.

According to the Dimensional analysis section, if we want to go all the way to finding the fluid velocity through the medium, we should start with finding K, hydraulic conductivity. Let us begin with a soil density of 1600 kg/m^3 and gravitational acceleration of around ⅙ of Earth, similar to what can be experienced on the Zero G plane. Using these values, we obtain $\gamma = 2616\frac{kg}{m^2 * s^2}$. Moving onto hydraulic conductivity, $\frac{k\gamma}{\eta}$, if we use a typical dynamic viscosity of water at 25 celsius (8.90e-4$\frac{kg}{m*s}$) and a typical intrinsic permeability of silty sand (10e-9 m^2) hydraulic conductivity comes out to be about .00294 $\frac{m}{s}$. Now we can find discharge rate (same thing as how fast the fluid drains from the soil) with $Q = -KA\frac{dh}{dx}$. If we assume the hydraulic gradient is one from the assumptions and area is one inch squared, Q is -1.48e-6 $\frac{m^3}{s}$. The negative in front denotes the direction it flows, downward. Hydraulic gradient is not going to be one on the flight, however. This will likely need to be calculated experimentally during the flight. After finding the discharge rate, multiplying by the one-inch squared area gives the Darcy flux, -.00294. This is the same as the hydraulic conductivity (besides sign, which denotes direction) as the Darcy flux. This means that for a hydraulic gradient of one, the Darcy flux and hydraulic conductivity are the exact same. Using the calculated Darcy flux, and a porosity of 0.43, the fluid velocity is -.00684 $\frac{m}{s}$.

Possibly the most important value to obtain using this theory is time to reach x amount of saturation. The "best" varies widely and depends on the plant and soil. This value can be found using a combination of Darcy parameters and flow rates from our apparatus. At the beginning of this section when deriving equations, the degree of saturation was found to be $\frac{volume\ of water}{\varphi * volume\ of soil}$. To find the time it takes to reach 100% saturation, volume of water must equal the volume of voids, so the volume of voids can be divided by the pipe volumetric flow in order to find the time it takes to fill that volume, and since that is equal to volume of water, the time to reach 100% saturation is found. Using the earlier porosity value of 0.43, and an area and depth of one inch squared and two inches, the volume of voids is 1.1e-5 m^3. Using an example pipe volumetric flow of 2.2e-6 $\frac{\mathrm{m}^3}{s}$, the time to reach 100% saturation is about 5.03 seconds, using the DOS definition, $\frac{volume\ of water}{volume\ of\ voids} = \frac{volume\ of water}{\varphi * volume\ of soil}$ and time to reach 100% saturation is $\frac{volume\ of water}{pipe\ volumetric\ flow} = \frac{volume\ of\ voids}{pipe\ volumetric\ flow}$.

Ground Experimentation

The most important value for us to determine experimentally is intrinsic permeability. Values for this vary widely and are not easy to obtain from online resources. To obtain this, our team will use a Piezometer to get an exact value in an environment like the zero-G plane. It is safe to have a similar environment, however, intrinsic permeability only changes with soil structure, so regardless of location, the soil structure should remain the same if it is in the same area and packed the same way. A permeameter can also be used to determine hydraulic conductivity and use that for calculating intrinsic permeability.

Another value that may have to be obtained experimentally is porosity. These values were easier to find online than intrinsic permeability, but they were ranges instead of precise values. Porosity will require ground experiments to get accurate values for the sample, since it varies with sample geometry and how much it is packed together. General ideas can be obtained for different soils because they can only be packed so much, but these ranges are wide and lead to large differences when going through the Darcy calculations.

The hydraulic gradient will likely vary a lot during the parabolic flight, so instruments like a piezometer (also used for intrinsic permeability) would be necessary. For the sake of the experimental calculations, it was kept as 1 to make things easier for the reader, but this assumption cannot be applied in an environment with gravity levels changing frequently.

Application for the Zero-G Plane Experiment

The Darcy equations are used for obtaining crucial values like time to reach 100% saturation and drainage rate. We can use the time to reach 100% saturation to know exactly how long to open and close the solenoid valves and how much voltage to supply the peristaltic pump. Our parabolas last only about 20 seconds in the Zero-G plane, so during the experiment it is imperative to be quick with watering and have time to reach 100% saturation hopefully less than 20 seconds to prepare for the next parabola. A detailed explanation on how to calculate this value is found in the example calculations section. Following the procedure in the example calculations section after ground testing has been performed to obtain things like intrinsic permeability and porosity, plugging in appropriate values can be used to find discharge rate. Using the volumetric flow rate of water through the pipe (given from pump specifications) and pipe area, the fluid velocity through the pipe can be found to ensure it is not moving fast enough to cause erosion. The given volumetric flow rate can be compared with the previously found discharge rate to see if there is too much water going in or too much water coming out.

Theory Notes

K and k (hydraulic conductivity and intrinsic permeability respectively) depend on different things. Intrinsic permeability depends only on soil geometry, not gravity like hydraulic conductivity. Therefore, in our calculations, we will be using intrinsic permeability as a given instead of hydraulic conductivity. If we use hydraulic conductivity as a given, we must calculate intrinsic permeability in terms of hydraulic conductivity, which makes it a gravity-dependent variable. This is not accurate.

Velocity is measured in meters per second according to the standardized units so after doing the calculations it will appear that the fluid is moving extremely slow, too slow to even measure. Fluids typically flow very slowly through porous mediums, so their units are often measured in cm per day. The units in the standardized section are simply meters per second such that they can be used in the future for integration of piping; it is more typical for fluid velocities to not be in centimeters per day.

The gravitational acceleration throughout the flight will not remain constant. The example calculations do not account for gradients, they are just using values at a single point in time. So, if using instruments to record and calculate Darcy parameters, they will need to be sampling rapidly to account for this gradient.

How the Zero-G Plane Works

The zero-gravity plane will use a zero-gravity parabolic flight (ZGPF) to create around 20 seconds of experimental test time. The plane will do around 5 parabolas then turn around, do 5 more parabolas, turn around, and so on. It will repeat this process until it completes 4 turns and 5 parabolas. To simplify this, we will call each group of 5 parabolas a *phase* of the test. Reference Figure 11 in the appendix for how this ties into the mission architecture.

Necessary Sizing

Pump
Tube
Pot
Reservoir

Full Assembly

Each test apparatus or "Pots" consist of a collection of smaller components (Lid, Test case, table, solenoid valve, funnel), that are built up to make the final pot (See Figure 3). Each component had been designed to satisfy a particular functioning need.

The Lid

The lid is a 1” outer diameter, 1.25” inner diameter cap with two extrusions on the top to allow for connecting the air and water inlets. The lid is 0.5” in height and has threading on the inner wall (refer Figure 4).

The manufacturing plan for the lid is to 3D print it.

The Test Case

The test case is a 1” outer diameter, 0.8” inner diameter cylinder with a height of 2” (See Figure 5). The test case is where the soil sample is to be placed to test the different parameters outlined by the mission requirements. The test case is threaded on both ends, to be screwed into its neighboring components (See Figure 5). The choice to thread the case from outside was made to minimize the contact of water with the threads and prevent water from getting stuck in the threads which would disrupt the accuracy of the tests. The case is transparent to monitor the tests from outside.

The manufacturing idea for the test case is to buy transparent acrylic, cut it to size and thread the outer surface.

The Table

The table depicted is a portion of a bigger table capable of holding all the test pots together (Figure 6). The manufacturing process for the table is to find a piece big enough to accommodate all the pots together (20 pots), and to drill holes where the pots go. The dimension required for this is 16”x 20” with a thickness of 0.25”. This includes the space for the pot themselves and a 2” space between each pot.

The table is then fitted with 3D printed attachments (Material to be tested before finalizing) on the top and bottom of the table (Figure 7). The dimensions for this connecting piece are 1.50” OD and 1” ID. The height of the piece is 0.5” (Figure 8). This is where the pot and the solenoid valve will screw into the table. The threads on both these connectors are internal for the same reasons as mentioned above.

Sitting between the top threaded connector and the table itself is a fine mesh to prevent soil from leaking into the funnel. The mesh is an off the shelf product.

Solenoid Valve

The solenoid valve is used to lock and open the experiment as needed. The purpose is to keep the experiment locked before the plane reaches the micro-g parabolas and open it once micro-g is achieved. This prevents water from collecting before and after the micro-g phase. Water collecting outside the micro-g phase would ruin the data of the drainage experiment results.

The plan for the Solenoid Valve is to use an off the shelf product. The valve is required to be 1-inch outer diameter and have external threading on both sides.

A CAD image of a potential solenoid valve has been attached below (Figure 9)

Funnel and Collection cylinder

The funnel is the final component of the test system. It consists of a funnel and a small cylindrical piece to hold the water. The funnel screws into the solenoid valve and collects the water that drains out of the test section. It has a small extrusion where the outlet of the air hose connects. The dimensions for the funnel are 1” ID, 1.25” OD and 1.15” height. The dimensions for the cylindrical piece are 0.2” ID and 0.51” height (Figure 9).

The idea to manufacture the funnel is to use transparent 3D printing filament and 3D print the part. The threading of the funnel is on the internal wall so that it can screw into the solenoid valve. (Figure 9)

Figures

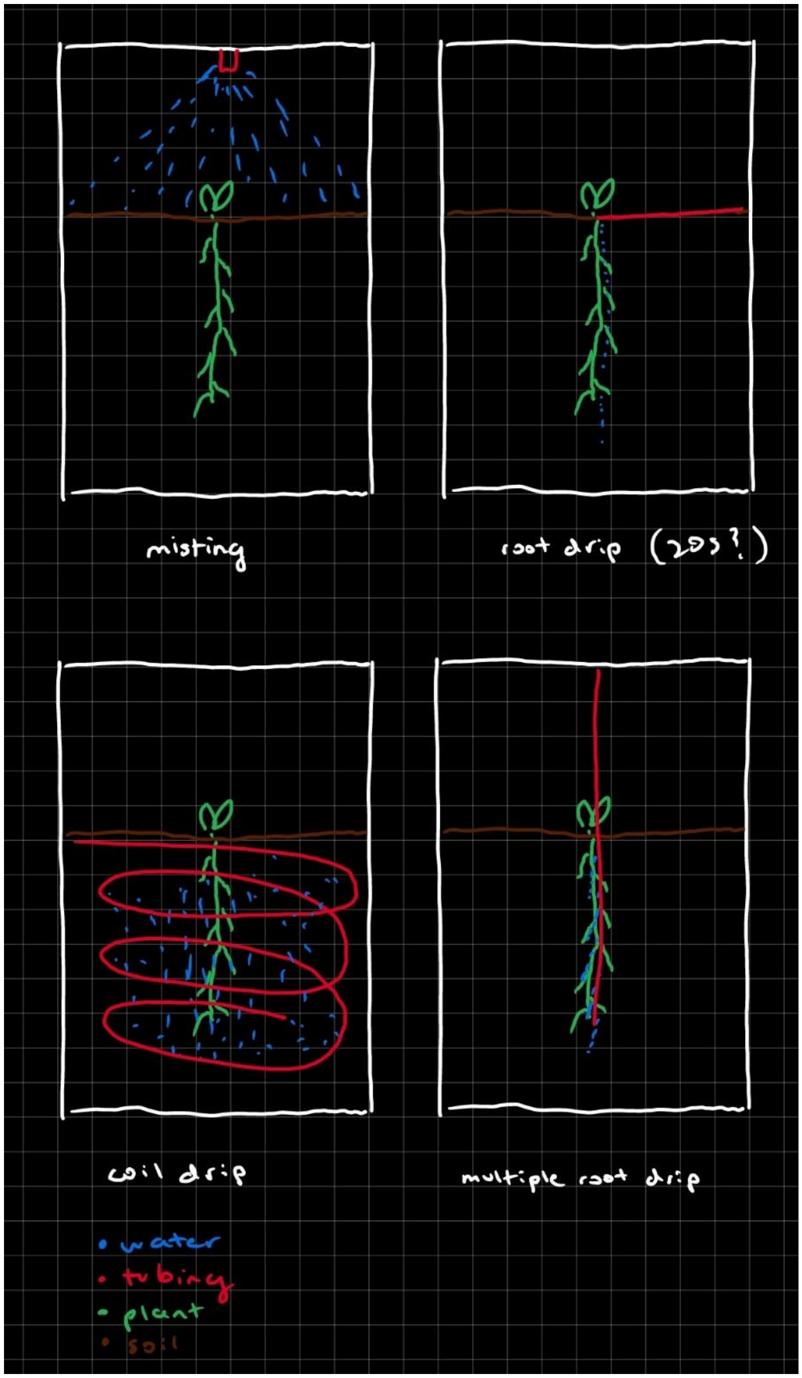

Figure 1: Watering Methods

Dynamic Viscosity (η)	$\frac{kg}{m*s}$
Area (A)	m^2
Depth (D)	m
Gravitational Acceleration (g)	$\frac{m}{s^2}$
Density (ρ)	$\frac{kg}{m^3}$
Specific Weight (γ)	$\frac{kg}{m^2*s^2}$
Intrinsic Permeability (k)	m^2
Hydraulic Gradient (dh/dx)	$\frac{m}{m}$
Hydraulic Conductivity (K)	$\frac{m}{s}$
Discharge Rate (Q)	$\frac{m^3}{s}$
Darcy Flux (q)	$\frac{m}{s}$
Porosity (φ)	$\frac{m^3}{m^3}$
Void Volume (v)	m^3
Fluid Velocity (u)	$\frac{m}{s}$
Time to reach 100% saturation (t)	s

Figure 2: table of units for theoretical calculations

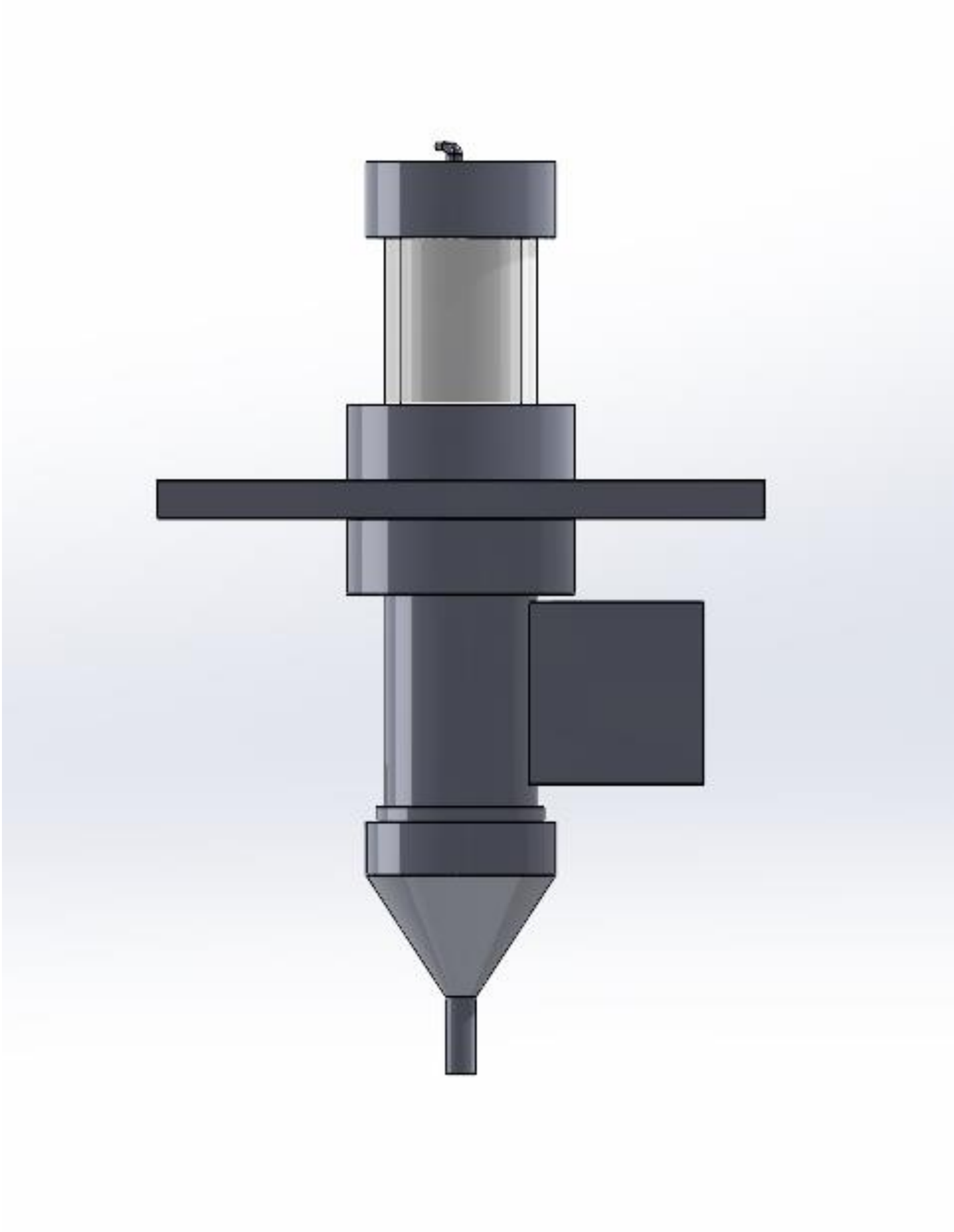

Figure 3: CAD of full Assembly

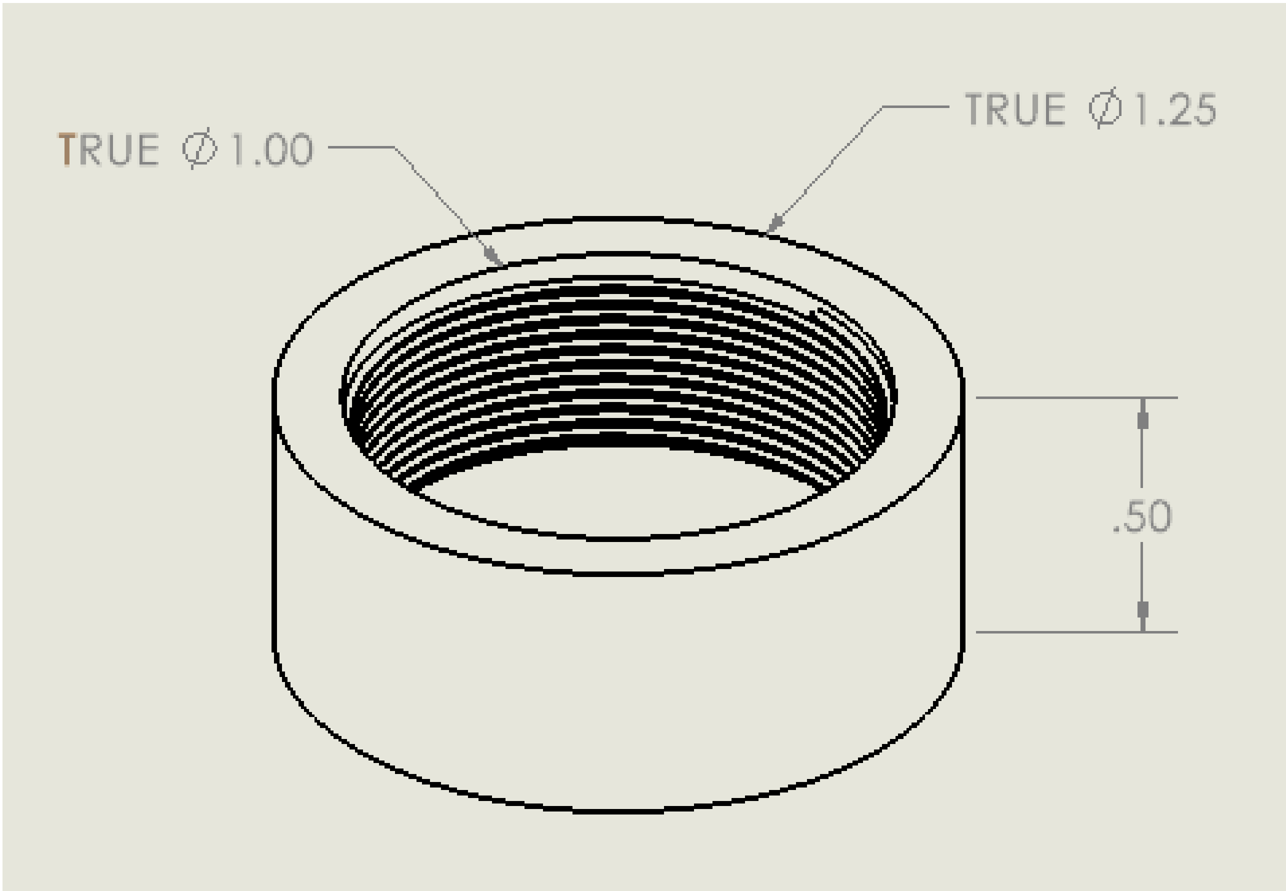

Figure 4: Lid with Dimensions

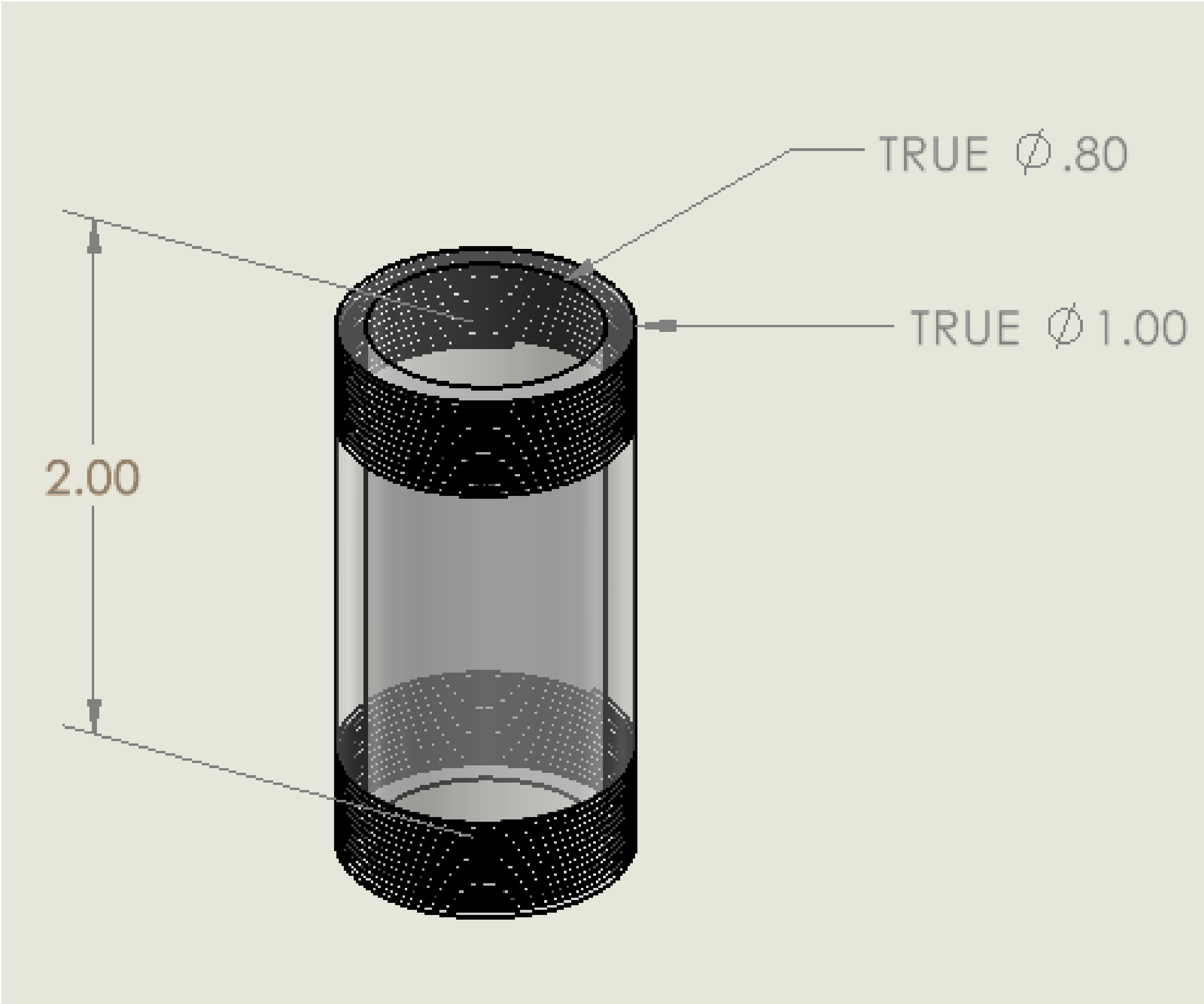

Figure 5: Test Case with dimensions

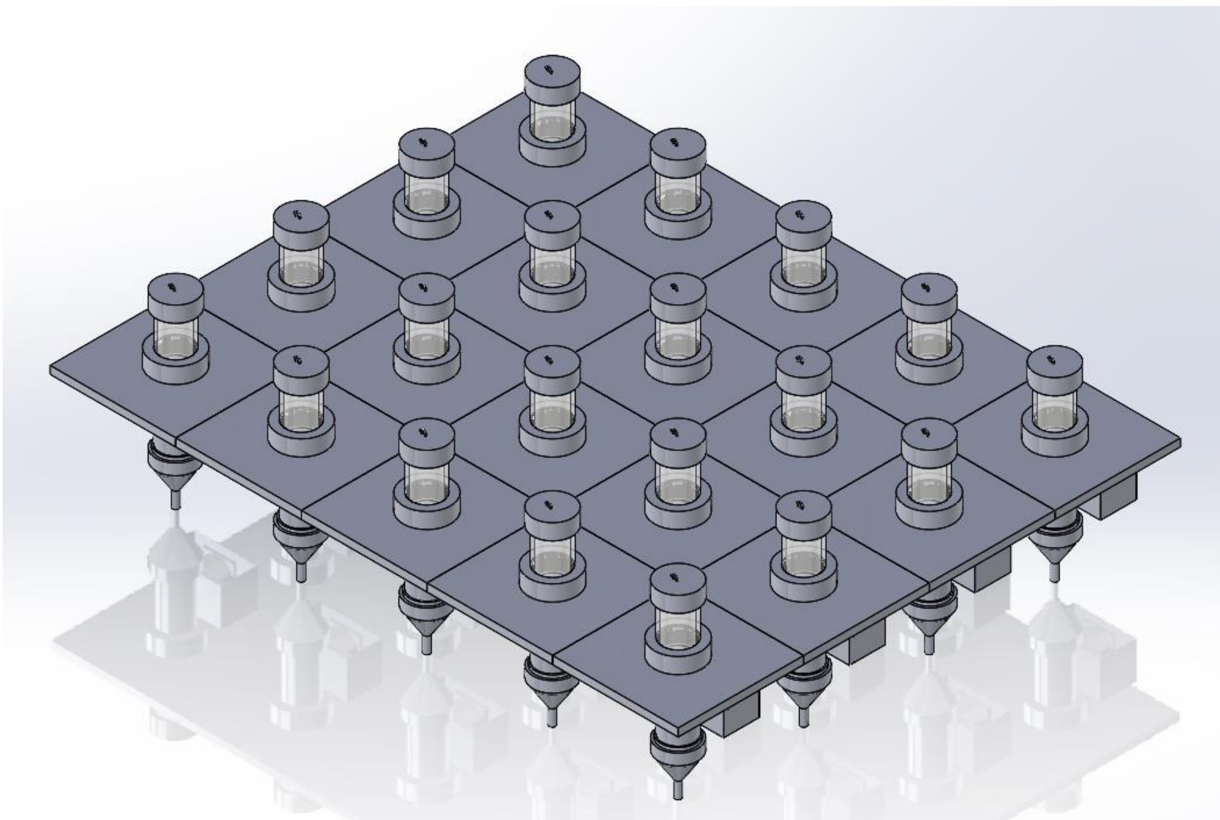
Figure 6: Full Assembly of all the test cases

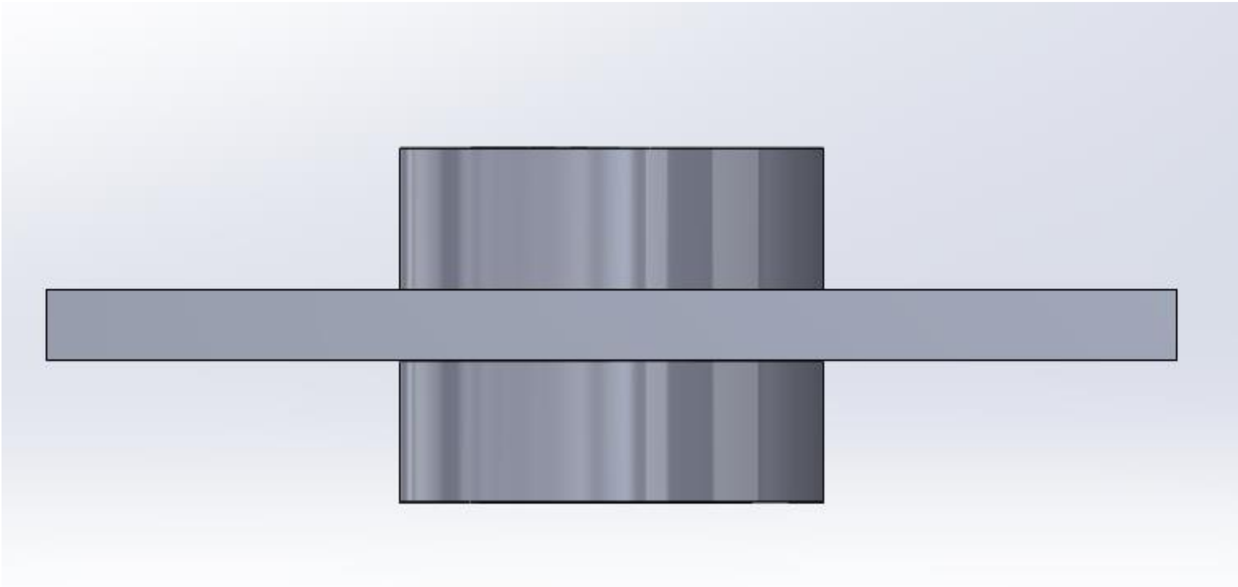

Figure 7: Table showing threaded fitting on both sides.

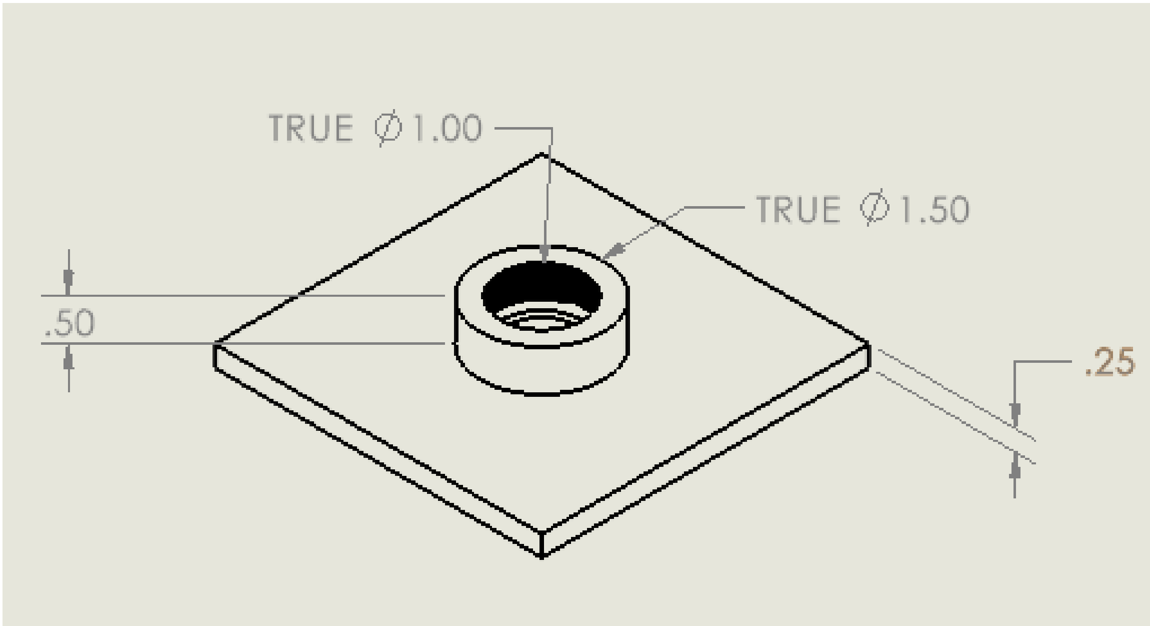

Figure 8: Table with Dimensions

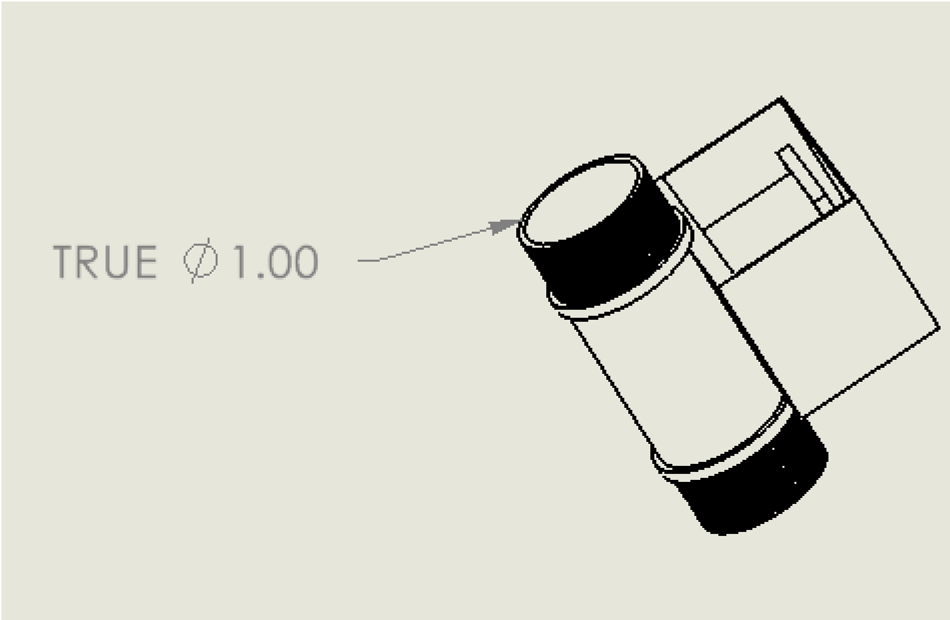

Figure 9: CAD of a potential solenoid valve

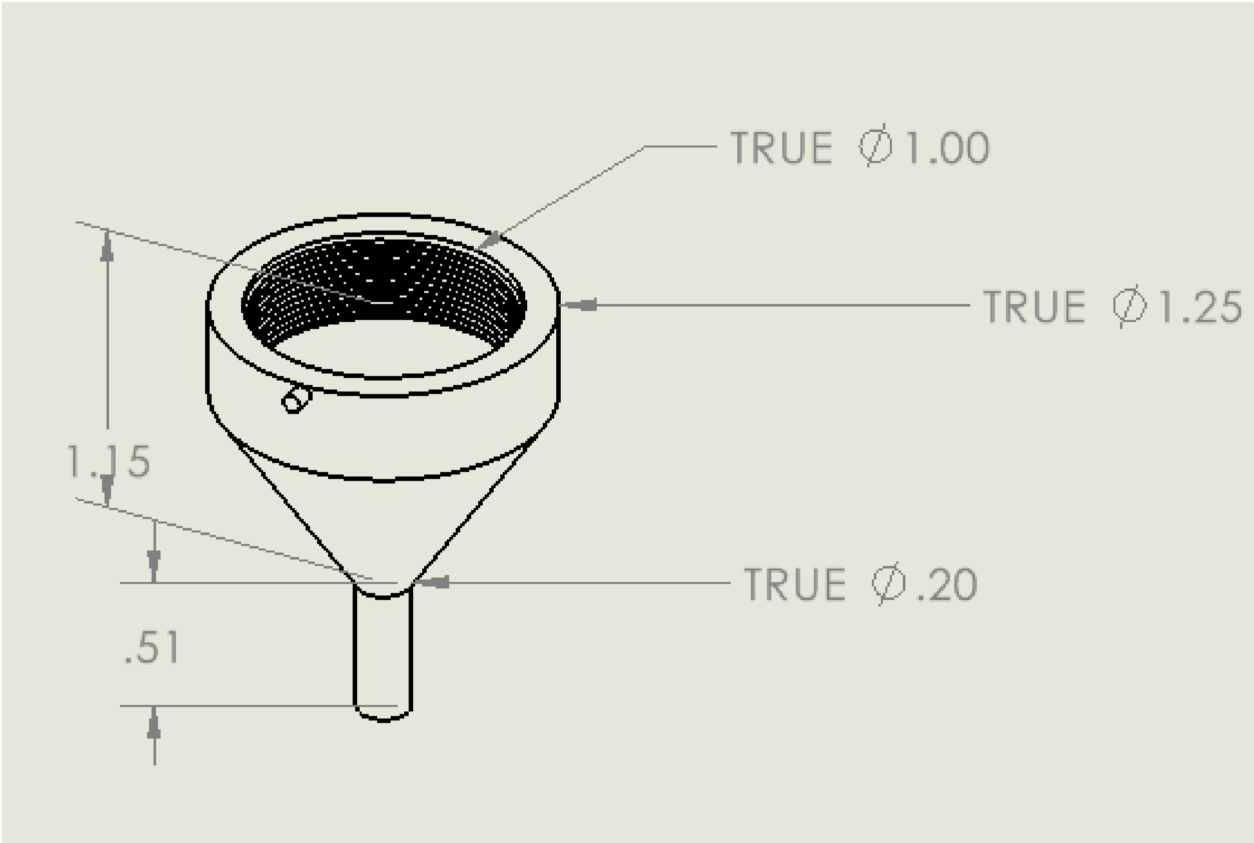

Figure 10: Funnel and Collection Cylinder

Phase 1		Phase 2		Phase3		Phase 4		
Experiment 1	Experiment 2	Experiment 1	Experiment 2	Experiment 1	Experiment 2	Experiment 1	Experiment 2	
No Flow	Mist	Flow Rate 1	Drip	Flow Rate 2	Coil	Flow Rate 3	Root Injection	Parabola 1
No Flow	Mist	Flow Rate 1	Drip	Flow Rate 2	Coil	Flow Rate 3	Root Injection	Parabola 2
No Flow	Mist	Flow Rate 1	Drip	Flow Rate 2	Coil	Flow Rate 3	Root Injection	Parabola 3
No Flow	Mist	Flow Rate 1	Drip	Flow Rate 2	Coil	Flow Rate 3	Root Injection	Parabola 4
No Flow	Mist	Flow Rate 1	Drip	Flow Rate 2	Coil	Flow Rate 3	Root Injection	Parabola 5

Figure 11: Mission Architecture for the Zero-G plane

(IMPORTANT NOTE: The plane does 5 parabolas, then turns around and repeats. It repeats this 4 times. In this case, we will call each set of 4 parabolas a *phase*. The plane completes 20 parabolas total, and we will conduct two experiments during each parabola for a total of 40 experiments as organized in figure 11).

Questions We Still Need Answered

- How valid are Darcy equations for soil mechanics in non-Earth gravity?
- Can Darcy equations be used for any fluid, not just water?
- For heavily experimental parameters like hydraulic gradient, can we make it so our ground conditions are the same as in the plane?
    - How reliable would ground experimentation be to obtain theoretical values of things like head loss and permeability?
- Where do we get data like porosity, intrinsic permeability, and other plant-specific parameters from?
- Is gravity the only way plants decide which way to grow? What can we do to minimize variation or control the direction they grow?
- How much would radiation and cosmic rays affect growth?
- Are there technology or engineering solutions that have been developed to help these problems?
- Are some plants better suited for microgravity, if so, why?
- How can we predict how much water, air, and nutrients our plants need? How can we hit the sweet spot, so we don't drown our plant, but we also don't want to make it dehydrated? Can we predict these thresholds mathematically?
- How can we mitigate microbial growth in our environment? Are there some microbes that can be beneficial to growth instead of harmful?
- How do you measure water drainage rate vs time?

Appendix

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