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Condensed Droplet Experiment for NASA in Sub-Orbital Spaceflight

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CONDENSED DROPLET EXPERIMENT FOR NASA IN SUB-ORBITAL SPACEFLIGHT

by

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Dedicated to my Mom and Dad, for always believing in me.

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LIST OF SYMBOLS

Symbol	Definition
$\tilde{E}$	Dimensionless energy
E	Energy
$\tilde{A}_{FS}$	Dimensionless free surface area
$\tilde{A}_{Wet}$	Dimensionless wetted surface area
A_{FS}	Free surface area
A_{Wet}	Wetted surface area
σ	Surface tension
R	Characteristic length
R_i	Radius of injection hole
θ	Tangential angle of the ellipse
y	Coordinate in the y axis
x	Coordinate in the x axis
z	Coordinate in the z axis
a	Semi major axis
b	Semi minor axis
t	An independent parameter from 0 to 2 π
L	Length
dx	Component of parametric arc length of an ellipse in the x direction
dy	Component of parametric arc length of an ellipse in the y direction
ds	Parametric arc length of an ellipse
W_e	Webber number
σ	Surface tension
σ_W	Wetted surface energy density
σ_{FS}	Surface tension

σ_D	Dry surface energy density
A	Area of injection hole
Q	Volumetric flow rate
v	Velocity of the liquid at the injection orifice
ρ	Liquid density
LED	Light emitting diode

ABSTRACT

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Purdue's Condensed Droplet Experiment for NASA in Sub-Orbital Spaceflight (ConDENSS) experiment was chosen by NASA's Flight Opportunities Program for sub-orbital flight testing on a future Blue Origin New Shepard sub-orbital mission. ConDENSS seeks to test several predictions of existence and stability of static capillary droplets, plugs, and annular sleeves predicted by computational modeling. Application of the results includes advancing zero-gravity condenser technology and several possible applications on Earth.

The payload is designed to form droplets, plugs, and sleeves of liquid by pumping pre-determined volumes of the liquid onto the walls of elliptical cone test sections. Four test sections with a static gas and four test sections with flowing gas are to be flown in one mission. The gas flow simulates conditions in the condenser Section of a phase-change heat transfer loop in spaceflight. Observations, collected by cameras throughout the payload, are to be compared with predictions from zero-gravity numerical modeling to validate or refute the zero-gravity fluids simulations

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CHAPTER 1. INTRODUCTION

1.1 Purpose

It is well understood that a liquid and gas (or vapor) system in thermal equilibrium will seek out a minimum-energy state while maintaining a constant Gaussian curvature in weightlessness and a given contact angle. This is the most basic explanation of the liquid energy equation and can include or neglect the effects of gravity the energies in the system are wetted surface energy, free surface energy, dry surface energy, and a body force energy if gravity or acceleration are present (Abramson et al., 1966).

By solving for minimum energy, it is possible to model liquid under different conditions, including: densities, gravity, forces acting on the system, container geometries, varying surface tension, and different contact angles (Rascon, Parry, and Aarts, 2016). Even though since the early 1990s the energy minimization can be modeled with the Surface Evolver code, there is little actual observational data obtained through testing to confirm that the modeling is correct. Observations can be taken on the ground, but the effects of gravity on the energy state of liquid are generally too significant to see the effects of contact angle and surface tension, and therefore observations must be made without gravity to test models.

The shape that liquid takes inside of tubes in microgravity is of interest because there are space applications that can benefit from this understanding. One example is a condenser: a system in which gas is pushed across a cool surface to move heat away from the gas to the surface. In the tubing in a condenser loop, the change in temperature causes condensation on the inside of the tubing. With the correct understanding of the effects of surface tension and wetting for a liquid, it is possible to use modeling of static equilibria to predict when the condensed volume will form either droplets, sleeves, or plugs inside of the tubing (Rascon et al., 2016). This is valuable information for use in designing a condenser for space applications. Therefore, this experiment is being designed to attempt to create droplets, sleeves, and plugs on the inside of mock condenser tubes. Additionally, and beyond the capabilities of Surface Evolver, half of the tubes in the experiment will have an axial airflow to observe the effects of air flow and surface tension inside of condenser tubing.

1.2 Why Surface Evolver is Necessary

Plugs and sleeves in circular tubes can be solved for analytically in two dimensions, respectively (Collicott, Linsdley, and Frazer, 2006). In contrast, wall-bound droplets in circular tubes require modeling in three dimensions, so Surface Evolver is used. Here, in the elliptic cones described below, every droplet, sleeve, and plug have free surfaces which require three-dimensional modeling capability. In this study, Surface Evolver, which has worked well in the past for modeling liquids in a three-dimensional environment as well as showing when critical wetting takes place, is used (Collicott, 2017) (Concus and Finn, 1990). Critical wetting is the phenomenon where an equilibrium state fails to exist and the liquid inside the test section is significantly redistributed (Chen, Jenson, Weslogel, and Collicott, 2008). Surface Evolver is a scalar minimization algorithm written by Professor Kenneth A. Brakke of Susquehanna University in the early 90s (Brakke, 1992). The ability of Surface Evolver to solve Minimal Surface Theory problems makes it possible to solve for minimal free surface area of a liquid, all while maintaining a constant Gaussian curvature. This is a key step in solving for the static equilibrium state of liquids and makes possible the study in three dimensions.

1.3 Zero-g Testing Options

There are few options available for Zero-g testing: drop towers, sub-orbital rocket launches, parabolic aircraft flights, and orbital research. Drop towers are the most cost effective, but do not provide long enough periods of microgravity for this topic. Parabolic flights are frequent and not too expensive. However, experiments like this one have been attempted on two different test flights and in both cases, there were too few instances of clean microgravity: periods where the net accelerations are close to zero. On these two test flights, not only were microgravity periods too short to inject enough liquid into the test sections, but the random accelerations from atmospheric layers and aircraft vibrations in flight proved to be too great and few stable droplets were created. The Blue Origin New Shepard re-usable commercial sub-orbital rocket provides a suitable test bed for microgravity experimentation, with periods of weightlessness more than three minutes. Weightlessness is also considered to be clean, meaning, that during the testing phase of the flight, nearly zero accelerations from atmosphere are experienced by the experiment. Clean weightlessness is important in this study as some shapes of liquid may prove to be unstable while experiencing perturbation. The long duration of weightlessness and the quality of the testing environment make Blue Origin's New Shepard the suitable test bed for this experiment.

CHAPTER 2. BACKGROUND

2.1 Review Droplet in Tube or Bubble in Tube Equivalence

The test sections used in this study are elliptical cones (see Section 3.1). Analytically, there are a lot of comparisons that can be made between the behaver of liquid on the wall of an elliptical cone test section, and a tube test section of constant inner radius. In 2006, Collicott, Lindsley, and Frazer, discussed the behavior of small liquid volumes inside of circular tubes (Collicott, William, and Frazer, 2006). Their work investigated the effects of varying liquid volume and contact angle, the same variables which are of interest to this study

2.2 Review of Collicott, Lindsley, and Frazer

The assumptions of Collicott et al. are also made in this study (Collicott et al., 2006). The assumptions are summarized here, and again in Section 6:

a) The test section wall is assumed to be perfectly smooth without any imperfections.
b) There are no gravitational or other body forces acting on the fluids.
c) The fluid does not experience phase change from a liquid to a vapor or vapor to liquid, therefor volume is considered constant.
d) Contact angle between the liquid and the test section wall is uniform on the wall. Note that this does not preclude pinning of the contact line at the ends of walls.
e) All solutions are static equilibria states. No kinematics are investigated, only equilibrium solutions without motion.

The previous modeling study concluded that there were three possible steady state solutions for the parameter space of zero to 180 degrees contact angle and zero volume up to sufficiently large volumes to guarantee that the tube is plugged with liquid. The types of static equilibria that were found are: droplets adhering to the inside wall of the test section, plugs of liquid covering the entire cross-Sectional area of the test section, and axisymmetric annular solutions, or sleeves. The three steady state solutions can be seen in Figure 2.1.

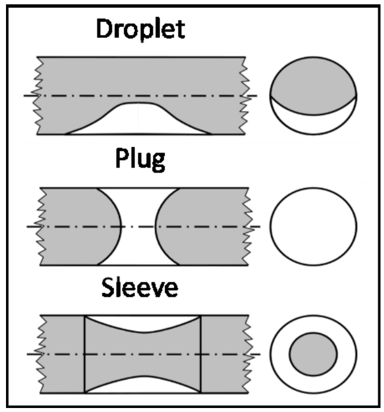


Figure 2.1: Droplet, plug, and sleeve inside of a cylindrical cross Section. The gray shading indicates the gas phase and the white shading indicates the liquid phase in this example of a wetting liquid.

The total energy of the system in zero-g is the sum of three energies:

$$E = E_{FS} + E_{Wet} + E_{Dry} \tag{1}$$

Here, E_{FS} is the energy of the free surface. The free surface energy is the product of the area of the liquid which is in contact with the gas and surface tension. E_{Wet} is the energy of the wetted area and pertains to the area that the liquid contacts a solid, in this case the test section walls. E_{Dry} is the surface energy of the dry walls of the system, Figure 2.1. For Surface Evolver simulations, either keeping E_{Wet} or E_{Dry} in Equation (1) will suffice. This is made possible by replacing either A_{Wet} or A_{Dry} from Equation (2) with their algebraic equivalence from Equation (3). Equation (3) is the total sum of all area along the surface of the interior of the test sections, or in other words the area of the solid that the liquid may come in contact with. This method of analysis eliminates A_{Dry} from the energy equation, by replacing A_{Dry} in Equation (2) with Equation (4). To compare energies between simulations with different total surface area, the energy component that contains the A_{Total} term is dropped, which leads to the form of Equation (1) used in this study, Equation (6).

$$E = \sigma_{Dry}A_{Dry} + \sigma A_{FS} + \sigma_{Wet}A_{Wet} \quad (2)$$

$$A_{Total} = A_{Dry} + A_{Wet} \quad (3)$$

$$A_{Dry} = A_{Total} - A_{Wet} \quad (4)$$

$$E = (\sigma_{Wet} - \sigma_{Dry})A_{Wet} + \sigma A_{FS} + \sigma_{Dry}A_{Total} \quad (5)$$

$$E = (\sigma_{Wet} - \sigma_{Dry})A_{Wet} + \sigma A_{FS} \quad (6)$$

The relationship in Equation (7) is used to consider surface tension of the liquid, and to eliminate the $\sigma_{Wet} - \sigma_{Dry}$ terms in Equation (6), which leads to Equation (8).

$$\sigma * \cos\theta = \sigma_{Dry} - \sigma_{Wet} \quad (7)$$

$$E = \sigma(A_{FS} - A_{Wet} * \cos\theta) \quad (8)$$

Replacing the area variables in terms of double integrals in Equation (9), and pulling out the characteristic length squared, allows for the nondimensionalization of the areas inside the energy equation, marked by tildes in Equation (10) where *R* is the characteristic length. The characteristic length of an elliptical cone is the square root of the major and minor semi axis.

$$E = \sigma(\iint d(\frac{A_{FS}}{R^2}) - \cos\theta * \iint 1\mathrm{d}(\frac{A_{Wet}}{R^2}) \quad (9)$$

$$E = \sigma(\tilde{A}_{FS} - \tilde{A}_{Wet} * \cos\theta) * R^2 \quad (10)$$

The characteristic length of an elliptical cone, the shape used in this study, shown in Equation (11), and uses the largest major and minor semi axes of the elliptical cones, *a* and *b*. Rearranging Equation (10), and replacing R, gives the nondimensionalized energy of an elliptical cone, marked by tilde in Equation (11). Equation (11) is used in the simulations in Section 6.3 (Collicott, 2017).

$$\frac{E}{\sigma * a * b} = \tilde{E} = \tilde{A}_{FS} - \tilde{A}_{Wet} * \cos\theta \quad (11)$$

2.3 Manning-Collicott-Finn Theory

While Sections 2.1 and 2.2 are about studies done in static steady states of liquid in micro gravity, research has also been done into static liquid steady states in gravity. Manning, Collicott, and Finn discuss methods to predict liquid steady states in their article: Occlusion Criteria in Tubes Under Transverse Body Forces (Manning, Collicott, and Finn, 2011). This study does not investigate the effects of gravity, but the data collected from the flow test sections of the experiment might show results that could be related to the work done by Manning et al. and could prove useful in the future studies of the flight data from this experiment. Without gravity, the MCF theory becomes the classical Concus-Finn (Concus and Finn, 1990) which defines conditions under which critical wetting occurs in arbitrary cross Section cylinders.

CHAPTER 3. EXPERIMENT DESIGN

3.1 Circular Tubes and Elliptic Cones

Circular cylinders were the geometry used in previous analytical studies (Chapter 2). To create dependable and repeatable conditions in weightlessness, the test sections in this study are elliptical cones instead of circular cylinders. There are two primary purposes in the choice elliptic cones, both driven by lessons learned in the failed parabolic flight experiments. For this test case, it is desirable to have the droplets, plugs, and sleeves constrained to a location in the test environment that keeps the liquid in contact with the injection point, even between minimum and maximum volumes in the study. Keeping the liquid in contact with the injection hole allows for the liquid to be retracted after it is injected so that the experiment can be repeated multiple times during the duration of the microgravity portion of the flight. First, droplets, plugs, and sleeves will move along the axial direction of a circular cylinder, see Figure 3.1 below, to the small end of the cone. Second, the injection hole is on the major axis of the elliptical cross Section, as this places droplet in the region of greatest wall curvature (smallest radius of curvature) which will cause droplets to stay in that position on the ellipse.

Cones have been shown, in Surface Evolver simulations, to produce lower energy for a given volume of a wetting liquid positioned near the small end of the cone. With these simulations in mind, cone shaped test sections force the liquid to remain in the small end in the axial direction. This is unlike a circular cylinder, which can have the lowest energy state at any location along the axial direction. Simulations have also shown that ellipses produce the lowest energy at either end of their major axis, causing the droplet to remain in that position if it is injected there. In contrast, to the lowest energy state of a circle can be located anywhere around the circumference. Thus, using a test section that is both an ellipse and a cone keeps the liquid in contact with the small end of the elliptical cone, as well as either end of the major axis. Knowing what location that the droplet will be in in advance also allows for the positioning of the cameras.

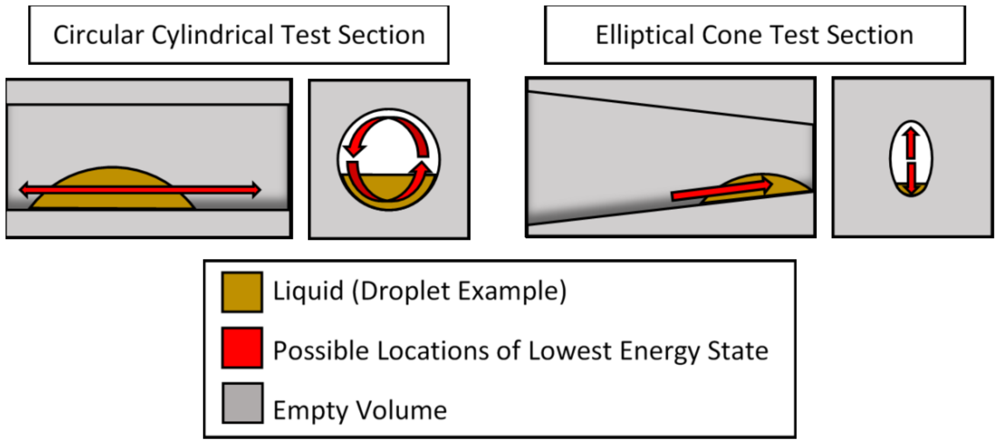


Figure 3.1: Possible locations of minimal energy states of droplets on the inside wall of a cylinder test section and an elliptical cone.

3.2 Interfacing: Payload size and other constraints

Blue Origin's single-height payload box and flight computer create multiple design constraints which are discussed in this Section. Blue Origin has hired NanoRacks to serve as the payload integrator, making sure that each individual experiment meets requirements as well as avoids possible dangers, such as: the payload must have two layers of liquid containment, not pose any fire hazards, and not emit any signals that may interfere with other payloads or electronics. NanoRacks also makes sure that hazards to the liquid containment hardware, such as sharp edges that may cut into the plastic bag, which is the second containment for the liquid in the experiment, the first being the syringes and tubing, are avoided.

Figure 3.2 and Figure 3.3 below show the payload dimensional constraints from the Blue Origin New Shepard Payload User's Guide (*New Shepard Payload User's Guide*, 2017). Figure 3.4 and Table 3.1 shows the center of mass constraints. The center of mass constraints is different depending on what location the payload is in the payload stack. At the time of writing this, the author has not been made aware of the payload location in the payload stack. The internal dimensional of the Blue Origin single-height payload box are 9:56 x 16.30 x 20.60 in.

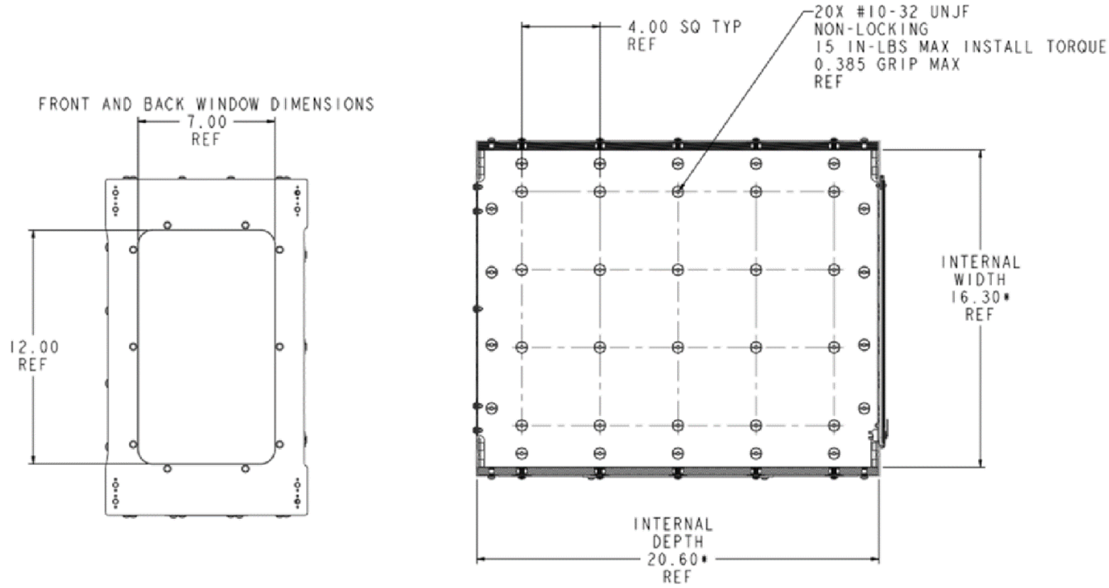


Figure 3.2: "Back Window Dimensions and Bolt Pattern of Single Payload Locker" (Blue Origin Payload User's Guide, page 28)

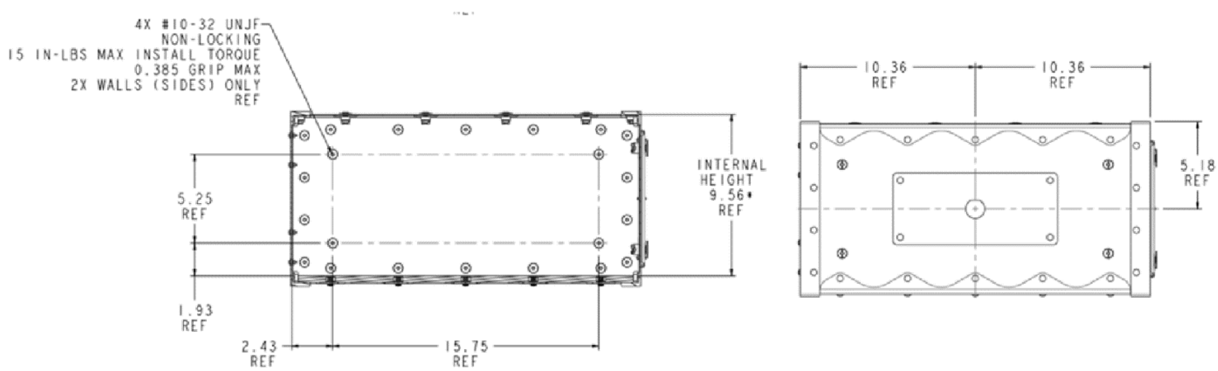


Figure 3.3: "Interior Left Panel View for Single Left-Sided Payload Locker" (Blue Origin Payload User's Guide, page 28)

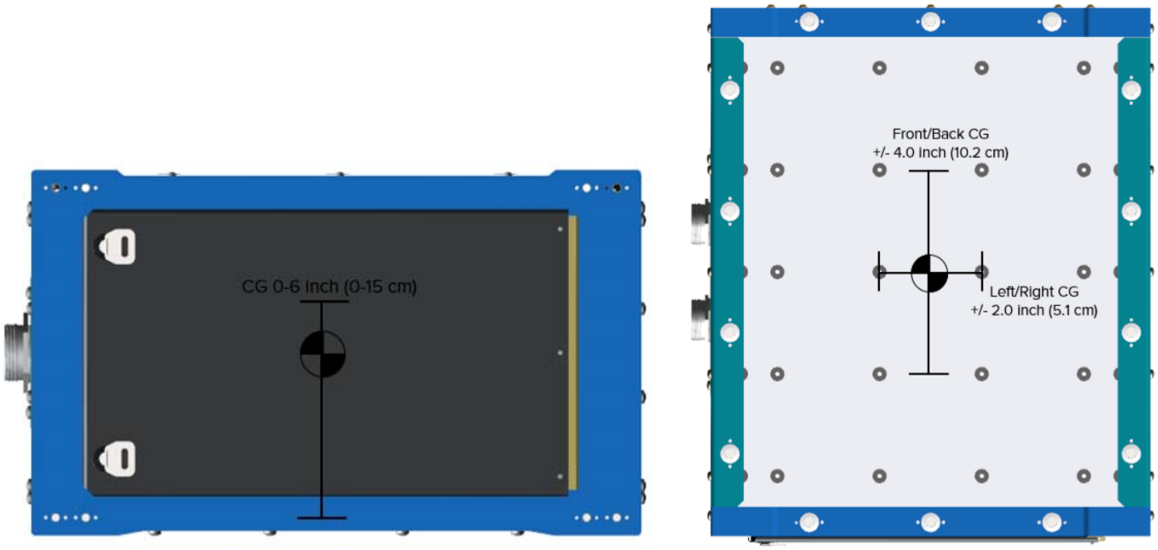


Figure 3.4: Center of mass allowable offsets (Blue Origin Payload User's Guide, page 23)

Table 3.1: Payload locker center of gravity relative to its center of mass (Blue Origin Payload User's Guide, page 23)

Location in Payload Stack	Vertical Direction [in]	Radial Direction [in]
Top two Payload Lockers	15.1	46.2
Middle two Payload Lockers	4.8	46.2
Bottom two Payload Lockers	5.6	46.2

3.3 Interfacing: Payload Interface (Power, Signals, Etc.)

There are six different interface signals for the flight computer: analog inputs, digital I/O, PWM output, RS-232, Ethernet, and RTD. This experiment is to be run using our own dedicated Arduino Mega 2560 which interfaces with all the electronics inside of the payload, except for the two Go-Pro video cameras provided by Blue Origin. Using the digital output channels from the flight computer, when the weightlessness portion of the flight begins, Blue Origin's flight computer will send a digital output signal to ConDENSS's Arduino Mega, which will then start the experiment. The Go-Pro cameras will be controlled directly from the Blue Origin flight computer, turning on before launch and after landing as is standard for the New Shepard flight.

Power options provided by the rocket for use by the payload include four 26+/- 4VDC circuits of up to 2 Amps each. Figure below shows the electrical schematic for the experiment, excluding the two Go-Pro cameras from Blue Origin. ConDENSS uses two of the DC power circuits and one digital out (out from the rocket, in to the experiment) circuit.

3.4 Injection System Sizing

To avoid geysering when liquid is injected into the test sections in zero-g, the Weber number of the flow exiting the injection hole must be less than 1.2 (Collicott and Kennedy, 2017). For this study, the Weber number is set equal to 1.0 and the volumetric flow rate is set to 1 $\frac{cm^3}{s}$ to solve for the radius of the injection hole for the test section. The radius of the injection hole is solved for by rewriting the weber number Equation (1) to the velocity at the injection hole. The velocity at the injection hole is then written as Equation (2).

$$w_e = \frac{\rho * {v_2}^2 * R_i}{\sigma} \tag{1}$$

$$v_2 = \sqrt{\frac{\sigma}{\rho R_i}} \tag{2}$$

Rewriting the area at the injection hole variable A_2 in the constant volumetric flow rate Equation (3) leads to volumetric flow rate in terms of the injection hole radius and the velocity at the injection hole, Equation (4).

$$Q = A_1 v_1 = A_2 v_2 \tag{3}$$

$$Q = \pi * R_i^2 * \; v_2 \tag{4}$$

Plugging in the velocity Equation (2) into the volumetric flow rate Equation (4) forms Equation (5), an Equation in terms of volumetric flow rate and injection hole radius.

$$Q = \pi * R^2 * \sqrt{\frac{\sigma}{\rho R_i}} \tag{5}$$

Setting volumetric flow rate equal to 1 $\frac{cm^3}{s}$, and rearranging of Equation 5, gives an Equation (6) for the radius of the injection hole.

$$R_i = \left(\frac{\rho}{\pi^2 \sigma}\right)^{\frac{1}{3}} \tag{7}$$

Table 3.2 shows all the values used while solving for the radius of the injection hole, which cumulate into Equation (6), and an injection hole radius of 1.376 mm. To achieve the volumetric flow rate of 1 $\frac{cm^3}{s}$, Welco WPM Peristaltic Pumps are used with a 12VDC compact motor, three rollers, and 3 mm tubing. With the 3 mm tubing and 10VDC supplied to the motor, the desired flow rate is achieved ("WPM DC Brush Motor and Gear," n.d.).

Table 3.2: All the values used to solve for the radius of the injection hole.

	Value
Webber Number w_e	1.0
Surface Tension $\sigma\left[\frac{dyne}{cm}\right]$	35.0
Density $\rho\left[\frac{g}{cm^3}\right]$	0.9
Flow rate $Q\left[\frac{cm^3}{s}\right]$	1.0

3.5 Test sections

Test sections are elliptical cones, for reasons discussed above in Section 3.1, and two types of elliptical cones are used: test sections with 1.1 and 1.5 aspect ratios for the elliptical cross Sections. Eccentricity is the more common measure of ellipses but aspect ratio, that is, the ratio of major to minor axis lengths, is simpler here for both modeling and manufacturing. Both test sections have major axis cone angles of six degrees, see Figure 3.5 and Figure 3.6. The injection hole of each test section is an axial distance away from the small end of the test section that is equal to about 20% of the semimajor axis.

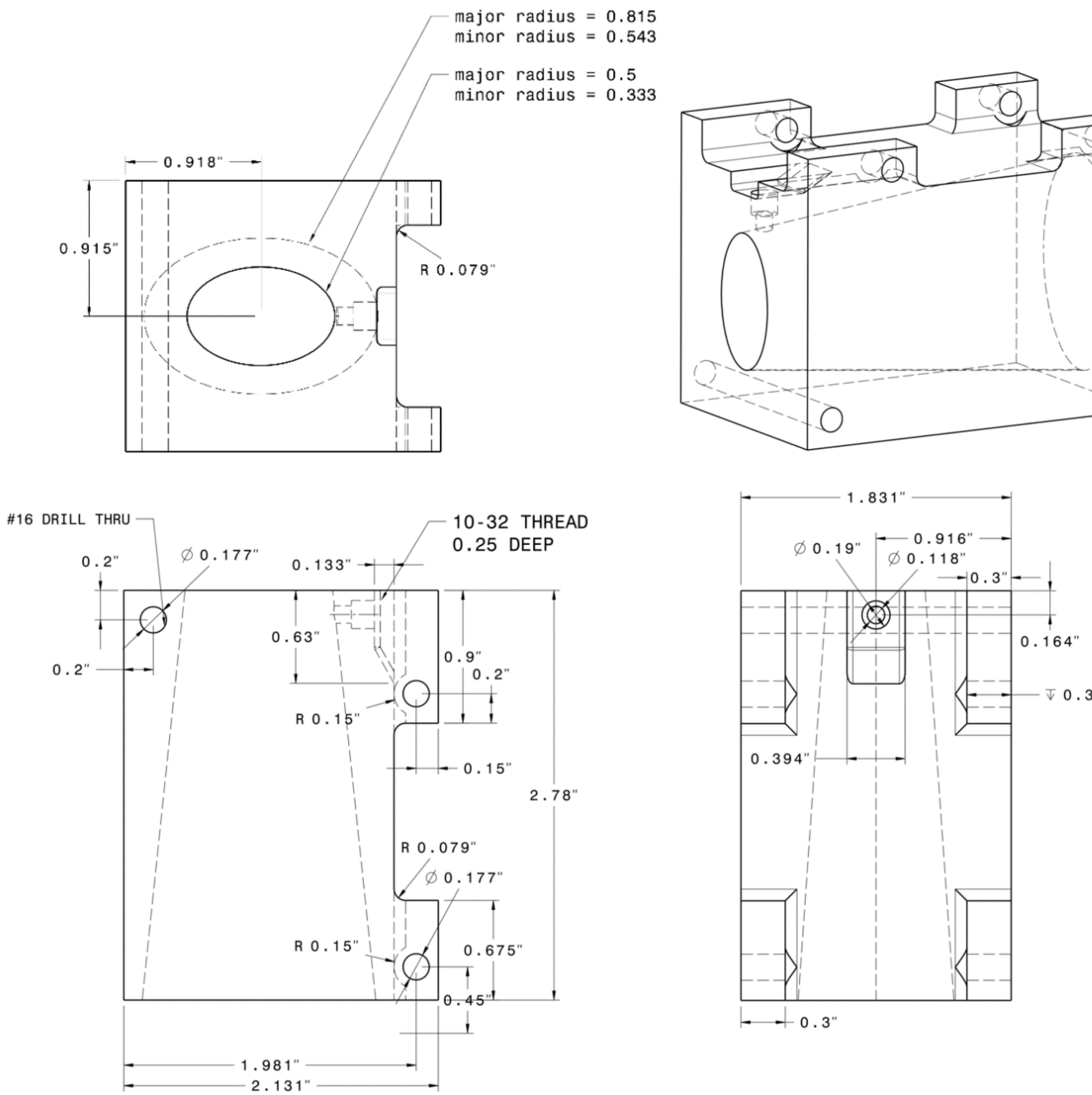


Figure 3.5: 1.5 aspect ratio test section, technical drawing, dimensions in inches.

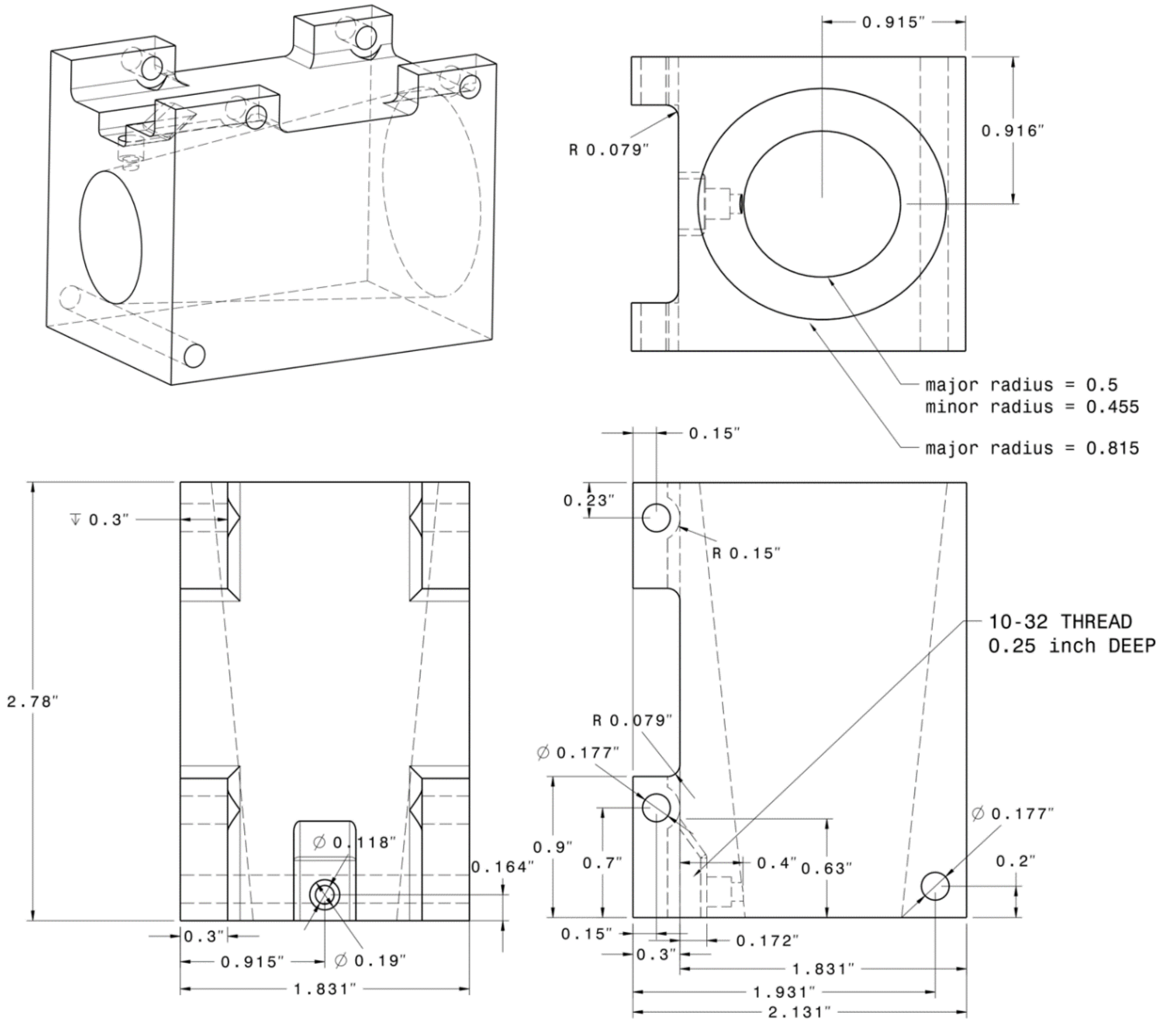


Figure 3.6: 1.1 aspect ratio test section, technical drawing, dimensions in inches.

The two aspect ratios of test sections are used to show the effect of eccentricity on the static steady state shapes of the liquid used in the experiment. Both halves of the experiment, the flow test sections and the static test sections, have two 1.5 aspect ratio and 1.1 aspect ratio test sections. The redundancy is in place in the event of equipment failure, or strong perturbation effects from the peristaltic pumps, which may or may not affect the formation of sleeves inside the test section. Sleeves are the least likely shapes that an attempt will be made to form with the liquid, and the perturbations from the pumps are not measurable in preflight, but there will be some form of perturbations from the pumps.

3.6 Electronics

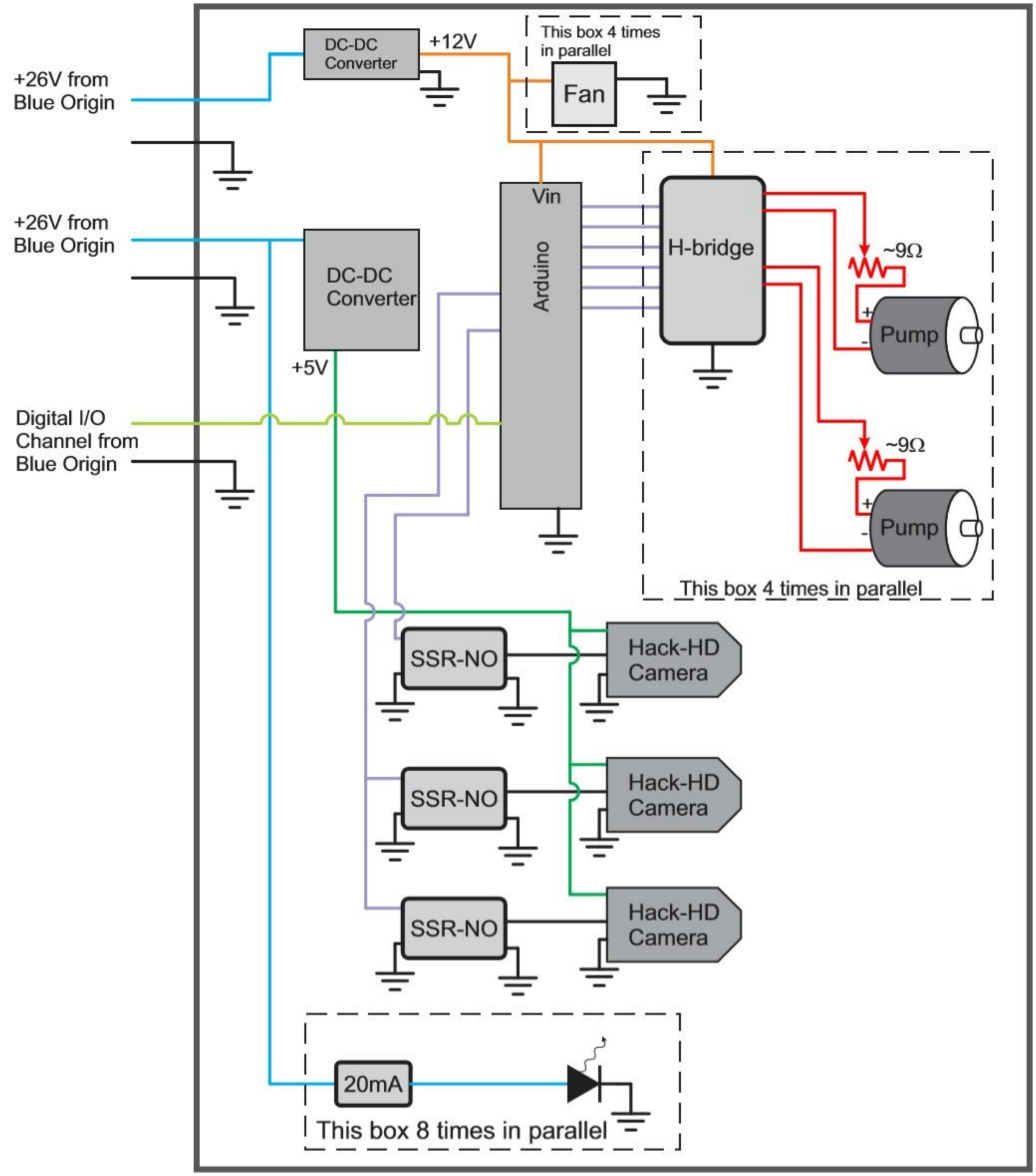


Figure 3.7: The electrical schematic for the experiment.

Table 3.3: Parts list for the schematic shown in Figure 3.7.

H-Bridge	DF Robot DR10041, 7 Amp dual DC motor driver
SSR	IXYS CPC-1709 single pole normally-open DC power relay
5V DC-DC Converter	Cui Inc., PYB20-Q24-S5-U
12V DC-DC Converter	Cui Inc., PQA50-D24-S12
Fan	Digi-key part 259-1571-ND, FAN AXIAL 25X10MM 12VDC WIRE
"20mA"	LED Supply, DynaOhm 20 mA in-line current regulator
LED	LED Supply, #L1-0-W5TH70-1, 5mm LED – Frosted White 70 Degree Viewing Angle
Pump	Welco, WPM1-S3CA, peristaltic pump, 12VDC motor
9Ω	Digikey #987-1623-ND, Trimmer pot, 3/4W, 20 Ohm

The electronics that control the pumps, LEDs, and Hack HD cameras use two of the four power supplies from the Blue Origin New Shepard rocket, see Figure 3.7. The 9Ω leading to the pumps are from a potentiometer with a trimmer knob allowing for adjustment in resistance. Section 5.1 explains that 10VDC powering the DC motor inside a peristaltic pump achieves a flowrate of $1.0\ \frac{cm^3}{s}$, but with the potentiometer used in this schematic, it is possible to adjust the flowrate by adjusting the resistance leading to the pump.

3.7 Camera Lens Selection

Blue Origin is supplying two Go-Pro HERO3 Silver Edition, modified with a back-bone ribcage mount (Blue Origin Payload User's Guide, page 31) for use in this experiment. These cameras have three ruggedized lens options that are available to us: 69, 49, and 36 degrees field of view. The experiment test sections will require three cameras to be used, so half of the test sections in the flow Section of the experiment will be viewed using one of the supplied Go-Pros, while all four no flow test sections will be observed using the remaining Go-Pro camera. The two Go-Pro cameras will view a combined three quarters of the test sections, and the remaining quarter will be observed using an entirely different camera not supplied by Blue Origin, a Hack HD camera.

To select the proper lenses, the required angular field of views were selected by calculating minimum object distance needed to see the flow and no flow test sections. The minimum object distance is the height of the triangle on the right in Figure 3.8 below. It is important to note that the angular field of view provided by the lens manufacturer is not from either side of the rectangular field of view area, but instead on the diagonal of a rectangular field of view area.

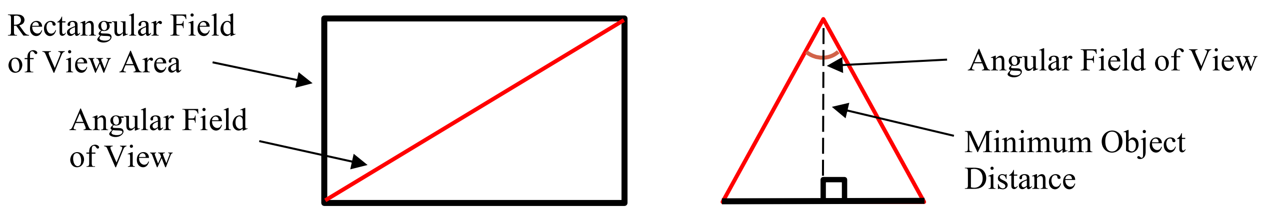


Figure 3.8: The Rectangular and Angular Feld of Views, as well as the minimum object distance.

With the distance inside of the payload away from the flow and no flow test sections, it was decided that one Go-Pro with a 49-degree lens will be used for observing the flow Section and one Go-Pro with a 69-degree lens will be used for observing the no-flow test sections. The Hack-HD camera will be placed 3.75 inches away from the remaining flow test sections. This distance for each lens was determined through table top testing and the results are displayed in Table 3.4.

Table 3.4: Minimum Focal Lengths for Go-Pros given desired observable space

Desired Rectangular Field of Views [in^2]	Angular Field of View [Degrees]	Minimum Object Distance [in]
Flow Test section [4x3 in]	69, 49, 36	3.64, 5.49 ,7.69
No Flow Test section [4x7 in]	69, 49, 36	5.87, 8.85, 12.41

CHAPTER 4. EXPERIMENT FABRICATION

4.1 Test sections

The test sections were machined on a five axis CNC mill from clear cast acrylic. Acrylic was chosen because it polishes up very well, to a state that looks clear enough to film liquid behaver inside each test section from a distance away from each test section. The machining process must be done on a five axis CNC mill because of the elliptical cone interior shape. The milling process does, however, make all machined surfaces look cloudy, which is why the polishing process is important. Polishing is done in a four-step process: using 1200 grit waterproof sandpaper followed by three-stages of different rubbing polishing solutions and cloth for rubbing them on each test section. The Novus polishing solutions used are shown in the Figure 4.1.

Figure 4.1: Stage 1-3 of the Novus brand polishing solutions used on the acrylic test sections.

4.2 Test section Back Plates

The experiment inside of the experiment box is not exposed to any light, because of that reason the experiment uses LEDs to illuminate each test section. Each test section has an acrylic back plate flanking it on the side opposite from the side viewed by the cameras. These acrylic back plates are made cloudy using a bead blaster. In this state they disperse the light coming through them from the LEDs, providing a more uniform illumination. The acrylic back plates are cut using a laser cutter at Purdue's Bechtel Innovation and Design Center and then bead blasted for their cloudy look, see Figure 4.2.

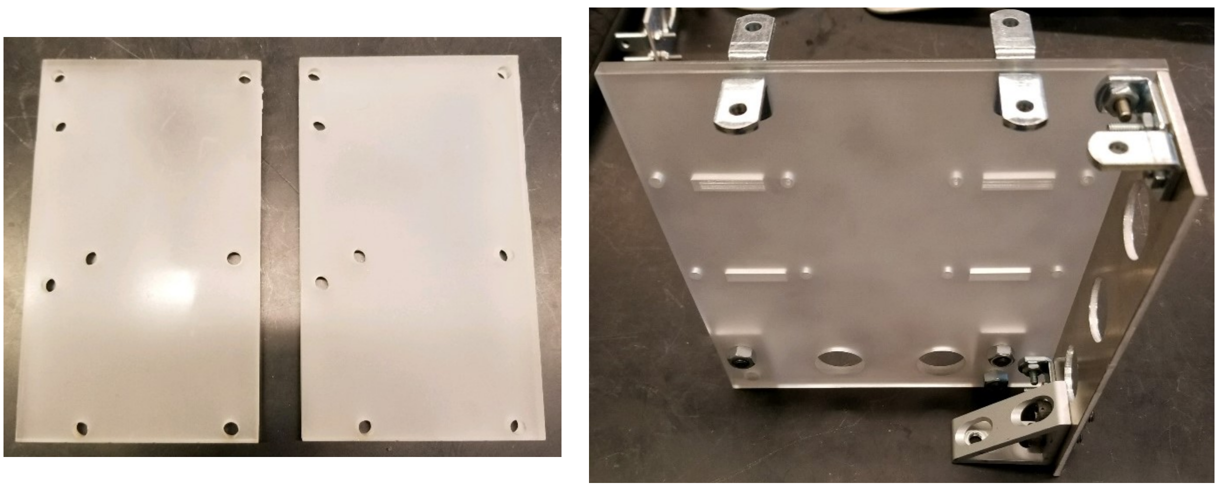


Figure 4.2: The Flow Section Back Plates (Left), and the No Flow Back Plate (right), which are about 3 in x 5 in, and 7 in x 9 in respectively.

4.3 Wind Tunnels

The experiment has four test sections sitting in small wind tunnels to simulate conditions inside a condenser. These four wind tunnels are part of what is called the flow test sections in this experiment. Where the static test sections collect data of static fluid equilibrium states, the flow test sections collect data of liquid which will, at some conditions, be moving from the air flow pushing it through the test section. Surface Evolver is only good for modeling static fluid equilibrium states, meaning that modeling fluid in a condenser loop, with an air speed fast enough to move a droplet, is not possible in Surface Evolver. Additionally, it is unlikely that any current CFD package can model the stick-slip behavior of a finite contact angle liquid droplet in an air stream in weightlessness. The goal of the flow test sections is to collect footage of fluid in a kinematic state in microgravity. The data will be used to try and understand kinematic fluid equilibrium states.

Each wind tunnel is split up into four parts: two bottom halves and two top halves, as shown in Figure 4.3. Each quarter of the wind tunnel is 3D printed using black Polylactic Acid (PLA), with a three-millimeter thick shell and a fifty percent fill ratio. The wind tunnels are 3D printed, because with the fins inside the tunnels being as small as they are, and the overall complexity of the shapes, rapid prototyping was necessary because CNC machining would have been expensive and would not permit inexpensive iteration of designs. The wind tunnels are printed in black, so any light sources used in the experiment will not reflect strongly off the wind tunnel surfaces and pollute the video data. Each wind tunnel uses a brushless DC computer cooling fan to move the air through each tunnel. Each wind tunnel achieves an air flow rate of 3.5 CFM, a flow rate which correlates to the flow found necessary to move droplets in table top testing.

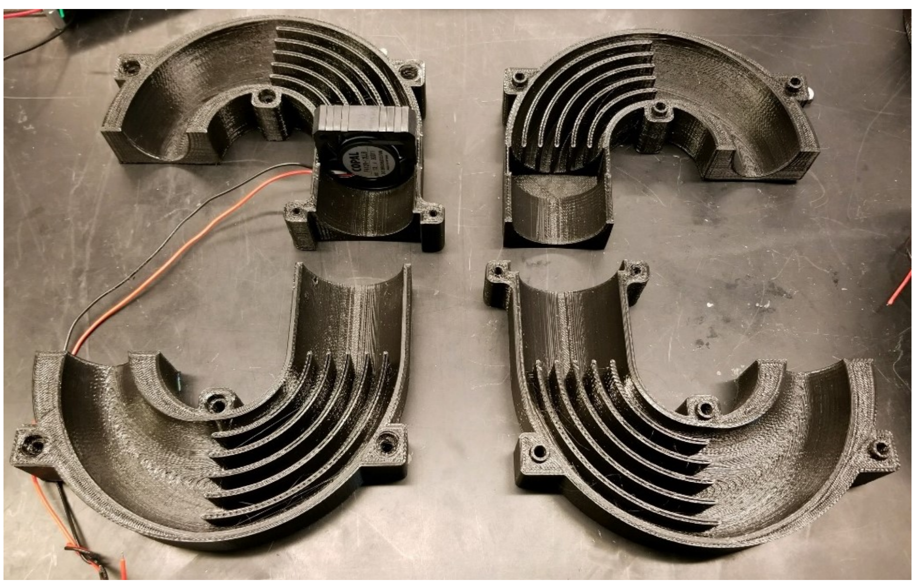


Figure 4.3: Wind tunnel split into its four parts and its fan sitting in its cradle. Each part fits within about a 4 in x 4 in square.

4.4 Liquid System

The first and second containment, mentioned in Section 3.2, are discussed and displayed for reference in this Section. The first containment includes all syringes, valves, test sections, tubing, tubing fixtures, and wind tunnels, which are shown in Figure 4.5 through Figure 4.13. Second containment is a plastic bag wrapping around the experiment and inside of the payload box, and in-between the legs and the base plate, seen in Figure 4.4. All the electronics shown in Section 3.6, Figure 3.7, are located outside of the plastic bag, accept the cameras, LEDs, fans, and pumps. The electronics outside of the plastic bag are mounted to the payload box by poking the mounting screws through the plastic bag. The electrical connections to the cameras, pumps, fans, and LEDs in Figure 3.7, from Section 3.6, are made by pushing male connecter pins through the bag from the inside to meet with female connecter pins located outside of the bag. At the time of writing this, these connecter pins have not been selected for purchase. The tube in Figure 4.8 uses the compressability of the air inside the tube to dampen the ocilations in the flow rate which occer from the rollers in the peristaltic pumps. There is one such apperatice attached to each end of the peristaltic pump, see Figure 4.9.

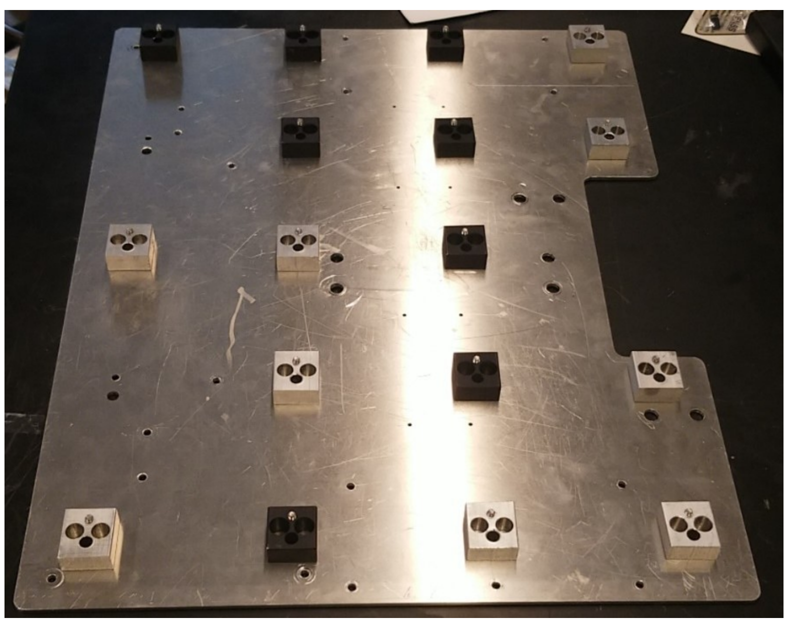


Figure 4.4: The bottom side of the base plate with the feet attached. The plastic bag for the second containment will be between these feet and the base plate. The base plate is about 16 in x 20 in.

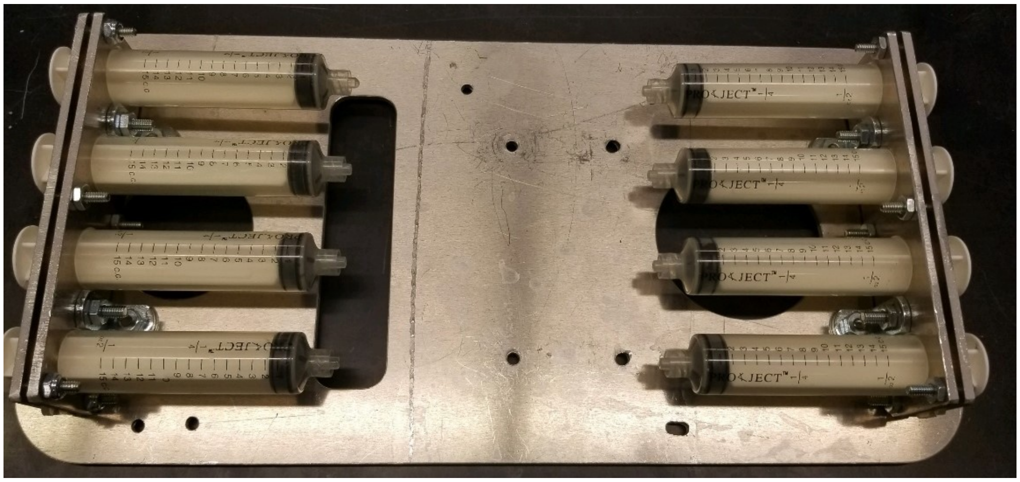


Figure 4.5: Liquid for injection is held inside eight 15 mL syringes, which are mounted to the syringe mounting plate. The plate is about 5 in x 12 in.

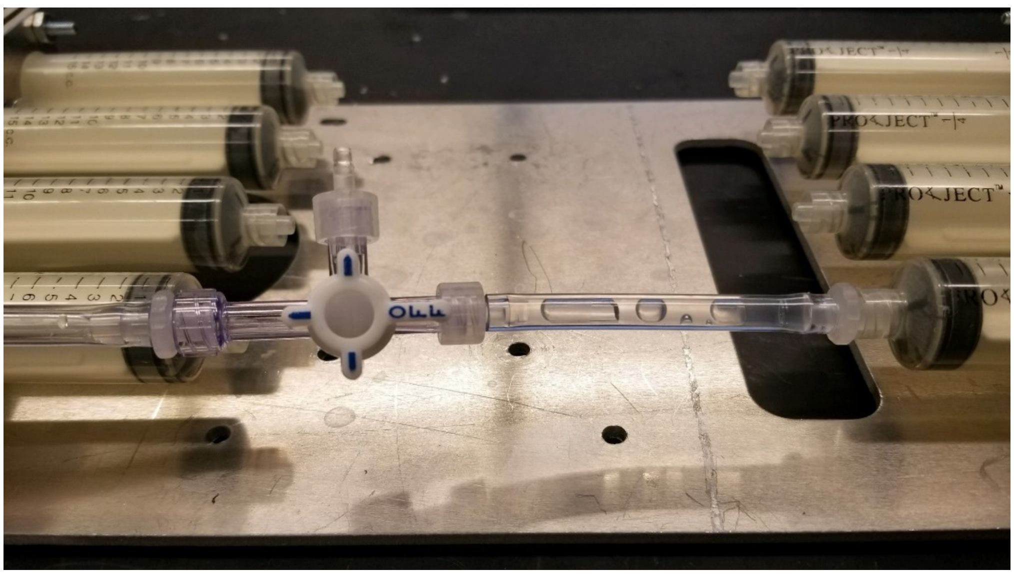


Figure 4.6: All eight syringes have a three-way valve, and 3 mm diameter tubing, which connect them to the test sections, shown here attached to a syringe.

Figure 4.7: The three-way valve, and 3 mm diameter tubing, which connect the syringes to the test sections. Tubing leading to the pumps is not shown.

Figure 4.8: 3 mm tubing with a stopper on the end, used to dampen the perturbations produced by the rollers in the peristaltic pump.

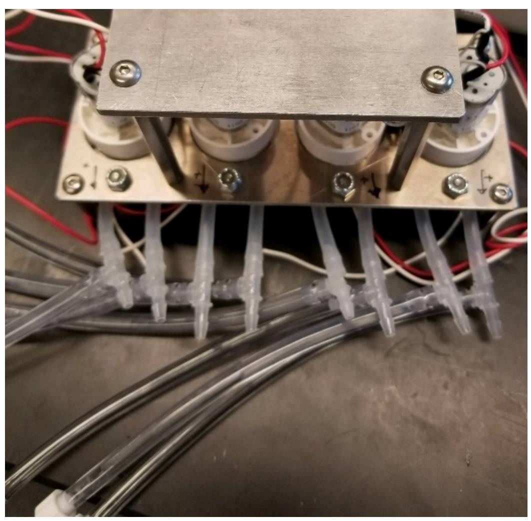


Figure 4.9: One of the pump assemblies with the damping tube, from Figure 4.8, attached to each end.

Figure 4.10: 14-inch long. 3 mm diameter tubing, connecting the pumps to the test sections.

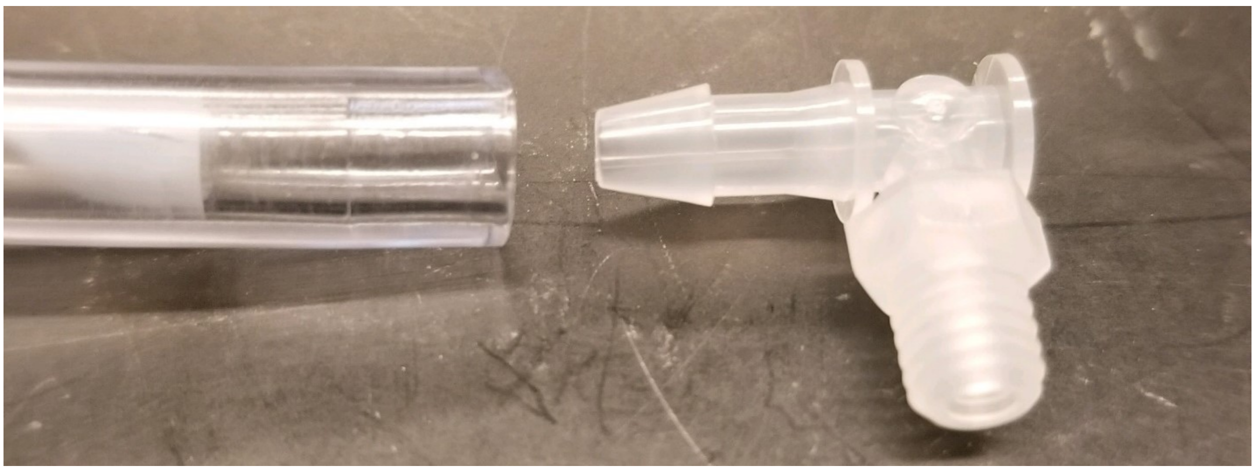


Figure 4.11: The tubing and the 10-32 UNF threaded connecter that thread into the injection hole in the test section.

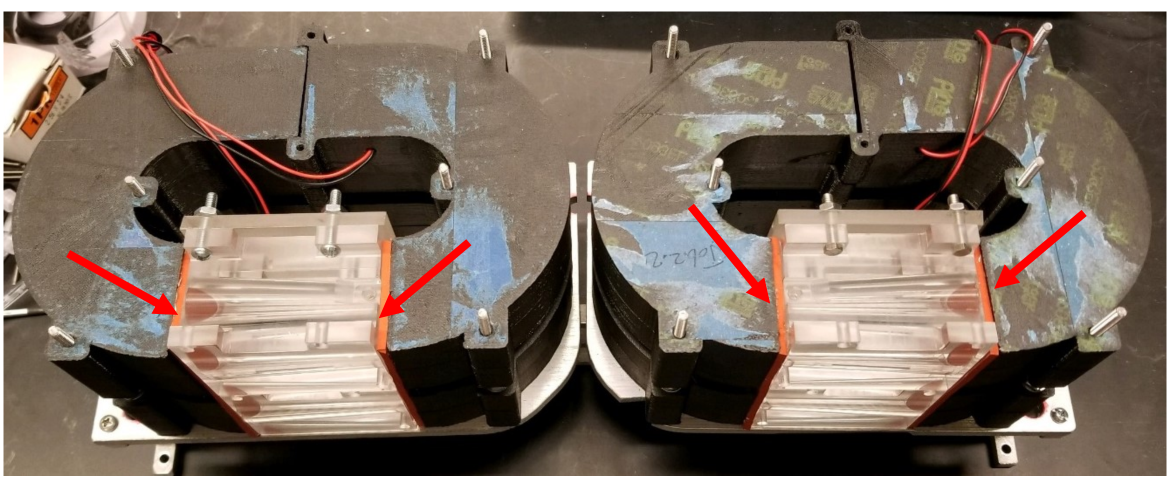


Figure 4.12: The orange gaskets prevent liquid from leaking from the wind tunnels, shown with red arrows.

For the no flow test sections, because the space is so small, there is a concern that the buildup of pressure, by injecting liquid into a sealed space, may cause problems. To avoid any issues, a tube leads from the end caps to empty syringes. The empty syringes can then expand or contract to accommodate change in pressure while injecting and retracting liquid into the no flow test sections. This setup is shown in Figure 4.13. The volume is large enough in the wind tunnels that a buildup of pressure in the flow test sections a less concern than the buildup of pressure in the no flow test sections, therefore there are no relief syringes for the wind tunnel and test section sealed space.

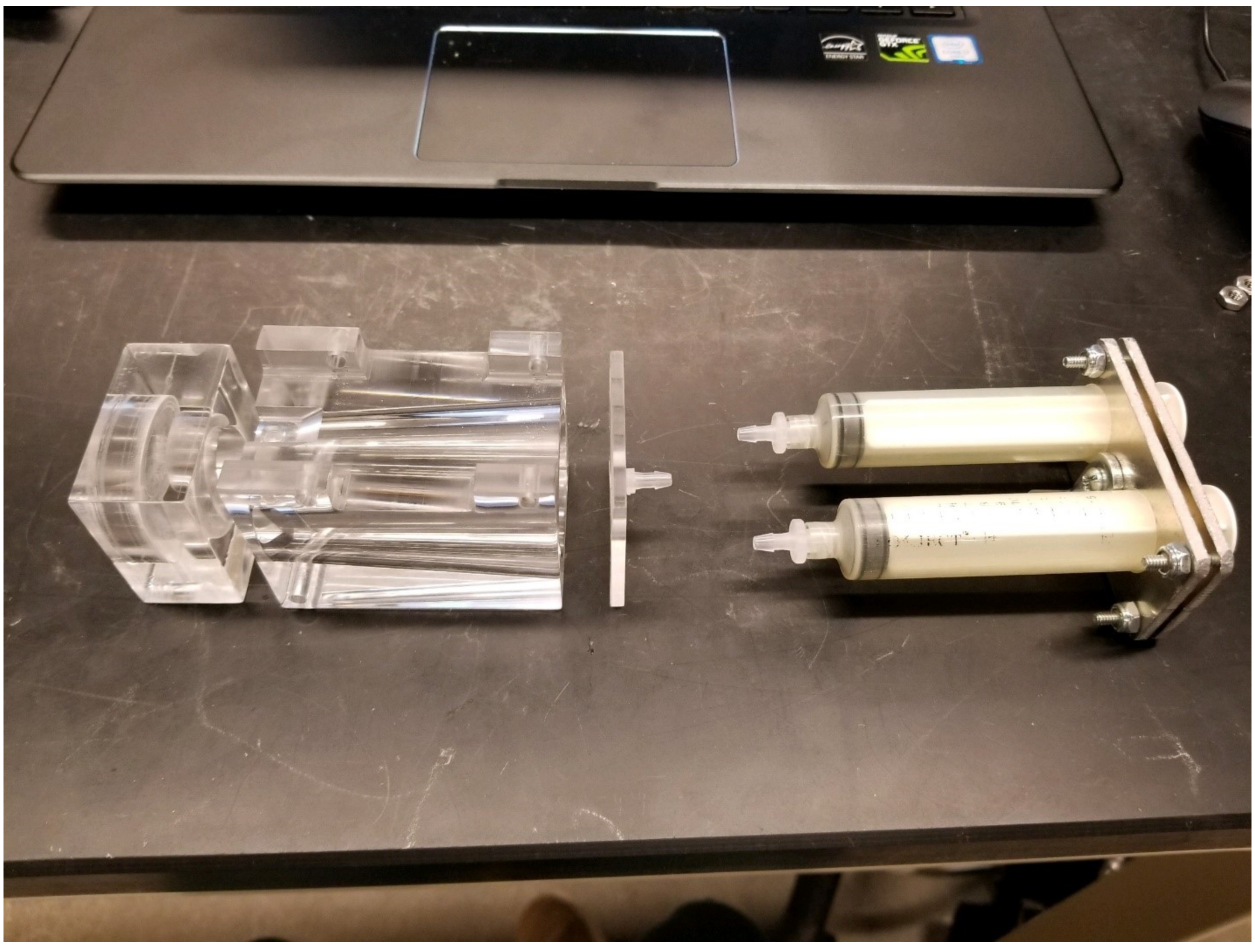


Figure 4.13: From left to right, the no flow middle end cap, no flow test section, no flow side end cap, and relief syringes. End caps are attached with ceramic adhesive before launch.

4.5 The Whole Package, to Drop into Top of Blue Origin Box

Major sub-assemblies, and where they are located on the base plate, are discussed here, for packaging inside the Blue Origin payload box. The base plate sub-assembly, shown in Figure 4.14 and Figure 4.15, consists of the base plate used for mounting components to, and the feet which raise the base plate 0.5 inches off of the bottom of the payload box as well as provide guides for mounting the experiment to the payload box screw holes.

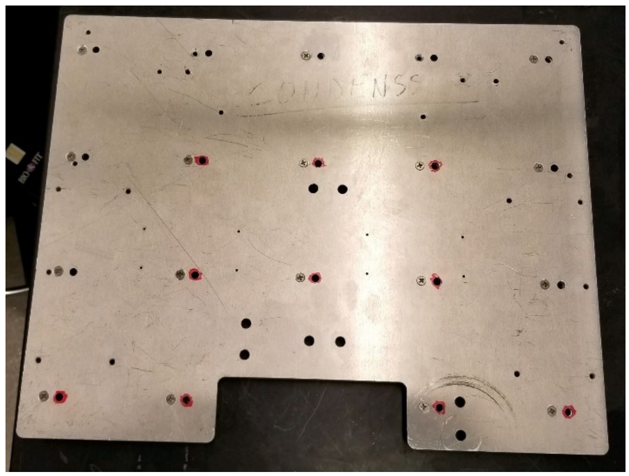


Figure 4.14: The base plate used for mounting components to the inside of the payload box.

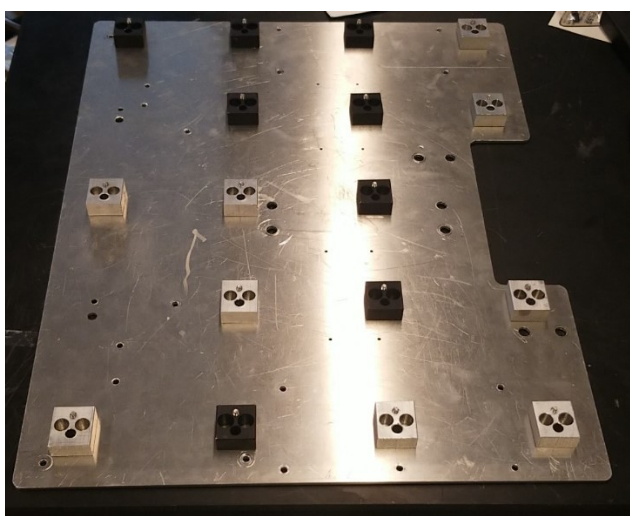


Figure 4.15: The base plate underside with mounting feet attached to it.

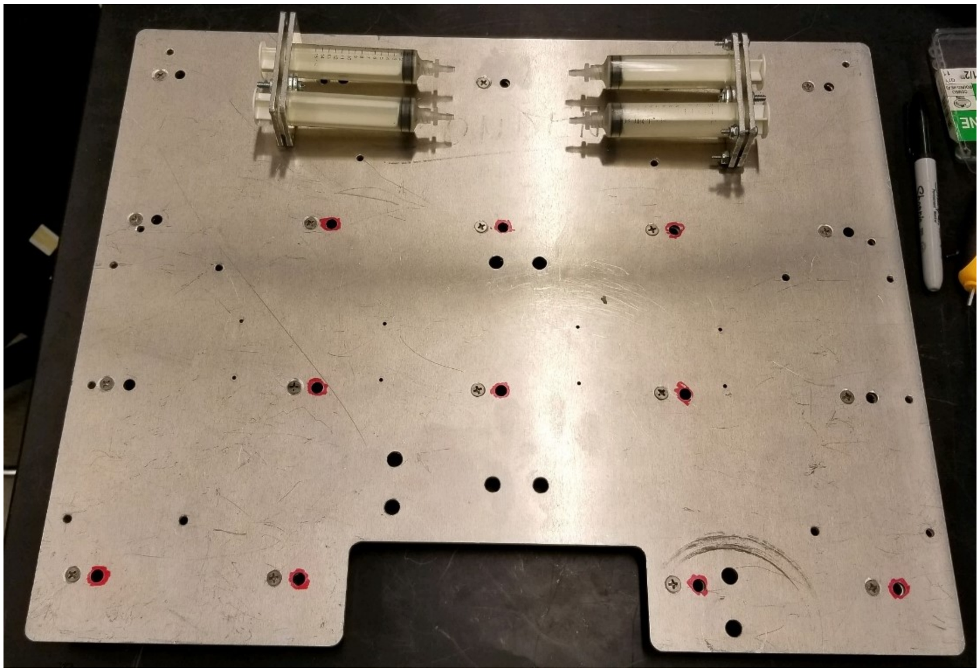


Figure 4.16: Relief syringes positioned on the base plate.

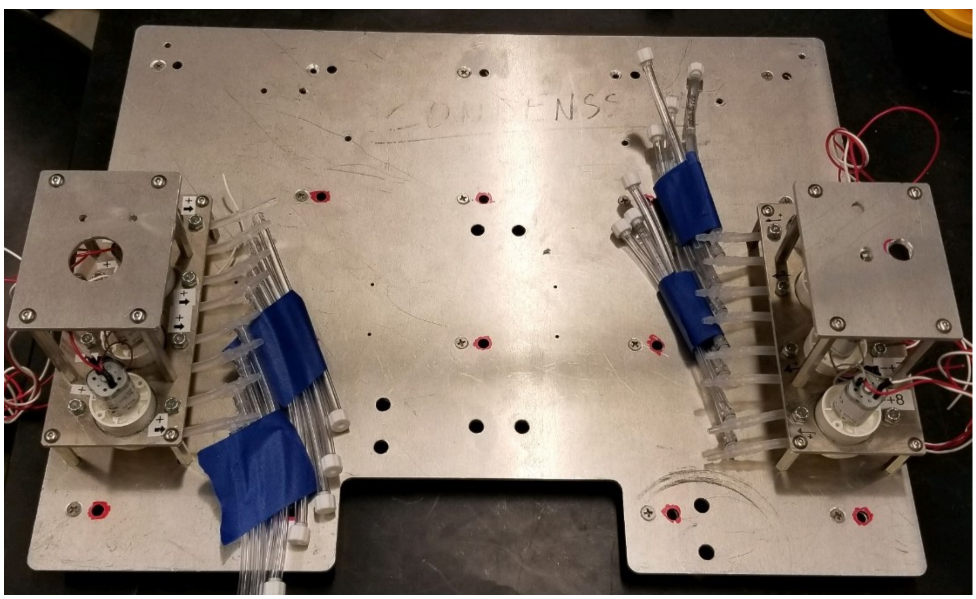


Figure 4.17: Pump assemblies positioned on the base plate.

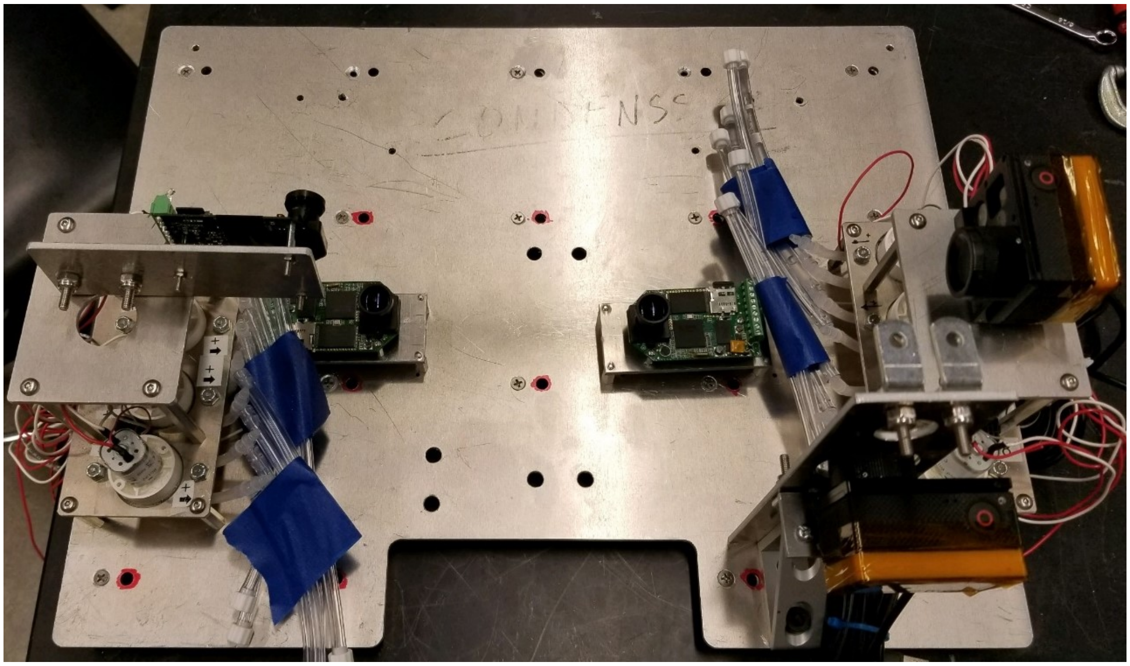


Figure 4.18: Pump assemblies positioned on the base plate.

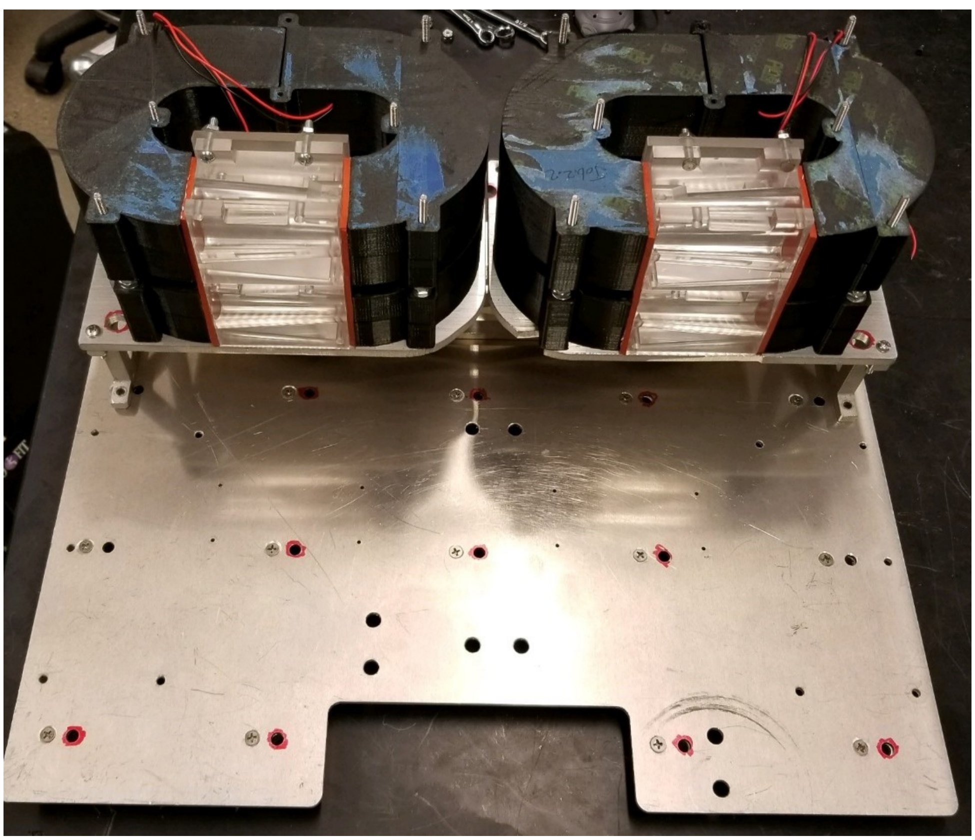


Figure 4.19: Flow test section assembly positioned on the base plate.

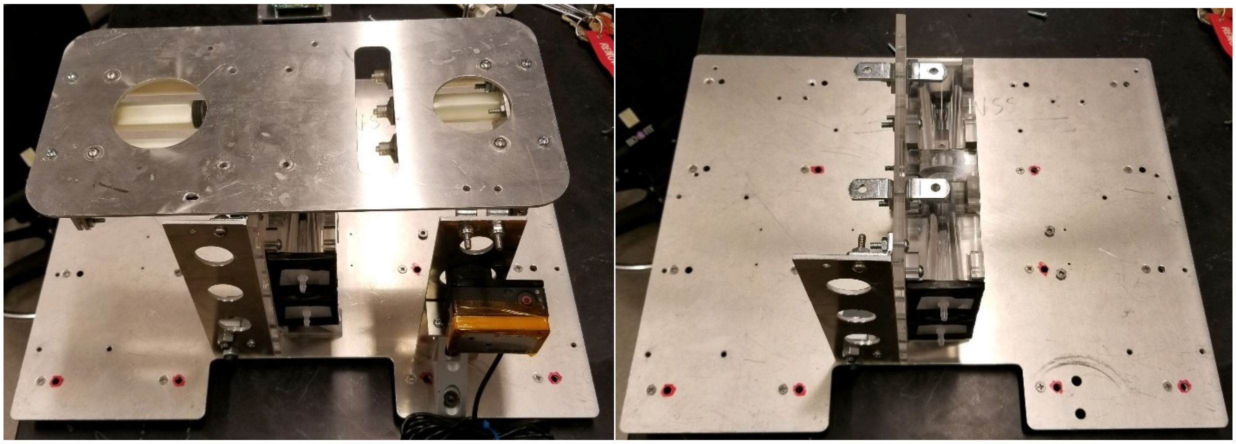


Figure 4.20: No flow test section assembly positioned on the base plate, with and without the syringe mounts.

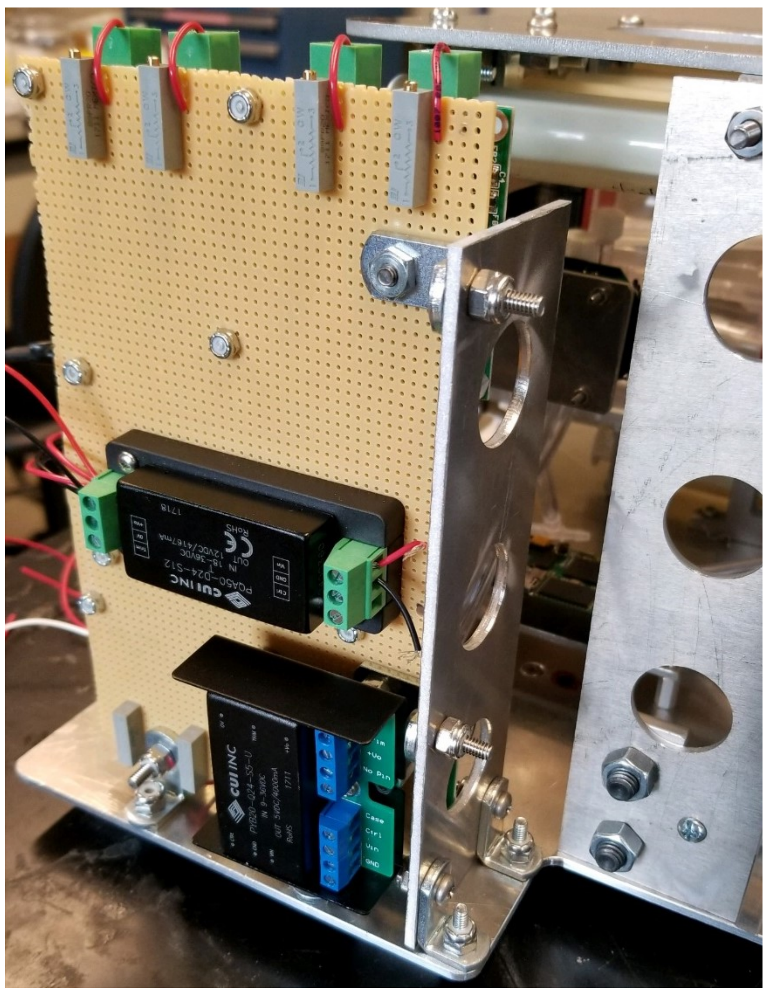


Figure 4.21: No flow test section assembly positioned on the base plate

CHAPTER 5. TESTING AND PREPARATION

5.1 Pre- Launch Operations: Fill Procedures

These fill procedures are for filling the syringes and tubes discussed in Section 4.4. The purpose of the filling process is to prepare the liquid system for flight. Figure 5.1 will be used repeatedly in this step by step process, depicting the path liquid takes between the syringe and the test sections. The blue boxes represent entities which should remain separated until specified in the directions. The fill procedures below are listed chronologically, and the figures are not to scale.

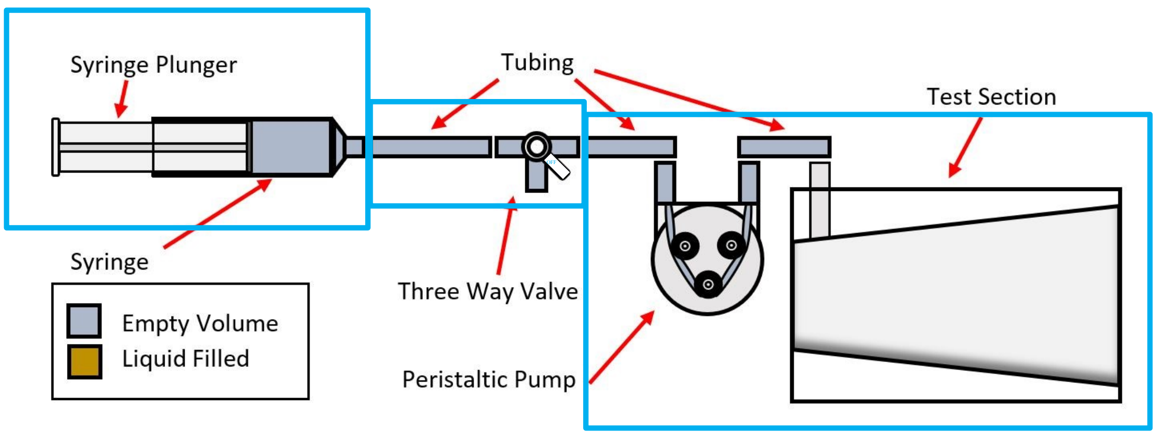


Figure 5.1: Empty liquid Injection System, with blue boxes representing separated entities at the start of the fill procedure, which will be attached during the filling process.

1. Using the liquid filling container, marked with the "ConDENSS" label, see Figure 5.2, fill each of the eight syringes with liquid. The filling container is just the right size to fit around the syringes without having to remove any of the syringes from the syringe plate. Holding the plate and container vertically, slide the syringe into the liquid inside the filling container, and draw liquid into the syringe until the syringe has been filled to 15 mL. Repeat this process for all eight syringes but be careful not to push the plungers into the syringe while the tubing is disconnected. Lay the syringe plate horizontal on a table, before moving onto the next step.

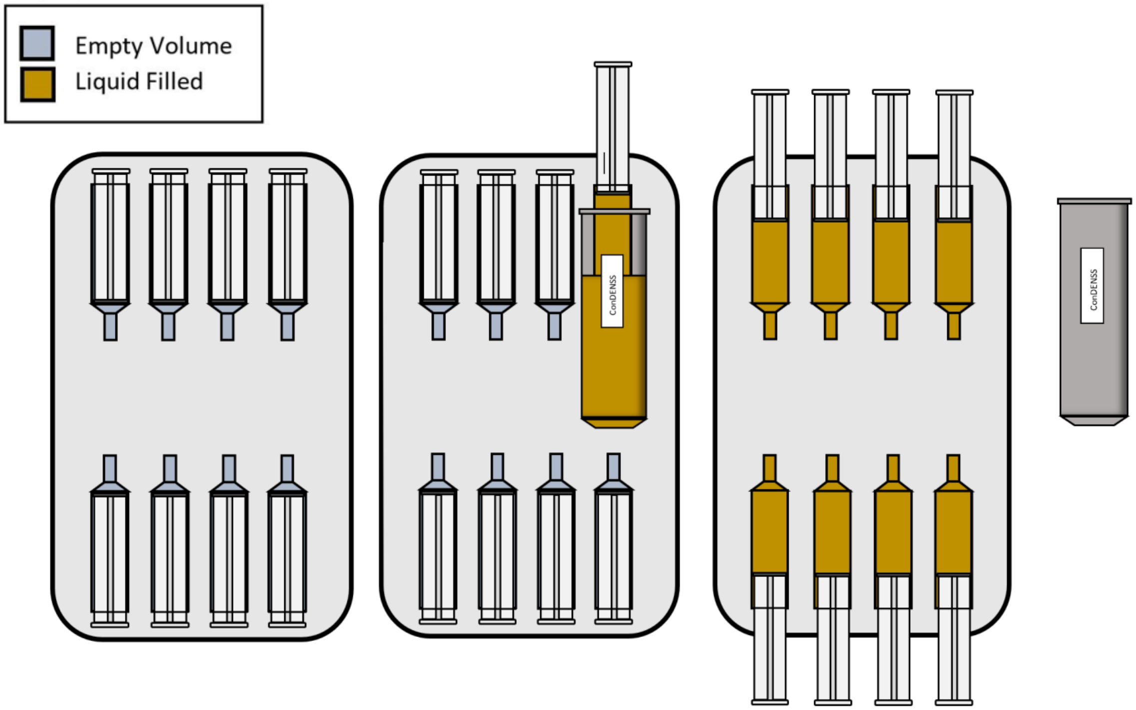


Figure 5.2: From left to right: syringes empty, syringes being filled using liquid filling container, all eight syringes filled with liquid, and the syringe filling container

2. Attach the tubing leading from the three-way valve to the syringe, with the valve closed facing towards the syringe. The syringe is now attached to the valve via tubing, but the valve is not attached to the tubing leading to the pump, and the liquid is not inside the tubing yet, see Figure 5.3.

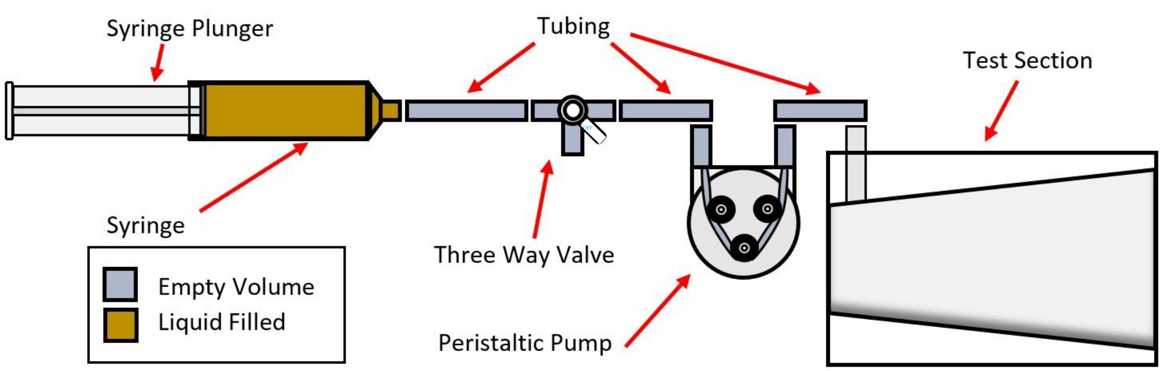


Figure 5.3: Liquid Injection System as depicted in step 2.

3. With the valve closed facing toward the pump, inject liquid, using the syringe plunger until the liquid reaches the three-way valve and ejects. Turn the valve facing towards the syringe as soon as liquid ejects from the valve. The objective is to fill the tubing between the syringe and the valve without creating an air bubble inside of the tubing or valve, see Figure 5.4.

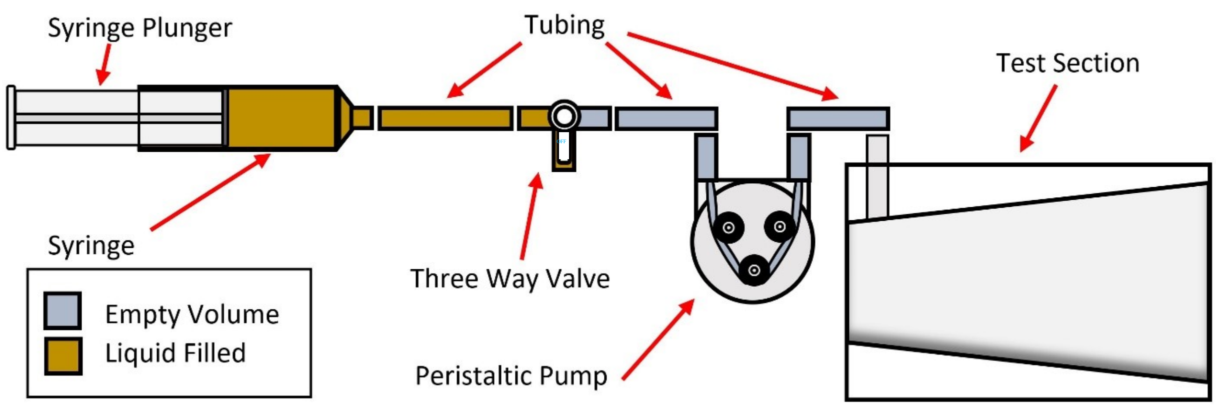


Figure 5.4: Liquid Injection System as depicted in step 3.

4. The liquid should be trapped between the syringe plunger and the three-way valve. Mount the syringe plate inside the payload using 8-32 screws and nylon nuts.

5. With the valve still shut off facing the syringe, attach the valve to the tube leading to the open end of the pump.

6. Using an external DC power supply, run the pumps in the direction marked in Figure 5.6 by the black arrow, that will pull liquid through the three-way valve towards the pump. Electrical pins where 10VDC should be applied to are shown and labeled in Figure 5.6. Attach a temporary 3mm tube, to the open end of the three-way valve. This tube should be 24 inches long and must be removed at the end of this step. Place the open end of the newly placed tube into the liquid syringe filling container. The liquid will be pulled into the valve. When the liquid starts to pass through the pump, shut off the DC power supply. Note that the rollers inside the pump act a closed valve between the three-way valve and the pump Section when the pump is not in operation, trapping the liquid and avoiding air bubbles.

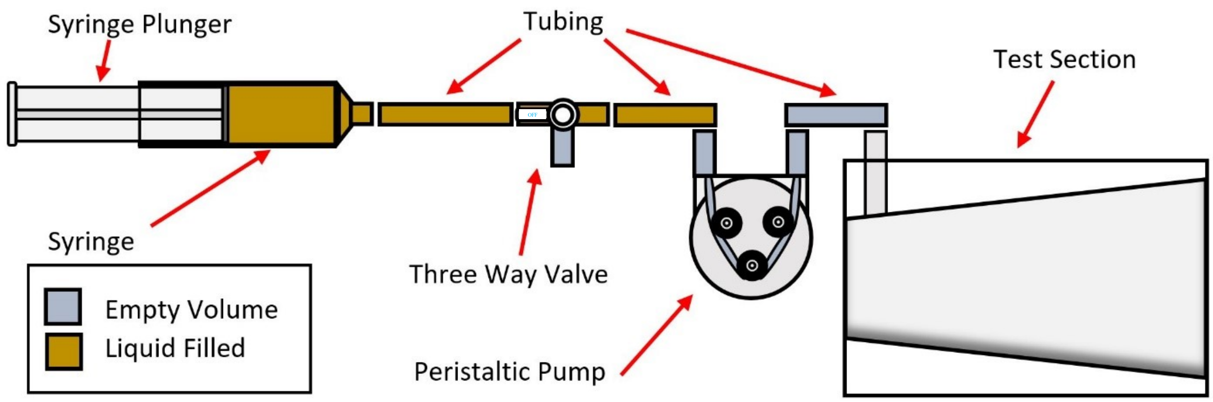


Figure 5.5: Liquid Injection System as depicted in step 6.

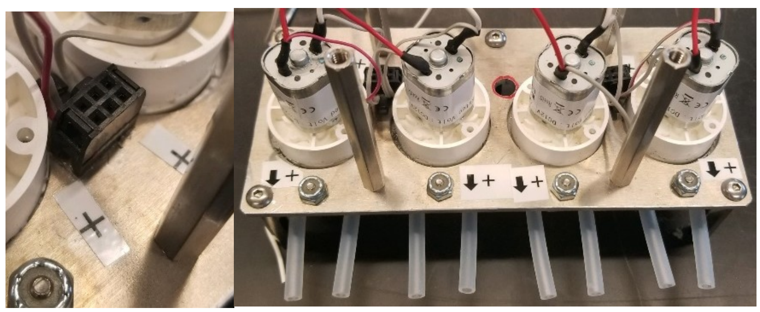


Figure 5.6: Positive electrical pins, and flow direction, marked for the pumps in step 6.

7. Open the valve between the tubing that leads from the syringe and to the pump. Secure the valve lever with electrical tape. There should be no liquid in the test sections before launch.

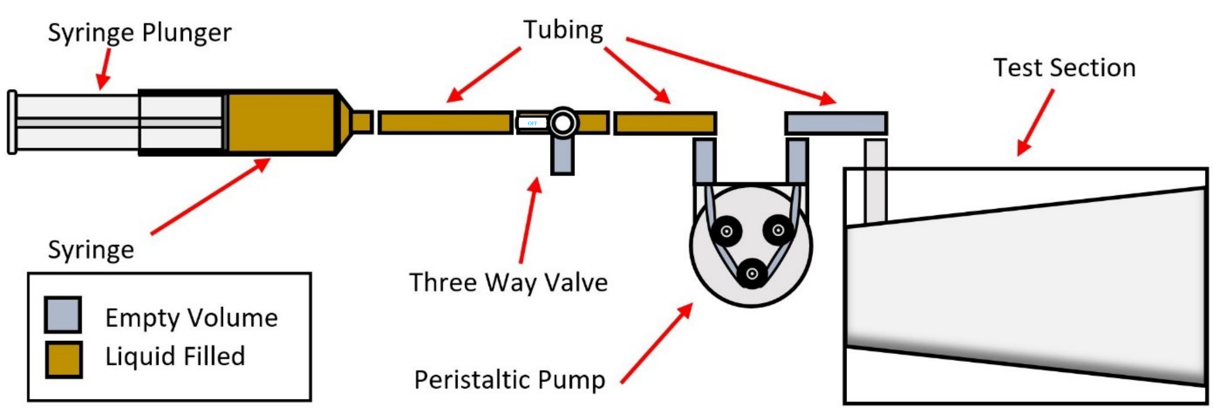


Figure 5.7: Liquid Injection System as depicted in step 7.

5.2 1-g Operations

With the fill procedures already done, see Section 5.1, trigger the start of the code running on the Arduino, that signifies the start of the microgravity portion of the flight, see Section 7.2 for details. The tubes that will run to the test sections for the actual flight, should instead be running to a bucket for 1-g operations. In addition to running the code on the Arduino to make sure that the mission code, the code that will run the Go Pros will also need to be tested. The Go Pros are operated by a signal from Blue Origin before launch and are turned off after landing by Blue Origin. For testing purposes, a mock flight computer is provided to the team which should be used to test the experiment and cameras in 1-g. Besides testing the electronics and fluid system in 1-g, fully assembling the payload and integrating the payload into the payload box also must be practiced before flight.

5.3 Vibration Testing

The experiment must be tested to assure that the experiment does not come apart during the rocket launch, during the inevitable violent shaking. The experiment will be tested long before launch on the TIRA shake table at Herrick Labs. The Blue Origin payload user's guide states that, "vibration testing should be done for 1 min in each of 3 axes" (*New Shepard Payload User's Guide*, 2017). Blue Origin's required vibration conditions, as of April 2018, are listed in Table 5.1. Vibration testing should be done after all nuts and bolts have been secured using steps discussed in Section 7.2.

Table 5.1: Blue Origin's suggested vibration conditions.

Frequency [Hz]	ASD [$\frac{g^2}{Hz}$]
20	0.0053
150	0.04
800	0.04
2000	0.0064

5.4 Post-launch Operations

When the payload box, with the experiment inside, is returned to the research team, begin post-launch operations by taking pictures and notes documenting the state of the experiment inside the payload box, before removing the experiment. Once any damage is documented, remove the experiment, cut the plastic bag off, and retrieve the micro SD cards from all three Hack HD cameras. Continue getting video footage by removing the Go-Pros and extract the video files via usb cable and a computer. Inspect the test sections for damage, and document with pictures and notes. Take necessary steps to clean the inside of the payload in the event of a leak. When removing the test sections, syringes, and tubing, for cleaning and shipping, use a towel placed inside the experiment to catch any liquid that will leak out during this process. Place all test sections back into the foam padded box for transport, see Figure 5.8, and repack the rest of the experiment for shipping. If the no flow test sections cannot be separated from the end caps they have been glued to, modify the foam transportation box so that they will fit by removing some of the foam cubes inside to make room.

Figure 5.8: Test section foam padded transportation box.

CHAPTER 6. COMPUTATIONAL MODELING

6.1 Surface Evolver Wetted Area Calculations

To calculate wetted surface area, the Surface Evolver code must be set up to calculate the length along the circumference the ellipse, of each edge representing the contact line, see Figure 6.1. This length, *ds* in Equation 3 and 4, is broken up into *x* and *y* components, *dx* and dy, calculated in Equations 3 and 4. With lines from the ends of *dx* and *dy* to the origin, *dx* and *dy* create long, slender triangles which Surface Evolver is programmed to compute the area of using constraint energy integrals. Thus, the wetted area is calculated by Surface Evolver by summing the triangle areas created by each edge on the contact line. To calculate the *dx* and *dy* values for each edge, the polar angle, Equation (1), with relation to the ellipse center, is used to calculate the parameter t, see Equation (2). The parameter *t* is then solved by rearranging the polar angle of an ellipse Equation (1) and is shown in Equation (2).

$$\theta = \tan^{-1}\left(\frac{y}{x}\right) = \tan^{-1}\left(\frac{b}{a}\tan t\right) \tag{1}$$

$$t = \tan^{-1}\left(\frac{y*a}{x*b}\right) \tag{2}$$

Parameter *t* is then used in the parameterization of the tangential vector of ellipse equations, *dx* and *dy* shown in Equations (3) and (4).

$$\frac{dx}{ds} = \frac{-a\sin t}{\sqrt{b^2cos^2t+a^2sin^2t}} \tag{3}$$

$$\frac{dy}{ds} = \frac{b\cos t}{\sqrt{b^2cos^2t+a^2sin^2t}} \tag{4}$$

The length to the origin from the tangential vector is calculated by calculating the distance between two points, the origin and the midpoint of edge, in Equation (5).

$$L = \sqrt{x^2 + y^2 + z^2} \tag{5}$$

The wetted area is calculated by adding the area of the triangles made from the tangential vectors of the ellipse to the origin, Equation (6).

$$dA_{wet} = \frac{1}{2}\left(\frac{dx}{ds} * dx + \frac{dy}{ds} * dy\right) * L \tag{6}$$

The direction of the edges gives the area positive or negative values, and by adding the wetted area segments, Surface Evolver totals the wetted surface area.

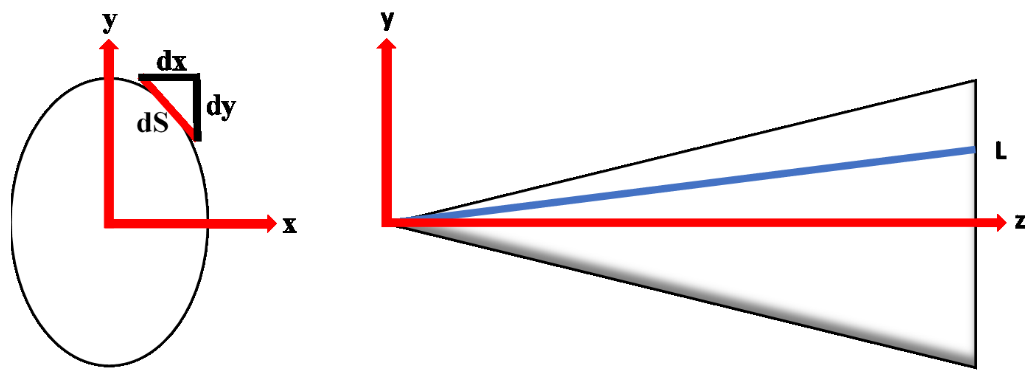


Figure 6.1: The differential segments of the segmented circumference of an ellipse and the length to an edge, L.

6.2 Surface Evolver File Validation

The author of the simulation must define how the Surface Evolver code will calculate wetted surface area, which is a key component of the energy equation, Equation (1). Free surface area of a liquid model is calculated by Surface Evolver automatically as the sum of the surface areas of all the triangular faces of the liquid-gas in the model. It is up to the user to set up the code to calculate the wetted surface area correctly. Thus, it is important that the user-defined wetted area formula be validated against analytical results.

$$\tilde{E} = \frac{E}{\sigma * R^2} = \tilde{A}_{FS} - \tilde{A}_{Wet} * \cos\theta \quad (1)$$

As mentioned, the test sections used in this experiment are elliptical cones. The Surface Evolver simulations use test sections made in three dimensional Cartesianspace, with the origin acting as the tip of the elliptical cone, see Figure 6.1. The *z* axis is the centerline of the cone, while the *x* and *y* axis form the major and minor semi axis of the ellipse of the test section, respectively. The gray face represents the initial geometry of the free surface of liquid filling the cone, located at the base of the cone, see figures Figure 6.2 and Figure 6.3. To validate the wetted surface area calculations, the simulation constrains the free surface to the plane normal to the axis, and this makes up the base of a right elliptical cone.

The wetted area calculated using the simulation is compared to calculations done outside of the simulation. The validation code depicts energy as energy over surface tension, which is in square inches. With contact angle set to 0°, the validation code outputs the difference between the free surface area and the wetted surface area, in the place of what Surface Evolver outputs as the total energy. Adding the free surface area, outputted by Surface Evolver, to the absolute value of the total energy divided by the surface tension, gives the total surface area of the entire solution It is important to note that for this validation code to work surface tension (σ) is not relevant as it is dived out while non-dimensionalizing the energy and characteristic length (R) is assumed to set to 1 in, see Section 2.2. Note too that in a zero-g fluid statics computation, magnitude of (non-zero) surface tension, density, and viscosity are irrelevant as the problem becomes merely a geometry problem. The actual characteristic length, used in calculating dimensionless energy in Equation (1), is calculated using Equation (2) for an elliptical cone, but to output free and wetted area in the validation code, both are assumed to have the values just mentioned.

$$R = \sqrt{a * b} \tag{2}$$

This method works for validation because it compares the geometric calculations set up in Surface Evolver to other geometric calculations done outside of Surface Evolver to calculate the surface area of an elliptical cone with the same dimensions. Table 6.1 below compares the results of the area calculations done in Surface Evolver to the actual surface area of the elliptical cones. The errors in the Surface Evolver calculations are within tolerable limits. In both variates of elliptical cones used, the error is below 0.8%.

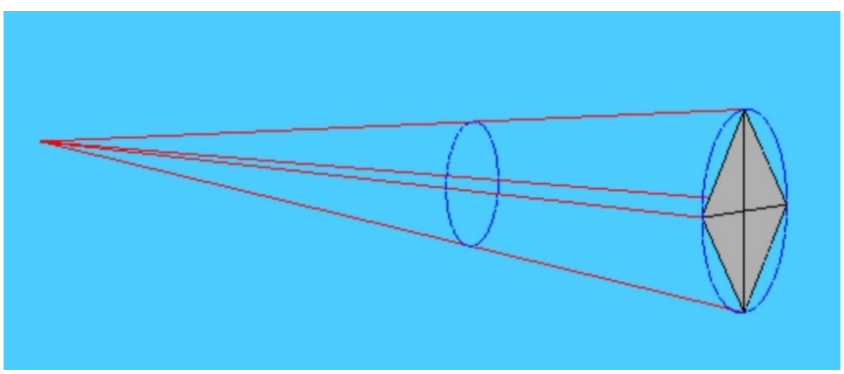


Figure 6.2: The Surface Evolver simulation validation file using the 1.5 elliptical cone as a test case. The origin is at the tip of the elliptical cone while the *x* and *y* axis are in the major and minor semi axes respectively.

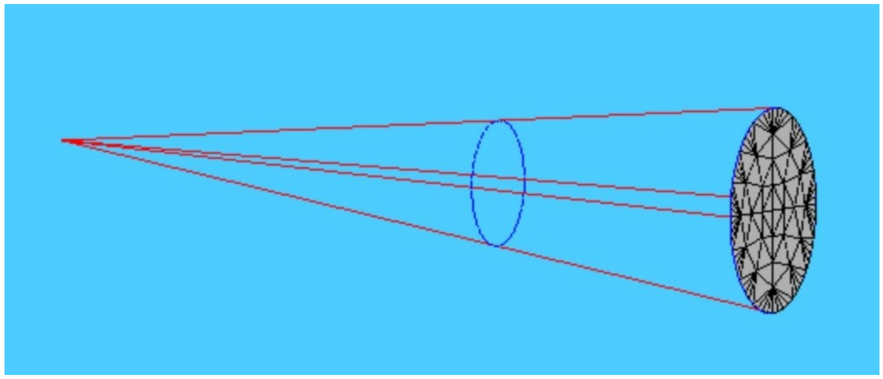


Figure 6.3: The Surface Evolver simulation validation file using the 1.5 elliptical cone as a test case, but after the face has been refined

Table 6.1: Comparing the area calculated inside of the Surface Evolver simulations to actual values (Weisstein, n.d.).

	Surface Evolver		Exact	
Ellipse Ratio:	1.1	1.5	1.1	1.5
Number of faces:	448	448		
(- Wetted Area) + (Free Surface Area) [in^2]:	-15.785	-14.167		
Free Surface Area [in^2]:	1.894	1.388	1.897	1.390
Wetted Area [in^2]:	17.648	15.527	17.682	15.408
Total % Error:	0.194	0.773		

To calculate the wetted and free surface area to compare with Surface Evolver, the parametric equations for an elliptical cone, Equations (1-3), where h is the height of the cone in the *z* axis, are needed.

$$x = a * \frac{h-u}{h} \cos v \quad (1)$$

$$y = b * \frac{h-u}{h} \sin v \quad (2)$$

$$z = u \quad (3)$$

Where *u* and *v* are defined as $v \in [0,2\pi)$ and $u \in [o, h]$, using the elliptical parametric equations, and the coefficient of the first fundamental forms, see Equation (4-6), lateral surface area can be calculated for an elliptical cone.

$$E = \frac{h^2+a^2(\cos v)^2+b^2\sin^2 v}{h^2} \tag{4}$$

$$F = \frac{(a^2-b^2)*(h-u)*\cos v \sin v}{h^2} \tag{5}$$

$$G = \frac{(h-u)^2(a^2\sin^2 v + b^2\cos^2 v)}{h^2} \tag{6}$$

The lateral surface area S, or the wetted surface area in this case, can be calculated with Equation (7) shown below.

$$S = \int_0^{2\pi}\int_0^h \sqrt{EG-F^2}\,du\,dv \tag{7}$$

Plugging in the elliptical parametric equations, Equations (4-6), into the surface area Equation (7) simplifies to Equation (8).

$$S = 2a\sqrt{b^2+h^2}E\left(\sqrt{\left(1-\frac{b^2}{a^2}\right)/\left(1+\frac{b^2}{h^2}\right)}\right) = 2b\sqrt{a^2+h^2}E\left(\sqrt{\left(1-\frac{a^2}{b^2}\right)/\left(1+\frac{a^2}{h^2}\right)}\right) \tag{8}$$

The free surface energy can be calculated by using the surface area of an ellipse Equation (9).

$$A = \pi * a * b \tag{9}$$

A sample calculation for the free surface area shown in Table 6.1 for the 1.1 ratio test section is shown below in Equation (10), see Table 6.2 for *a* and *b* values.

$$A = \pi * 0.815 * 0.741 = 1.897\ [in^2] \tag{10}$$

A sample for the calculation for the wetted surface area shown in Table 6.1 for the 1.1 ratio test section is shown below in Equation (11).

$$S = 2 * 0.815 * \sqrt{0.741^2 + 7.193^2} * E\left(\sqrt{\left(1-\frac{0.741^2}{0.815^2}\right)/\left(1+\frac{0.741^2}{7.193^2}\right)}\right) = 17.682\ [in^2] \tag{11}$$

6.3 Surface Evolver Results

For both test sections, variations in volume, from 0.1 to 0.9 in^3, were simulated for two contact angles: 30 and 50 degrees. Volume is calculated using symmetric content in Surface Evolver, which calculates volume using polar coordinates from the origin, instead of the default Cartesiancoordinates from the *xy* plane. This is ideal for simulations involving elliptical cones because the tip of the cone can be placed at the origin (Collicott, 2017). These simulations were done to find possible contact angles to use in the experiment. In an ideal case, contact angles would be found which avoid critical wetting along the inside walls of the test section and create all three target steady states for this study: a droplet, a sleeve, and a plug of liquid. For each different possible shape that the liquid might take in its state of static equilibrium, a different simulation with different initial geometry was used. It was up to the user to find at which volume each target steady state would evolve into a different target steady state. Energy was nondimensionalized by dividing the total energy by an assumed surface tension of one, see Section 2.2, and the characteristic length of the elliptical test section, calculated using Equation (2) from Section 6.2, and listed in Table 6.2 along with semi major and minor axis, *a* and *b*, for both test sections.

Table 6.2: Semi major and minor axis values as well as the characteristic length of each elliptical cone squared.

Semi major and minor axis	R^2
Ratio 1.1: a = 0.815, b = 0.741	0.604
Ratio 1.5: a = 0.815, b = 0.543	0.443

In the case of the 1.1 ratio test section, and a 30-degree contact angle, Table 6.3, it was found that a droplet would not transition into a sleeve at all with an increase in volume, but instead transition directly to a plug. With a decrease in volume of a plug, however, it was shown that a sleeve would appear to form, even around relatively small volume, in this case 0.1 in^3. In this specific case the simulation is unreliable, as sleeves are extremely unstable steady states. Most executions of the simulations with initial sleeve geometry, can depict the formation of a sleeve, but the geometry depicted at 0.1 in^3 in this simulation case looks like a sleeve trying to become two separate droplets, each at opposite sides of the major semi axis. It is more likely that by decreasing the volume a plug, the liquid splits into two droplets instead of the one droplet it started out as.

Figure 6.7 shows the dimensionless energy of the simulation case vs volume. Figure 6.5 shows examples of the droplets formed in Table 6.3, Figure 6.5 shows examples of the sleeves formed in Table 6.3, and Figure 6.6 shows examples of the plugs formed in Table 6.3. The corresponding shapes in Figure 6.4 through Figure 6.6 are also marked in the graph in Figure 6.7.

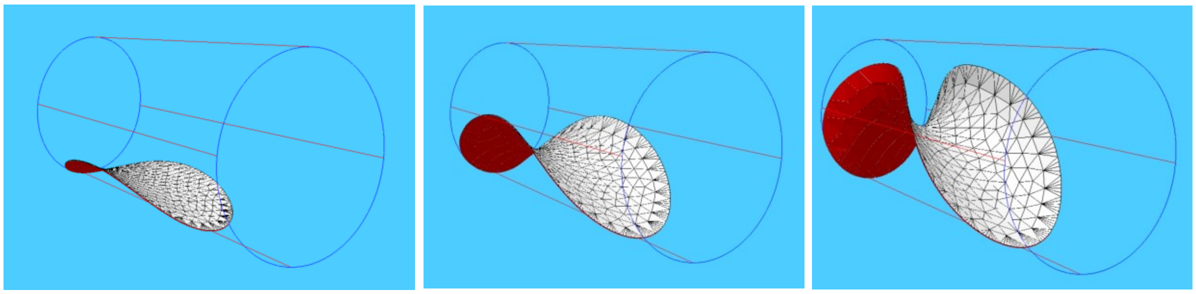


Figure 6.4: From left to right: contact angle 30 degrees, volume 0.1 in^3 [A], volume 0.4 in^3 [B], and volume 0.7 in^3 [C], see Figure 6.7.

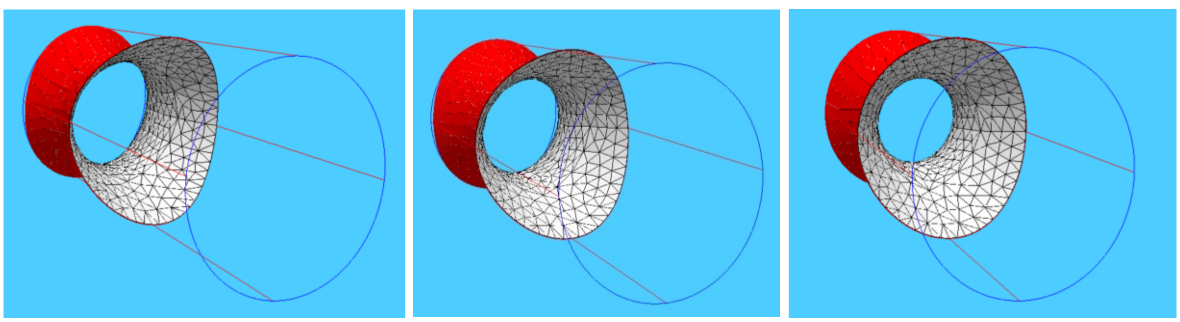


Figure 6.5: From left to right: contact angle 30 degrees, volume 0.1 in^3 [D], volume 0.4 in^3 [E], and volume 0.5 in^3 [F], see Figure 6.7.

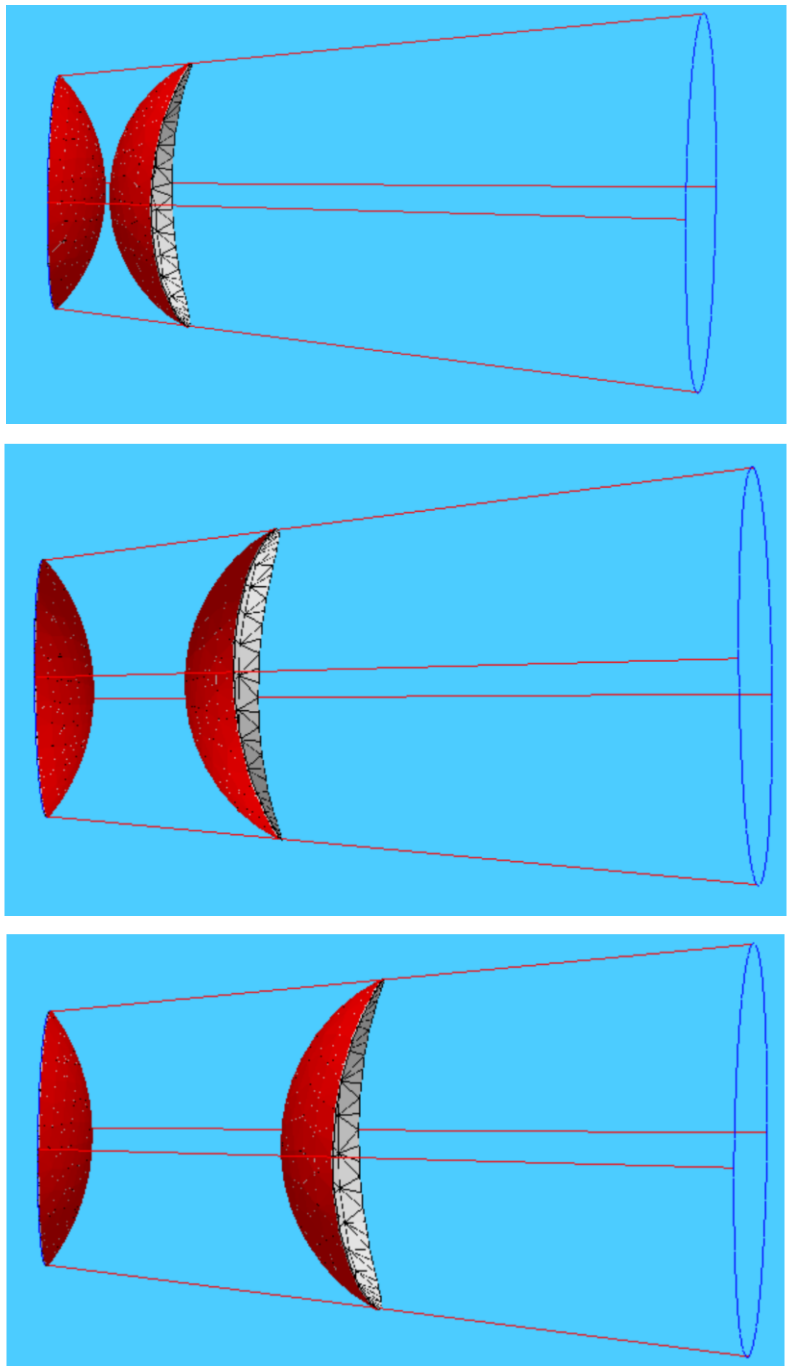


Figure 6.6: From top to bottom: contact angle 30 degrees, volume 0.2 in^3 [G], volume 0.5 in^3 [H], and volume 0.9 in^3 [I], see Figure 6.7.

Table 6.3: Simulation data using a contact angle of 30-degrees and a 1.1 ratio elliptical cross Section

CA: 30, Ratio 1.1	Total Energy [Dimensionless]		
Volume [in^3]	Droplet	Sleeve	Plug
0.1	-0.01999	DROPLET	2XDROPLET
0.2	-0.10377	DROPLET	0.95908199
0.3	-0.20733	-0.01476	0.46174842
0.4	-0.32756	-0.20763	-0.02439259
0.5	-0.46334	-0.43741	-0.50018885
0.6	-0.61719	PLUG	-0.96640794
0.7	-0.80048		-1.42385932
0.75	PLUG		-1.64947216
0.8			-1.8731005
0.9			-2.31467884

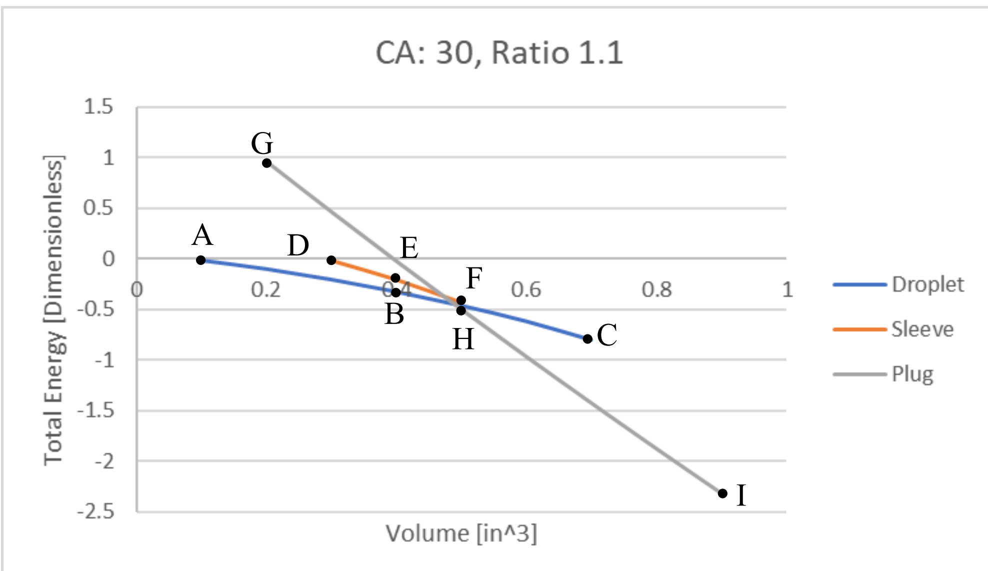


Figure 6.7: Graph showing the different volumes at which a droplet, sleeve, and plug can exist in the 1.1 ratio test section with a 30-degree contact angle.

The 1.1 ratio test section with a 50-degree contact angle, see Table 6.4 and Figure 6.8, proves a similar trend, where increase in droplet slide leads to plug, but decrease in plug size leads to two droplets. In both the 30 and 50-degree simulations, the only case in which a sleeve was formed was when the initial geometry was a sleeve, a case which is not possible to produce in an actual experiment, meaning that in the experiment it can be expected not to see a sleeve, even though a steady state sleeve does exist for both contact angles.

Table 6.4: Simulation data using a contact angle of 50-degrees and a 1.1 ratio elliptical cross Section

CA: 50, Ratio 1.1	Total Energy [Dimensionless]		
Volume [in^3]	Droplet	Sleeve	Plug
0.1	0.397955	DROPLET	2XDROPLET
0.2	0.53277	DROPLET	1.48700327
0.3	0.601928	DROPLET	1.1371405
0.4	0.629727	0.909736	0.79546128
0.5	0.623491	PLUG	0.46124521
0.6	0.581756		0.13389096
0.7	PLUG		-0.18712567
0.8			-0.50226837
0.9			-0.81193736

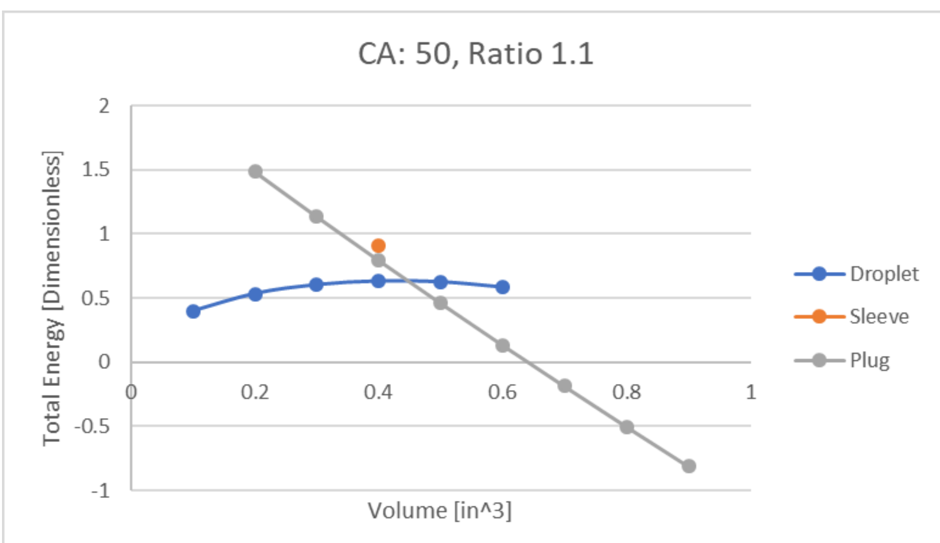


Figure 6.8: Graph showing the different volumes at which a droplet, sleeve, and plug can exist in the 1.1 ratio test section with a 50-degree contact angle.

The 1.5 ratio test section was also simulated using 30 and 50-degree contact angles. In the 30-degree case, critical wetting occurs, and a steady state cannot be achieved, shown in Figure 6.9.

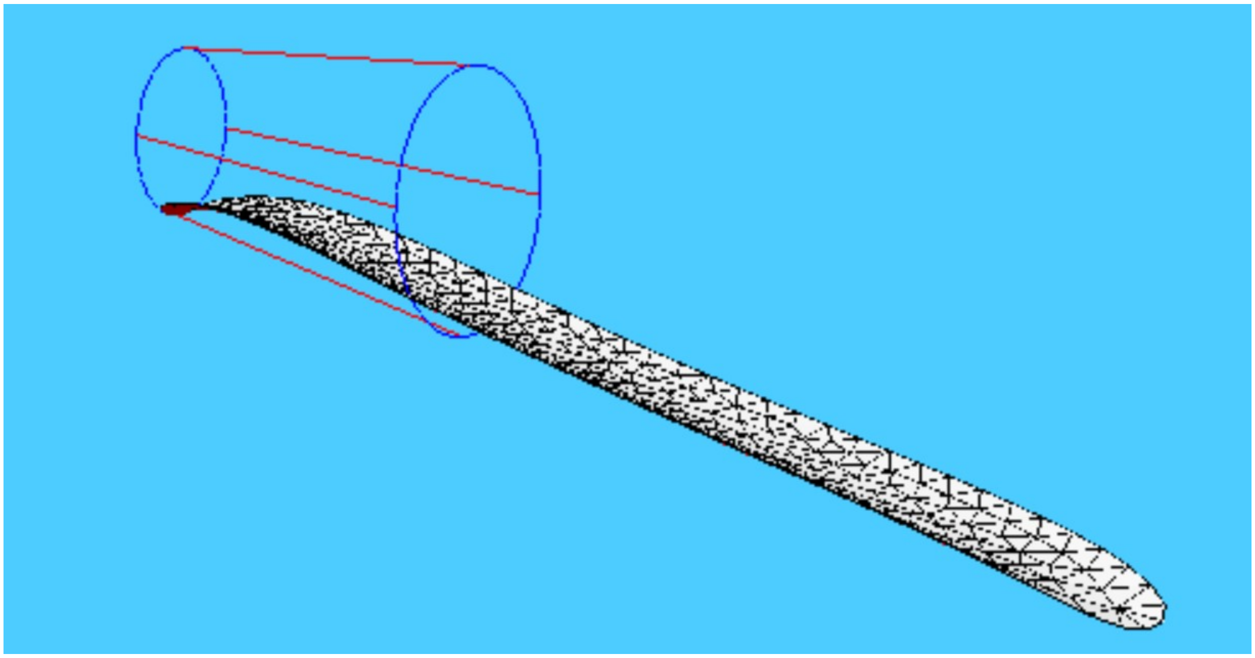


Figure 6.9: The 1.5 ratio elliptical test section, with critical wetting, and no achievable steady state solution.

A contact angle of 50-degrees inside the 1.5 ratio test section does not encounter critical wetting, but instead shows the same trend as the 1.1 ratio test section, and has a plug going directly to two droplets with some decrees in volume. The significant difference being, at 0.1 in^3, the 50-degree contact angle, 1.5 ratio test section, simulation remains a plug. It isn't until lower volume, at least 0.05 in^3, the plug breaks into two droplets, meaning that in the experiment if liquid with a 50-degree contact angle were to be used in the 1.5 ratio test section, then experiment repeatability would be dependent on extracting more liquid than in the case of the 1.1 ratio test section. If not enough liquid is retracted, then the experiment could result in the expansion and retraction of a plug after the initial droplet geometry has been exceeded.

Data for the 50-degree contact angle in the 1.5 ratio test section is shown in Table 6.5 and Figure 6.12. Figure 6.10 shows examples of the droplets formed in Table 6.5, and Figure 6.11 shows examples of the plugs formed in Table 6.5. The corresponding shapes in Figure 6.10 and Figure 6.11 are also marked in the graph in Figure 6.12.

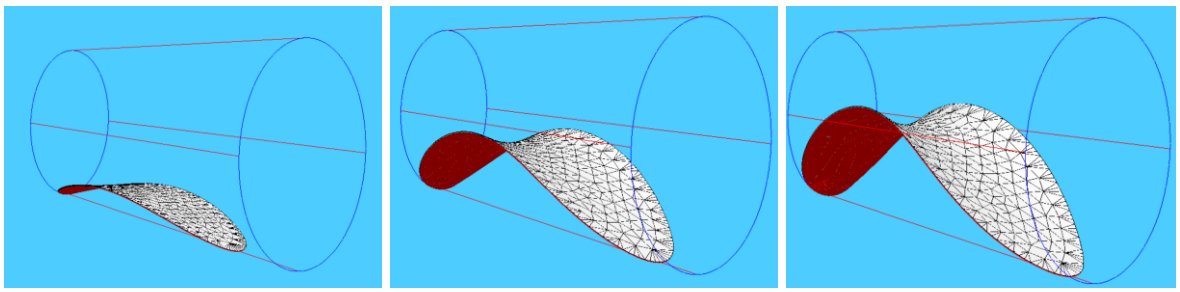


Figure 6.10: From left to right: contact angle 50 degrees, volume 0.1 in^3 [A], volume 0.4 in^3 [B], and volume 0.6 in^3 [C], see Figure 6.12.

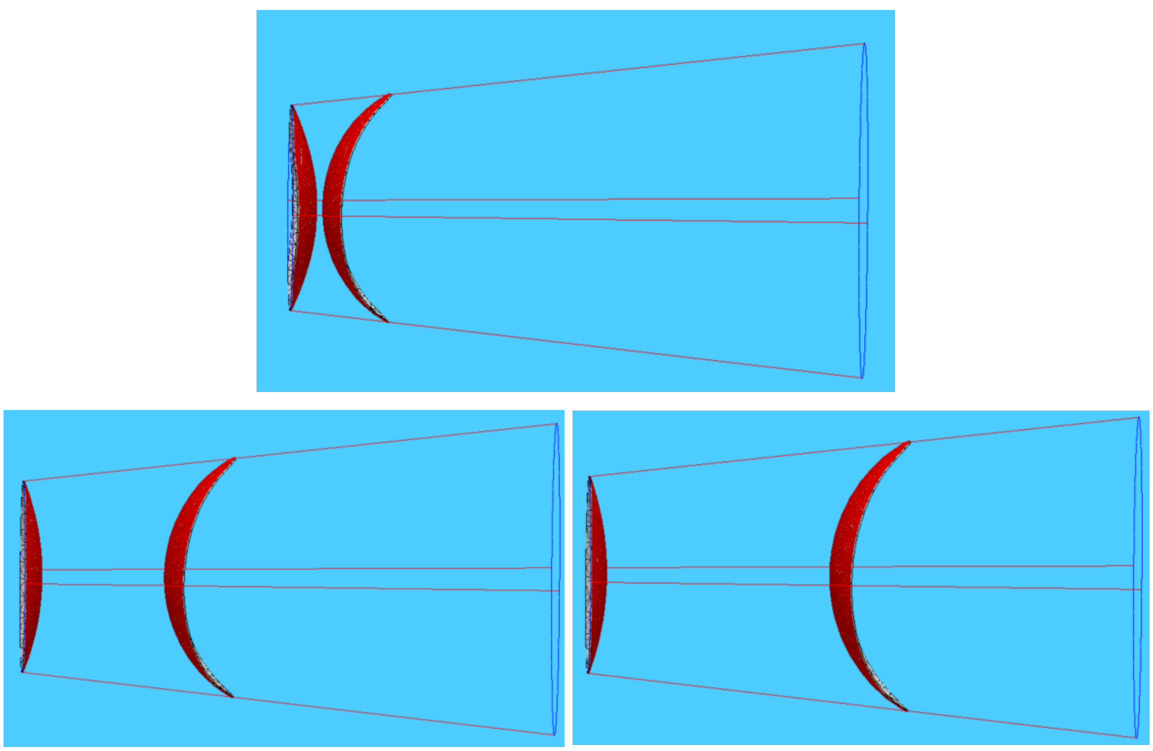


Figure 6.11: From top, to bottom left and right: contact angle 50 degrees, volume 0.1 in^3 [D], volume 0.5 in^3 [E], and volume 0.9 in^3 [F], see Figure 6.12.

Table 6.5: Simulation data using a contact angle of 50-degrees and a 1.5 ratio elliptical cross Section

CA: 50, Ratio 1.5	Total Energy [Dimensionless]		
Volume [in^3]	Droplet	Sleeve	Plug
0.05	N/A	N/A	2XDROPLET
0.1	0.029711	DROPLET	1.52126224
0.2	0.041945	DROPLET	0.91949067
0.3	0.026424	DROPLET	0.33601668
0.4	-0.01075	DROPLET	-0.23034577
0.5	-0.06685	PLUG	-0.7813322
0.6	-0.14216	PLUG	-1.31843871
0.7	PLUG	PLUG	-1.84292671
0.8			-2.35589594
0.9			-2.85828967

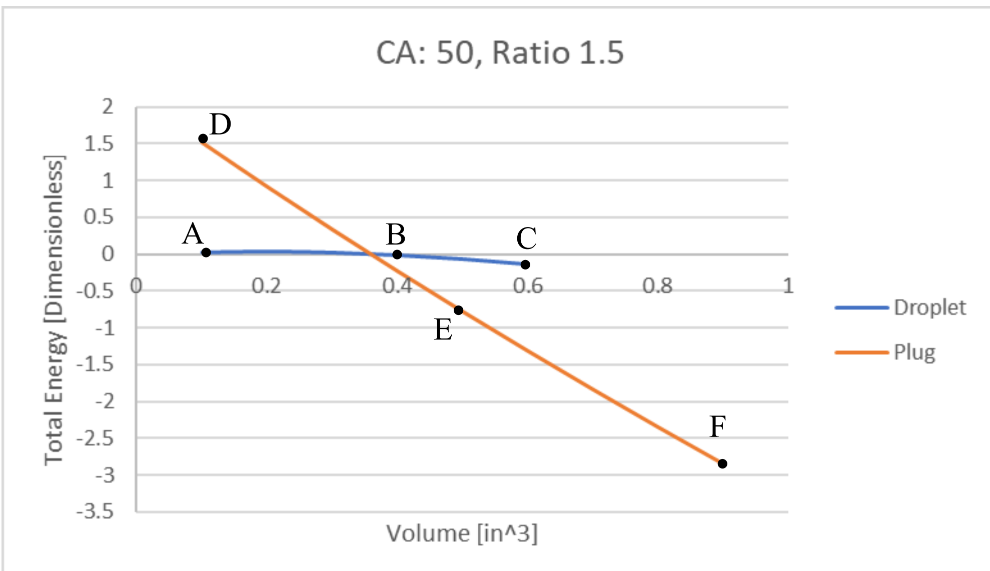


Figure 6.12: Graph showing the different volumes at which a droplet, sleeve, and plug can exist in the 1.5 ratio test section with a 50-degree contact angle.

CHAPTER 7. CONCLUSIONS

7.1 Experiment Final Photos

This Section showcases final photos of the experiment at the time of writing this. More details can be found in Section 4.5. All photos shown here do not have LEDs installed, or all the tubing, see Section 7.2.

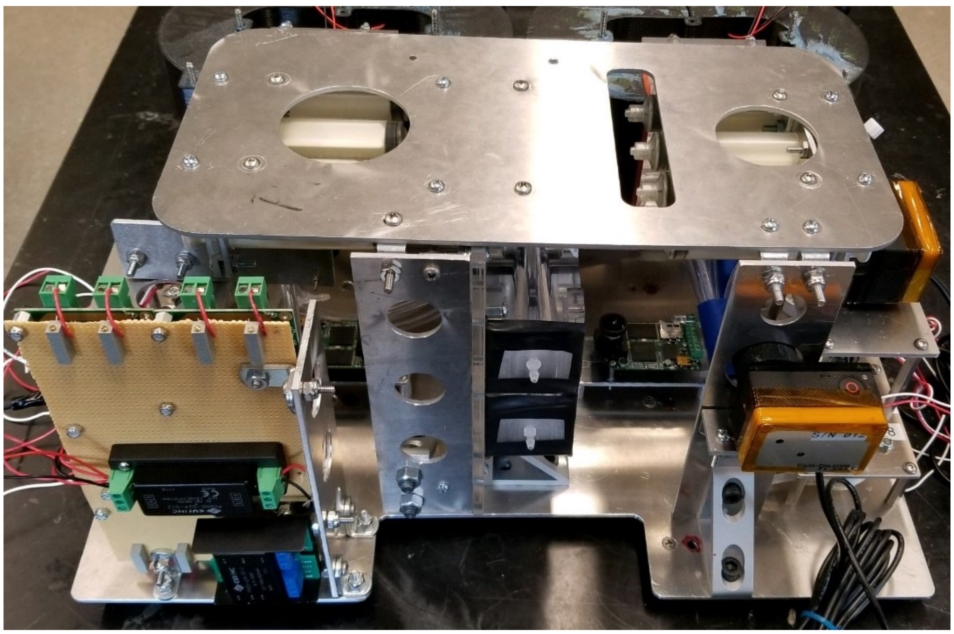
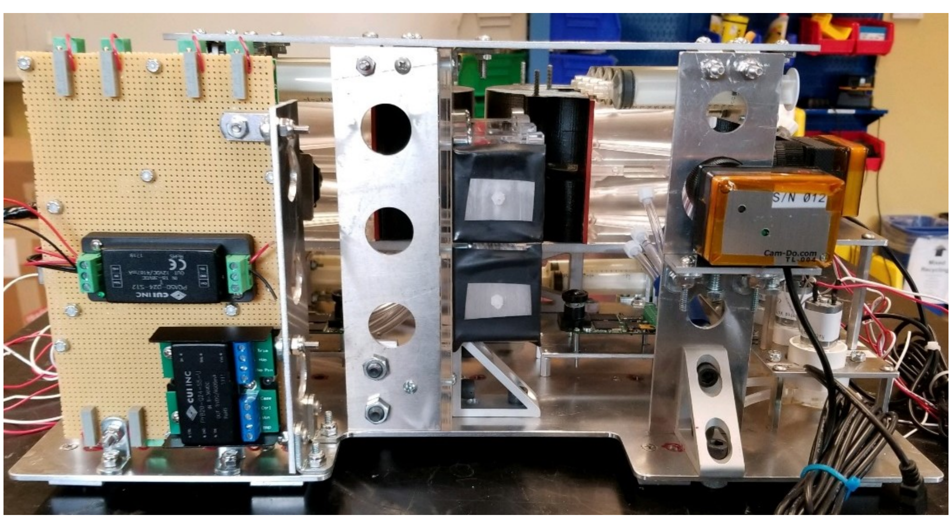


Figure 7.1: Front view of experiment.



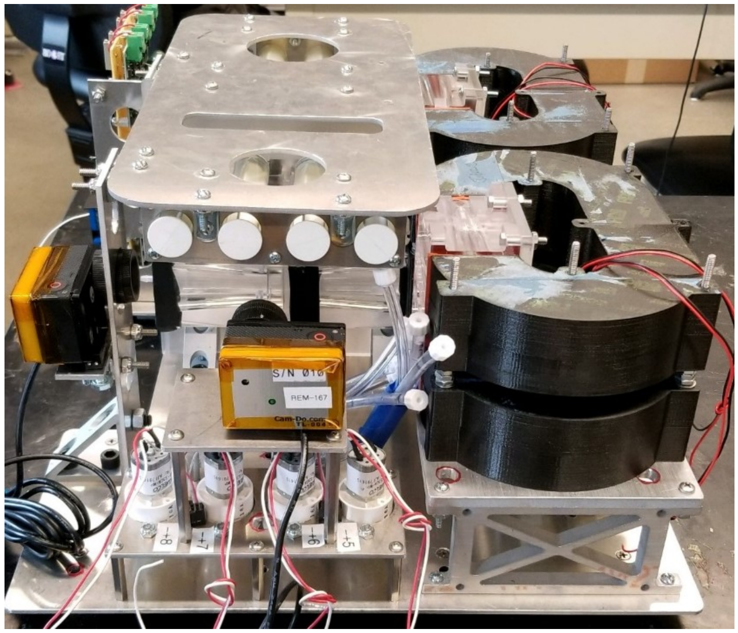


Figure 7.2: Side view of experiment.

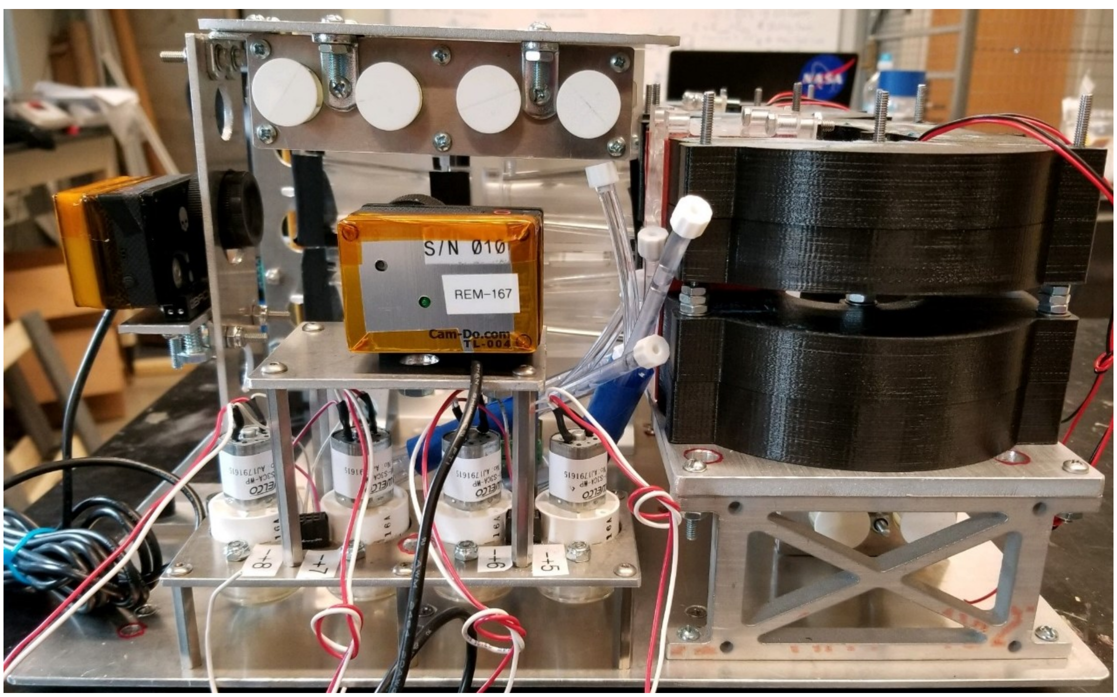


Figure 7.3: Side view of experiment.

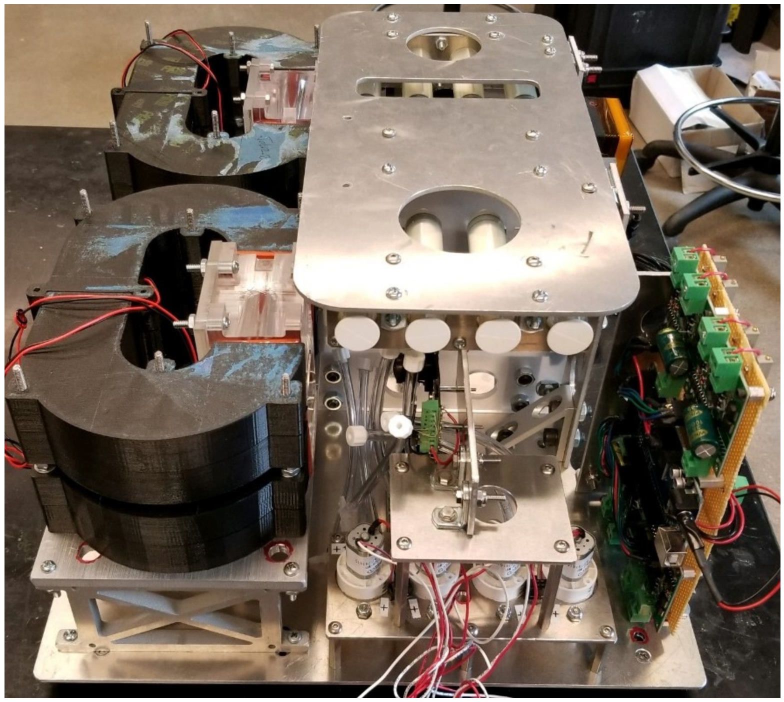


Figure 7.4: Side view of experiment.

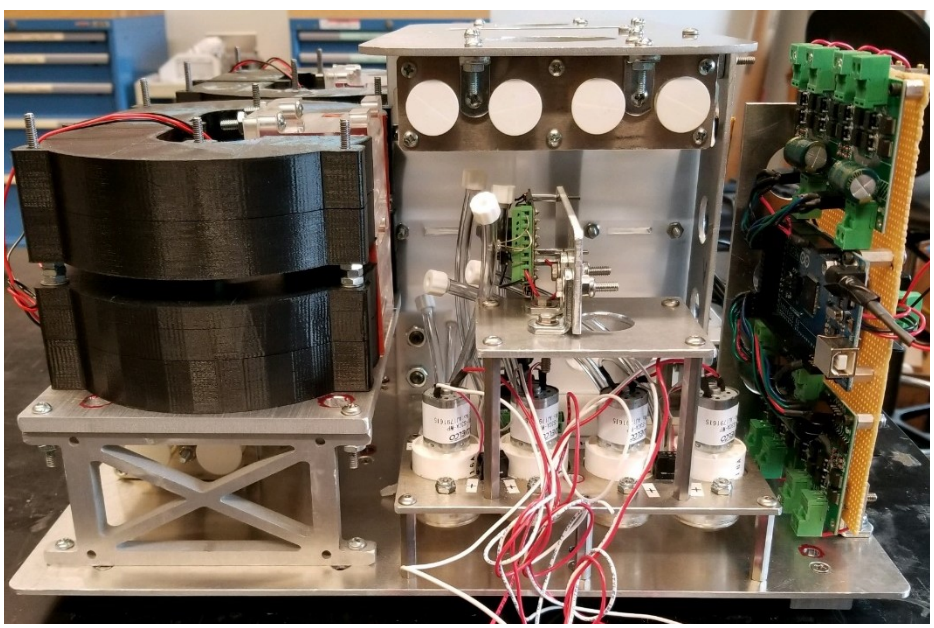


Figure 7.5: Side view of experiment.

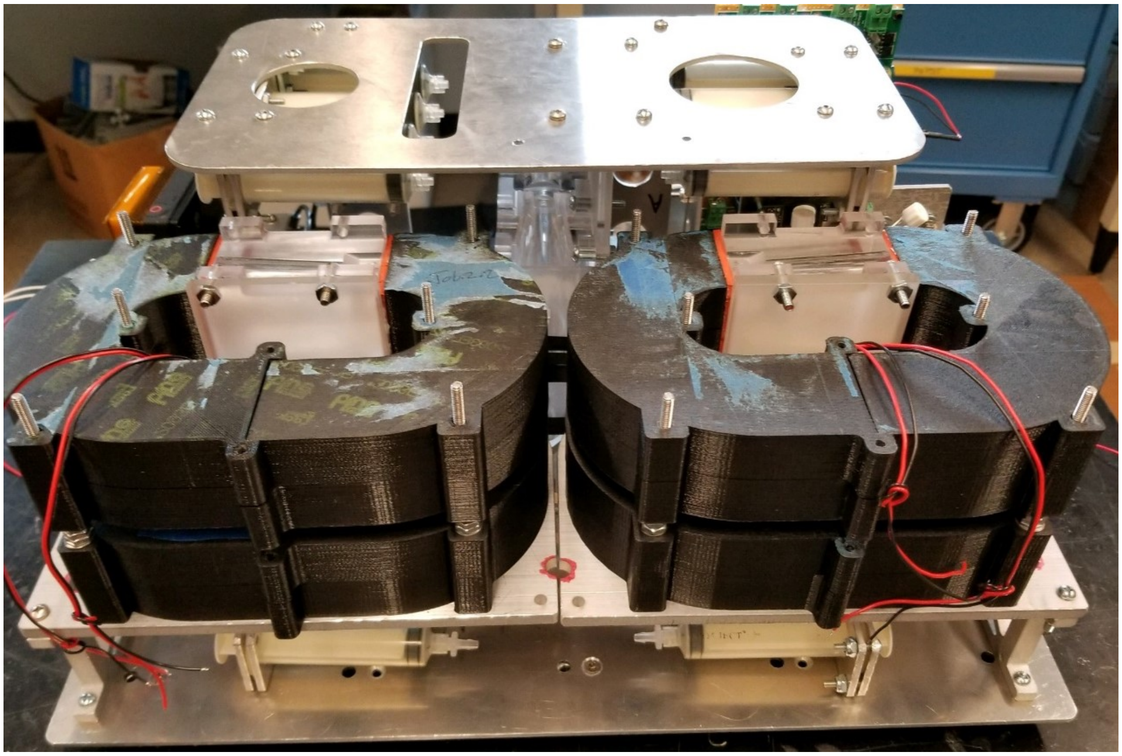


Figure 7.6: Back view of experiment.

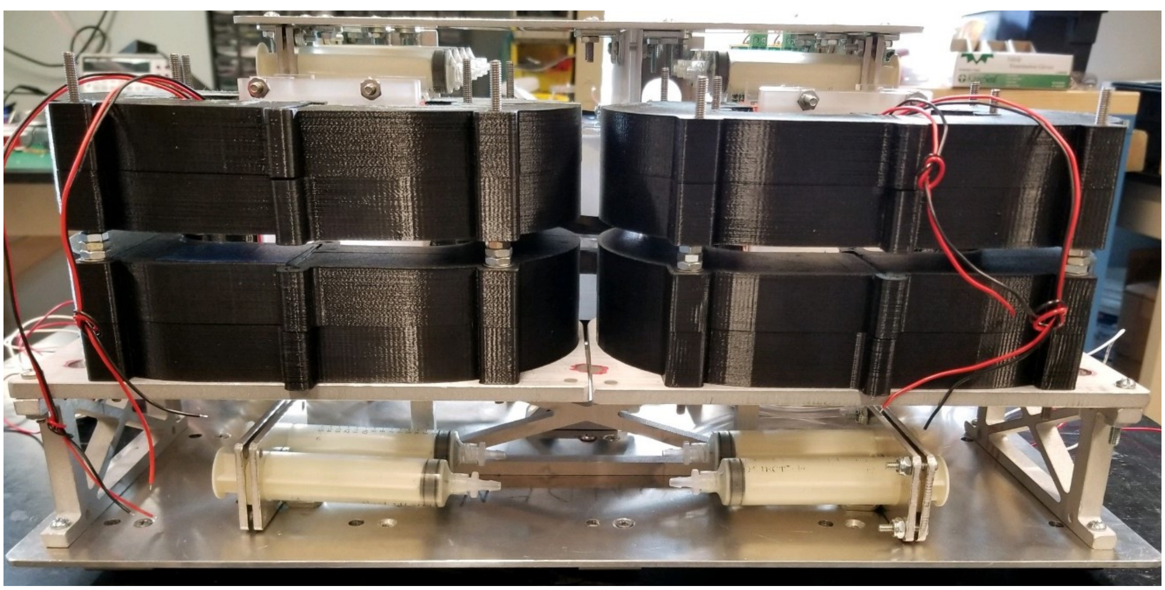


Figure 7.7: Back view of experiment.

7.2 Experiment Ready Status

As of the writing of this document, the payload remains to be completed. The remaining steps are few but need to be completed before the launch date. The mission code still needs to be written for the Arduino to control the Hack HD cameras, lights, and injection system on trigger from the Blue Origin flight computer, the code for the flight computer that will trigger the Go-Pros still needs to be written and tested, the final tube lengths need to be cut and installed, and all of the test sections in the no flow test section need to be glued to their end plugs using acrylic adhesive. The wind tunnels in the flow test sections need to be glued together with silicone adhesive to prevent leaks, as well as having the rubber gaskets installed with holes that match the geometry of the wind tunnels, see Figure 7.8. All the nuts need to be replaced with new nylon lock nuts. Any nuts that cannot be replace with lock nuts need to be screwed in place with lock tight applied to the threading. The bag and LEDs also need to be installed. Optional steps include: black anodizing all the aluminum parts and covering the inside walls of the payload with black paper or another applicant that is black to prevent light prolusion in the video footage from light bouncing around from the LEDs. Electrical connections must all be finalized, and electrical connecters for connecting electronics through the plastic bag also must be selected and purchased.

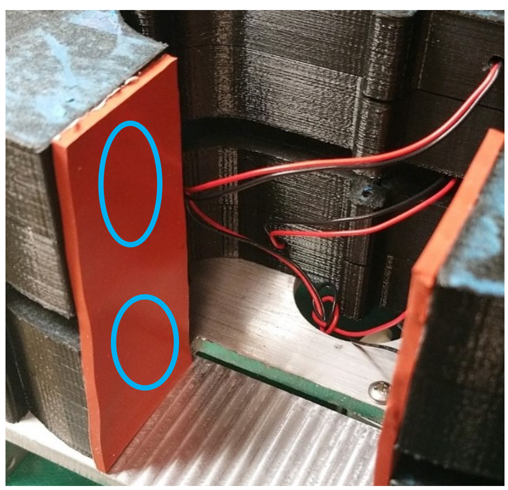


Figure 7.8: The orange rubber gaskets from Figure 4.12, need holes matching the wind tunnels cut in them, see blue ellipses not to scale.

7.3 Surface Evolver and Mission Ops

The graphs from Section 6.3 will be used to put together a code to fill and drain the liquid in the test sections. A possible mission plan for the injection and retraction of liquid can be seen in Figure 7.9 and Figure 7.10, over the course of 3 min of weightlessness. Liquid will be injected along the volume range at which a droplet exists, before becoming a plug, in the test sections. Injection volumes will range between zero mL and a volume before the Surface Evolver simulations predict the steady state of the liquid to switch geometry to a plug. During the mission, after liquid has been injected and retracted along the predicted volume range at which a droplet is the steady state of the liquid, liquid will be injected to the point at which the simulations predict to see the formation of plugs. When plugs are formed in the test sections, the volume will be injected and retracted across the predicted volume space that the surface evolver simulations predict plugs to exist in the test sections. The volume of liquid needs to be that which the simulations do not show exiting the test sections. Surface Evolver results will vary for different contact angles, so any liquid used in the experiment that uses a different contact angle than the two explored in Section 6.3 needs to be simulated to develop mission code.

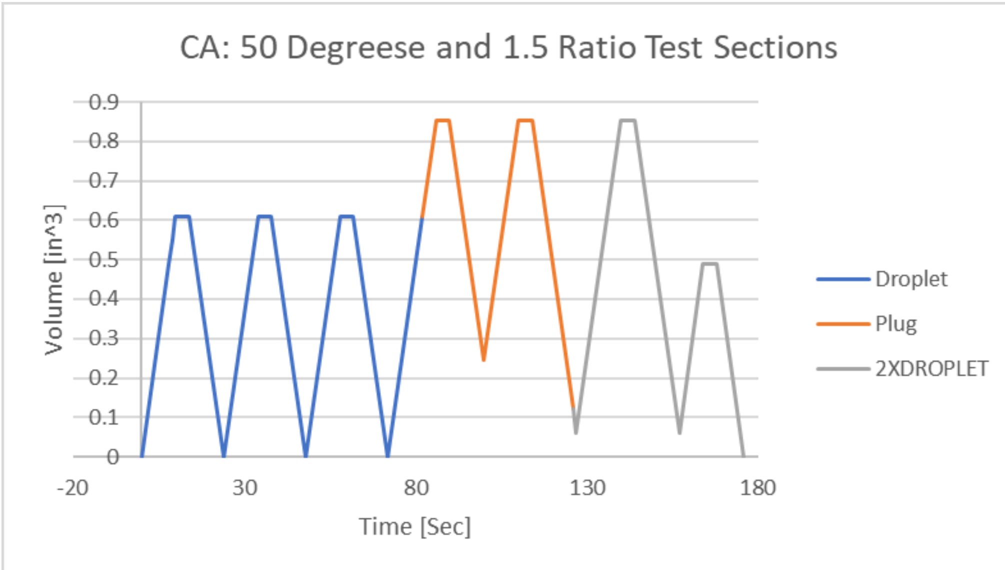


Figure 7.9: Showing liquid volumes inside the 1.5 ratio test sections across 3 minutes of weightlessness.

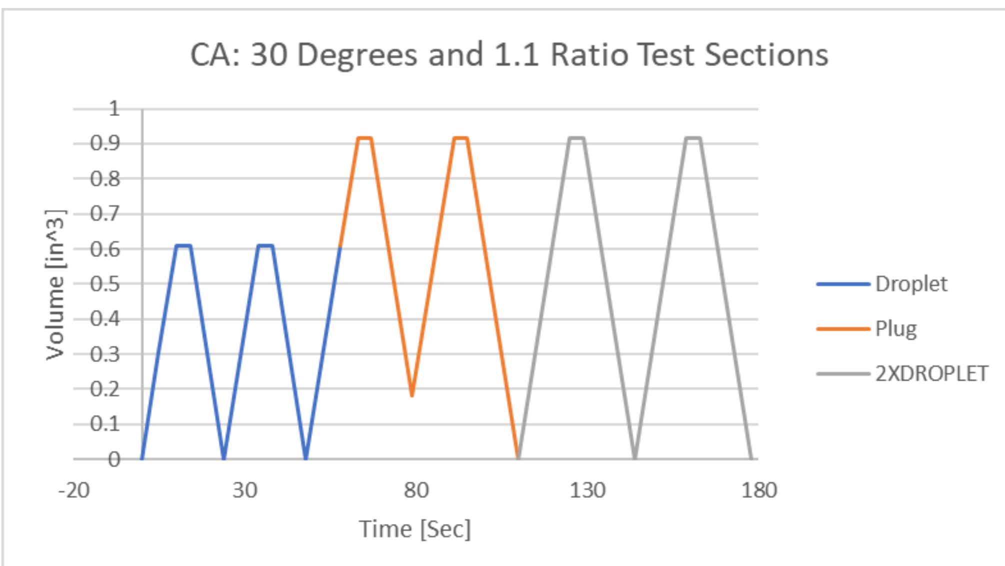


Figure 7.10: Showing liquid volumes inside the 1.1 ratio test sections across 3 minutes of weightlessness.

APPENDIX

Surface Evolver Validation Code

```
//Surface Evolver Elliptical Cone Validation
//Trevor Jahn

SYMMETRIC_CONTENT
gravity _constant 0  // start with gravity off

PARAMETER cang = 360  // contact angle in degrees
#define WALLT  (-cos(cang*pi/180))  // virtual tension of facet on plane

// Ellipse Large
PARAMETER Ra1 = 0.815 // side to side
PARAMETER Rb1 = 0.741 //0.543 // up and down
PARAMETER Rz1 = Ra1/((Ra1-0.5)/2.78) // height of the cone

PARAMETER AlphaA = atan(Ra1/Rz1) // cone half angle // angle of the semi
major axis
PARAMETER AlphaB = atan(Rb1/Rz1) // cone half angle // angle of the semi
minor axis

// Ellipse Small
PARAMETER Rz = Rz1-2.78 // height of the cone
PARAMETER Ra = Rz*tan(AlphaA) // side to side
PARAMETER Rb = Rz*tan(AlphaB) // up and down

// Initial Geometry
PARAMETER Rz2 = Rz+2 // height of the cone
PARAMETER Ra2 = Rz2*tan(AlphaA) // side to side
PARAMETER Rb2 = Rz2*tan(AlphaB) // up and down

#define TERM1 sqrt( (x^2) + (y^2) + (z^2) ) // L

#define tt (atan2(y*Ra,x*Rb))
#define T2 sqrt((Rb^2)*((cos(tt))^2)+(Ra^2)*((sin(tt))^2))

#define dSx ((-Ra*sin(tt))/T2) // dx
#define dSy ((Rb*cos(tt))/T2) // dy

constraint 1 // outline only for only the post // Small Ellipse
formula: (x^2)/(Ra^2) + (y^2)/(Rb^2) - 1 = 0

constraint 2 convex // contact line
formula: (x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2) -  1 = 0
energy:
e1: 0.5*TERM1*dSx*WALLT
e2: 0.5*TERM1*dSy*WALLT
e3: 0

constraint 3 nonnegative// in plane of waist
formula: z - Rz
```

```
constraint 4 nonnegative // inside of cone
formula: 1 - ((x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2)) = 0

constraint 5 // outline only for only the post // Large Ellipse
formula: (x^2)/(Ra1^2) + (y^2)/(Rb1^2) - 1 = 0

constraint 6 nonnegative
formula: z - Rz1

vertex
1 0 0 0 fixed // origin

// Small Ellipse
2 0 Rb Rz fixed // Up (y)
3 0 -Rb Rz fixed // Down (-y)

4 Ra 0 Rz fixed // Right (x)
5 -Ra 0 Rz fixed // Left (-x)

// Initial Geometery
// 6   0   rb  Rz constraint 2 3 // (y)
// 7  Ra    0  Rz constraint 2 3 // (x)
// 8   0  -rb  Rz constraint 2 3 // (-y)

 9   0  rb2 Rz2 constraint 2 6// (y)
10 Ra2    0 Rz2 constraint 2 6// (x)
11   0 -rb2 Rz2 constraint 2 6// (-y)

// Large Ellipse
12 0 Rb1 Rz1 fixed // Up (y)
13 0 -Rb1 Rz1 fixed // Down (-y)

14 Ra1 0 Rz1 fixed // Right (x)
15 -Ra1 0 Rz1 fixed // Left (-x)

// Initial Geometry
//16  -Ra    0  Rz constraint 2 3 // (-x)
17 -Ra2    0 Rz2 constraint 2 6// (-x)


edge
// outline of the wall of the cone
1 1 12 fixed bare no_refine color red
2 1 13 fixed bare no_refine color red
3 1 14 fixed bare no_refine color red
4 1 15 fixed bare no_refine color red

//Small Ellipse
5 2 4 fixed constraint 1 bare no_refine color blue // large end outline
6 4 3 fixed constraint 1 bare no_refine color blue // large end outline
7 3 5 fixed constraint 1 bare no_refine color blue // large end outline
8 5 2 fixed constraint 1 bare no_refine color blue // large end outline

// Initial Geometry
// 9  6  7 constraint 2 3 4
//10  7  8 constraint 2 3 4
// 11  8  6 constraint 2 3 4
```

```
12 11 10 constraint 2 4 6
13 10  9 constraint 2 4 6
// 14  9 11 constraint 2 4

// 15  9  6 constraint 2
// 16  8 11 constraint 2

//Large Ellipse
17 12 14 fixed constraint 5 bare no_refine color blue // large end outline
18 14 13 fixed constraint 5 bare no_refine color blue // large end outline
19 13 15 fixed constraint 5 bare no_refine color blue // large end outline
20 15 12 fixed constraint 5 bare no_refine color blue // large end outline

// Initial Geometry
//21 8 16 constraint 2 3 4
//22 16 6 constraint 2 3 4

23 9 17 constraint 2 4 6
24 17 11 constraint 2 4 6


face
//1 9 10 21 22 constraint 4
// 1 10  11   9 constraint 4
2 12 13 23 24 constraint 4 6
//2 12  13  14 constraint 4
// 3 16 -14  15 -11 constraint 4

body
1 2 density 0 // volume 2

read
{refine edge where on_constraint 1}5  // make outline look smooth
{refine edge where on_constraint 5}5  // make outline look smooth
lh:={histogram(edge where not fixed, length)}
ah := histogram(face, area)
vug := {{V 3; u 3; g3}3;}
showq
set face backcolor red
k 10
rcl := refine edge where on_constraint 2
```

Surface Evolver 1.1 Ratio Test section, Droplet

```
//Surface Evolver 1.1 Ratio Test section, Droplet
//Trevor Jahn

SYMMETRIC_CONTENT
gravity_constant 0  // start with gravity off

PARAMETER cang = 30  // contact angle in degrees
#define WALLT  (-cos(cang*pi/180))  // virtual tension of facet on plane

// Elipse Large
PARAMETER Ra1 = 0.815 // side to side
PARAMETER Rb1 = 0.741 // up and down
PARAMETER Rz1 = Ra1/((Ra1-0.5)/2.78) // height of the cone

PARAMETER AlphaA = atan(Ra1/Rz1) // cone half angle // angle of the semi
major axis
PARAMETER AlphaB = atan(Rb1/Rz1) // cone half angle // angle of the semi
minor axis

// Elipse Small
PARAMETER Rz = Rz1-2.78 // height of the cone
PARAMETER Ra = Rz*tan(AlphaA) // side to side
PARAMETER Rb = Rz*tan(AlphaB) // up and down

// Initial Geometery
PARAMETER Rz2 = Rz+2 // height of the cone
PARAMETER Ra2 = Rz2*tan(AlphaA) // side to side
PARAMETER Rb2 = Rz2*tan(AlphaB) // up and down

#define TERM1 sqrt( (x^2) + (y^2) + (z^2) ) // L

#define tt (atan2(y*Ra,x*Rb))
#define T2 sqrt((Rb^2)*((cos(tt))^2)+(Ra^2)*((sin(tt))^2))

#define dSx ((-Ra*sin(tt))/T2) // dx
#define dSy ((Rb*cos(tt))/T2) // dy

constraint 1 // outline only for only the post // Small Ellipse
formula: (x^2)/(Ra^2) + (y^2)/(Rb^2) - 1 = 0

constraint 2 convex // contact line
formula: (x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2) -  1 = 0
energy:
e1: 0.5*TERM1*dSx*WALLT/((Ra1*Rb1)^2)
e2: 0.5*TERM1*dSy*WALLT/((Ra1*Rb1)^2)
e3: 0

constraint 3  nonnegative // in plane of waist
formula: z - Rz

constraint 4 nonnegative // inside of cone
formula: 1 - ((x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2)) = 0

constraint 5 // outline only for only the post // Large Ellipse
```

```
formula: (x^2)/(Ra1^2) + (y^2)/(Rb1^2) - 1 = 0

vertex
1 0 0 0 fixed // origin

// Small Ellipse
2 0 Rb Rz fixed // Up (y)
3 0 -Rb Rz fixed // Down (-y)

4 Ra 0 Rz fixed // Right (x)
5 -Ra 0 Rz fixed // Left (-x)

// Initial Geometery
 6   0   rb  Rz constraint 2 3 // (y)
 7  Ra    0  Rz constraint 2 3 // (x)
 8   0  -rb  Rz constraint 2 3 // (-y)
 9   0  rb2 Rz2 constraint 2 // (y)
10 Ra2    0 Rz2 constraint 2 // (x)
11   0 -rb2 Rz2 constraint 2 // (-y)

// Large Ellipse
12 0 Rb1 Rz1 fixed // Up (y)
13 0 -Rb1 Rz1 fixed // Down (-y)

14 Ra1 0 Rz1 fixed // Right (x)
15 -Ra1 0 Rz1 fixed // Left (-x)


edge
// outline of the wall of the cone
1 2 12 fixed bare no_refine color red
2 3 13 fixed bare no_refine color red
3 4 14 fixed bare no_refine color red
4 5 15 fixed bare no_refine color red

//Small Elipse
5 2 4 fixed constraint 1 bare no_refine color blue // large end outline
6 4 3 fixed constraint 1 bare no_refine color blue // large end outline
7 3 5 fixed constraint 1 bare no_refine color blue // large end outline
8 5 2 fixed constraint 1 bare no_refine color blue // large end outline

// Initial Geometery
 9  6  7 constraint 2 3
10  7  8 constraint 2 3
11  8  6 constraint 4
12 11 10 constraint 2
13 10  9 constraint 2
14  9 11 constraint 4
15  9  6 constraint 2
16  8 11 constraint 2

//Large Elipse
17 12 14 fixed constraint 5 bare no_refine color blue // large end outline
18 14 13 fixed constraint 5 bare no_refine color blue // large end outline
19 13 15 fixed constraint 5 bare no_refine color blue // large end outline
20 15 12 fixed constraint 5 bare no_refine color blue // large end outline
```

```
face
1 10  11   9 constraint 4
2 12  13  14 constraint 4
3 16 -14  15 -11 constraint 4

body
1 1 2 3 density 0 volume 0.75

read
{refine edge where on_constraint 1}5  // make outline look smooth
{refine edge where on_constraint 5}5  // make outline look smooth
lh:={histogram(edge where not fixed, length)}
ah := histogram(face, area)
vug := {{V 3; u 3; g3}3;}
showq
set face backcolor red
k 10
rcl := refine edge where on_constraint 2
```

Surface Evolver 1.5 Ratio Test section, Droplet

```
// Surface Evolver 1.5 Ratio Test section, Droplet
//Trevor Jahn

SYMMETRIC_CONTENT
gravity_constant 0  // start with gravity off

PARAMETER cang = 30  // contact angle in degrees
#define WALLT  (-cos(cang*pi/180))  // virtual tension of facet on plane

// Ellipse Large
PARAMETER Ra1 = 0.815 // side to side
PARAMETER Rb1 = 0.543 // up and down
PARAMETER Rz1 = Ra1/((Ra1-0.5)/2.78) // height of the cone

PARAMETER AlphaA = atan(Ra1/Rz1) // cone half angle // angle of the semi
major axis
PARAMETER AlphaB = atan(Rb1/Rz1) // cone half angle // angle of the semi
minor axis

// Ellipse Small
PARAMETER Rz = Rz1-2.78 // height of the cone
PARAMETER Ra = Rz*tan(AlphaA) // side to side
PARAMETER Rb = Rz*tan(AlphaB) // up and down

// Initial Geometry
PARAMETER Rz2 = Rz+2 // height of the cone
PARAMETER Ra2 = Rz2*tan(AlphaA) // side to side
PARAMETER Rb2 = Rz2*tan(AlphaB) // up and down

#define TERM1 sqrt( (x^2) + (y^2) + (z^2) ) // L

#define tt (atan2(y*Ra,x*Rb))
#define T2 sqrt((Rb^2)*((cos(tt))^2)+(Ra^2)*((sin(tt))^2))

#define dSx ((-Ra*sin(tt))/T2) // dx
#define dSy ((Rb*cos(tt))/T2) // dy

constraint 1 // outline only for only the post // Small Ellipse
formula: (x^2)/(Ra^2) + (y^2)/(Rb^2) - 1 = 0

constraint 2 convex // contact line
formula: (x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2) -  1 = 0
energy:
e1: 0.5*TERM1*dSx*WALLT/((Ra1*Rb1)^2)
e2: 0.5*TERM1*dSy*WALLT/((Ra1*Rb1)^2)
e3: 0

constraint 3  nonnegative // in plane of waist
formula: z - Rz

constraint 4 nonnegative // inside of cone
formula: 1 - ((x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2)) = 0

constraint 5 // outline only for only the post // Large Ellipse
```

```
formula: (x^2)/(Ra1^2) + (y^2)/(Rb1^2) - 1 = 0

vertex
1 0 0 0 fixed // origin

// Small Ellipse
2 0 Rb Rz fixed // Up (y)
3 0 -Rb Rz fixed // Down (-y)

4 Ra 0 Rz fixed // Right (x)
5 -Ra 0 Rz fixed // Left (-x)

// Initial Geometry
 6   0   rb  Rz constraint 2 3 // (y)
 7  Ra    0  Rz constraint 2 3 // (x)
 8   0  -rb  Rz constraint 2 3 // (-y)
 9   0  rb2 Rz2 constraint 2 // (y)
10 Ra2    0 Rz2 constraint 2 // (x)
11   0 -rb2 Rz2 constraint 2 // (-y)

// Large Ellipse
12 0 Rb1 Rz1 fixed // Up (y)
13 0 -Rb1 Rz1 fixed // Down (-y)

14 Ra1 0 Rz1 fixed // Right (x)
15 -Ra1 0 Rz1 fixed // Left (-x)


edge
// outline of the wall of the cone
1 2 12 fixed bare no_refine color red
2 3 13 fixed bare no_refine color red
3 4 14 fixed bare no_refine color red
4 5 15 fixed bare no_refine color red

//Small Ellipse
5 2 4 fixed constraint 1 bare no_refine color blue // large end outline
6 4 3 fixed constraint 1 bare no_refine color blue // large end outline
7 3 5 fixed constraint 1 bare no_refine color blue // large end outline
8 5 2 fixed constraint 1 bare no_refine color blue // large end outline

// Initial Geometry
 9  6  7 constraint 2 3
10  7  8 constraint 2 3
11  8  6 constraint 4
12 11 10 constraint 2
13 10  9 constraint 2
14  9 11 constraint 4
15  9  6 constraint 2
16  8 11 constraint 2

//Large Elipse
17 12 14 fixed constraint 5 bare no_refine color blue // large end outline
18 14 13 fixed constraint 5 bare no_refine color blue // large end outline
19 13 15 fixed constraint 5 bare no_refine color blue // large end outline
20 15 12 fixed constraint 5 bare no_refine color blue // large end outline
```

```
face
1 10  11   9 constraint 4
2 12  13  14 constraint 4
3 16 -14  15 -11 constraint 4

body
1 1 2 3 density 0 volume 0.75

read
{refine edge where on_constraint 1}5  // make outline look smooth
{refine edge where on_constraint 5}5  // make outline look smooth
lh:={histogram(edge where not fixed, length)}
ah := histogram(face, area)
vug := {{V 3; u 3; g3}3;}
showq
set face backcolor red
k 10
rcl := refine edge where on_constraint 2
```

Surface Evolver 1.1 Ratio Test section, Sleeve

```
// Surface Evolver 1.1 Ratio Test section, Sleeve
// Trevor Jahn

SYMMETRIC_CONTENT
gravity_constant 0  // start with gravity off

PARAMETER cang = 30  // contact angle in degrees
#define WALLT  (-cos(cang*pi/180))  // virtual tension of facet on plane

// Ellipse Large
PARAMETER Ra1 = 0.815 // side to side
PARAMETER Rb1 = 0.741 // up and down
PARAMETER Rz1 = Ra1/((Ra1-0.5)/2.78) // height of the cone

PARAMETER AlphaA = atan(Ra1/Rz1) // cone half angle // angle of the semi
major axis
PARAMETER AlphaB = atan(Rb1/Rz1) // cone half angle // angle of the semi
minor axis

// Ellipse Small
PARAMETER Rz = Rz1-2.78 // height of the cone
PARAMETER Ra = Rz*tan(AlphaA) // side to side
PARAMETER Rb = Rz*tan(AlphaB) // up and down

// Initial Geometry
PARAMETER Rz2 = Rz+2 // height of the cone
PARAMETER Ra2 = Rz2*tan(AlphaA) // side to side
PARAMETER Rb2 = Rz2*tan(AlphaB) // up and down

#define TERM1 sqrt( (x^2) + (y^2) + (z^2) ) // L

#define tt (atan2(y*Ra,x*Rb))
#define T2 sqrt((Rb^2)*((cos(tt))^2)+(Ra^2)*((sin(tt))^2))

#define dSx ((-Ra*sin(tt))/T2) // dx
#define dSy ((Rb*cos(tt))/T2) // dy

constraint 1 // outline only for only the post // Small Ellipse
formula: (x^2)/(Ra^2) + (y^2)/(Rb^2) - 1 = 0

constraint 2 convex // contact line
formula: (x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2) -  1 = 0
energy:
e1: 0.5*TERM1*dSx*WALLT/((Ra1*Rb1)^2)
e2: 0.5*TERM1*dSy*WALLT/((Ra1*Rb1)^2)
e3: 0

constraint 3 nonnegative // in plane of waist
formula: z - Rz

constraint 4 nonnegative // inside of cone
formula: 1 - ((x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2)) = 0

constraint 5 // outline only for only the post // Large Ellipse
```

```
formula: (x^2)/(Ra1^2) + (y^2)/(Rb1^2) - 1 = 0

vertex
1 0 0 0 fixed // origin

// Small Ellipse
2 0 Rb Rz fixed // Up (y)
3 0 -Rb Rz fixed // Down (-y)

4 Ra 0 Rz fixed // Right (x)
5 -Ra 0 Rz fixed // Left (-x)

// Initial Geometry
 6   0   rb  Rz constraint 2 3 // (y)
 7  Ra    0  Rz constraint 2 3 // (x)
 8   0  -rb  Rz constraint 2 3 // (-y)

 9   0  rb2 Rz2 constraint 2 // (y)
10 Ra2    0 Rz2 constraint 2 // (x)
11   0 -rb2 Rz2 constraint 2 // (-y)

// Large Ellipse
12 0 Rb1 Rz1 fixed // Up (y)
13 0 -Rb1 Rz1 fixed // Down (-y)

14 Ra1 0 Rz1 fixed // Right (x)
15 -Ra1 0 Rz1 fixed // Left (-x)

// Initial Geometry
16  -Ra    0  Rz constraint 2 3 // (-x)
17 -Ra2    0 Rz2 constraint 2 // (-x)

// Initial Geometry Inner Squares
18   0   (rb)/2  Rz // (y)
19  (Ra)/2    0  Rz // (x)
20   0  (-rb)/2  Rz // (-y)
21  (-Ra)/2    0  Rz // (-x)

22   0  (rb2)/2 Rz2 // (y)
23 (Ra2)/2    0 Rz2 // (x)
24   0 (-rb2)/2 Rz2 // (-y)
25 (-Ra2)/2    0 Rz2 // (-x)

edge
// outline of the wall of the cone
1 2 12 fixed bare no_refine color red
2 3 13 fixed bare no_refine color red
3 4 14 fixed bare no_refine color red
4 5 15 fixed bare no_refine color red

//Small Ellipse
5 2 4 fixed constraint 1 bare no_refine color blue // large end outline
6 4 3 fixed constraint 1 bare no_refine color blue // large end outline
7 3 5 fixed constraint 1 bare no_refine color blue // large end outline
8 5 2 fixed constraint 1 bare no_refine color blue // large end outline

// Initial Geometry
```

```
 9  6  7 constraint 2 3 4
10  7  8 constraint 2 3 4
// 11  8  6 constraint 2 3 4

12 11 10 constraint 2 4
13 10  9 constraint 2 4
// 14  9 11 constraint 2 4

// 15  9  6 constraint 2
// 16  8 11 constraint 2

//Large Ellipse
17 12 14 fixed constraint 5 bare no_refine color blue // large end outline
18 14 13 fixed constraint 5 bare no_refine color blue // large end outline
19 13 15 fixed constraint 5 bare no_refine color blue // large end outline
20 15 12 fixed constraint 5 bare no_refine color blue // large end outline

// Initial Geometry
21 8 16 constraint 2 3 4
22 16 6 constraint 2 3 4

23 9 17 constraint 2 4
24 17 11 constraint 2 4

25 18 19 constraint 4
26 19 20 constraint 4
27 20 21 constraint 4
28 21 18 constraint 4

29 22 23 constraint 4
30 23 24 constraint 4
31 24 25 constraint 4
32 25 22 constraint 4

33 18 6 constraint 4
34 7 19 constraint 4
35 8 20 constraint 4
36 16 21 constraint 4

37 9 22 constraint 4
38 23 10 constraint 4
39 24 11 constraint 4
40 25 17 constraint 4

41 22 18 constraint 4
42 19 23 constraint 4
43 20 24 constraint 4
44 25 21 constraint 4

face
1 9 34 -25 33 // constraint 4
2 10 35 -26 -34 // constraint 4
3 21 36 -27 -35 // constraint 4
4 22 -33 -28 -36 // constraint 4

5 13 37 29 38 // constraint 4
6 12 -38 30 39 // constraint 4
```

```
7 24 -39 31 40 // constraint 4
8 23 -40 32 -37 // constraint 4

9 41 25 42 -29 // constraint 4
10 26 43 -30 -42 // constraint 4
11 27 -44 -31 -43 // constraint 4
12 -41 -32 44 28 // constraint 4

body
1 1 2 3 4 5 6 7 8 9 10 11 12 density 0 volume 0.3

read
{refine edge where on_constraint 1}5  // make outline look smooth
{refine edge where on_constraint 5}5  // make outline look smooth
lh:={histogram(edge where not fixed, length)}
ah := histogram(face, area)
vug := {{V 3; u 3; g3}3;}
showq
set face backcolor red
k 10
rcl := refine edge where on_constraint 2
```

Surface Evolver 1.5 Ratio Test section, Sleeve

```
// Surface Evolver 1.5 Ratio Test section, Sleeve
// Trevor Jahn

SYMMETRIC_CONTENT
gravity_constant 0  // start with gravity off

PARAMETER cang = 30  // contact angle in degrees
#define WALLT  (-cos(cang*pi/180))  // virtual tension of facet on plane

// Ellipse Large
PARAMETER Ra1 = 0.815 // side to side
PARAMETER Rb1 = 0.543 // up and down
PARAMETER Rz1 = Ra1/((Ra1-0.5)/2.78) // height of the cone

PARAMETER AlphaA = atan(Ra1/Rz1) // cone half angle // angle of the semi
major axis
PARAMETER AlphaB = atan(Rb1/Rz1) // cone half angle // angle of the semi
minor axis

// Ellipse Small
PARAMETER Rz = Rz1-2.78 // height of the cone
PARAMETER Ra = Rz*tan(AlphaA) // side to side
PARAMETER Rb = Rz*tan(AlphaB) // up and down

// Initial Geometry
PARAMETER Rz2 = Rz+2 // height of the cone
PARAMETER Ra2 = Rz2*tan(AlphaA) // side to side
PARAMETER Rb2 = Rz2*tan(AlphaB) // up and down

#define TERM1 sqrt( (x^2) + (y^2) + (z^2) ) // L

#define tt (atan2(y*Ra,x*Rb))
#define T2 sqrt((Rb^2)*((cos(tt))^2)+(Ra^2)*((sin(tt))^2))

#define dSx ((-Ra*sin(tt))/T2) // dx
#define dSy ((Rb*cos(tt))/T2) // dy

constraint 1 // outline only for only the post // Small Ellipse
formula: (x^2)/(Ra^2) + (y^2)/(Rb^2) - 1 = 0

constraint 2 convex // contact line
formula: (x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2) -  1 = 0
energy:
e1: 0.5*TERM1*dSx*WALLT/((Ra1*Rb1)^2)
e2: 0.5*TERM1*dSy*WALLT/((Ra1*Rb1)^2)
e3: 0

constraint 3 nonnegative // in plane of waist
formula: z - Rz

constraint 4 nonnegative // inside of cone
formula: 1 - ((x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2)) = 0

constraint 5 // outline only for only the post // Large Ellipse
```

```
formula: (x^2)/(Ra1^2) + (y^2)/(Rb1^2) - 1 = 0

vertex
1 0 0 0 fixed // origin

// Small Ellipse
2 0 Rb Rz fixed // Up (y)
3 0 -Rb Rz fixed // Down (-y)

4 Ra 0 Rz fixed // Right (x)
5 -Ra 0 Rz fixed // Left (-x)

// Initial Geometry
 6   0   rb  Rz constraint 2 3 // (y)
 7  Ra    0  Rz constraint 2 3 // (x)
 8   0  -rb  Rz constraint 2 3 // (-y)

 9   0  rb2 Rz2 constraint 2 // (y)
10 Ra2    0 Rz2 constraint 2 // (x)
11   0 -rb2 Rz2 constraint 2 // (-y)

// Large Ellipse
12 0 Rb1 Rz1 fixed // Up (y)
13 0 -Rb1 Rz1 fixed // Down (-y)

14 Ra1 0 Rz1 fixed // Right (x)
15 -Ra1 0 Rz1 fixed // Left (-x)

// Initial Geometry
16  -Ra    0  Rz constraint 2 3 // (-x)
17 -Ra2    0 Rz2 constraint 2 // (-x)

// Initial Geometry Inner Squares
18   0   (rb)/2  Rz // (y)
19  (Ra)/2    0  Rz // (x)
20   0  (-rb)/2  Rz // (-y)
21  (-Ra)/2    0  Rz // (-x)

22   0  (rb2)/2 Rz2 // (y)
23 (Ra2)/2    0 Rz2 // (x)
24   0 (-rb2)/2 Rz2 // (-y)
25 (-Ra2)/2    0 Rz2 // (-x)

edge
// outline of the wall of the cone
1 2 12 fixed bare no_refine color red
2 3 13 fixed bare no_refine color red
3 4 14 fixed bare no_refine color red
4 5 15 fixed bare no_refine color red

//Small Ellipse
5 2 4 fixed constraint 1 bare no_refine color blue // large end outline
6 4 3 fixed constraint 1 bare no_refine color blue // large end outline
7 3 5 fixed constraint 1 bare no_refine color blue // large end outline
8 5 2 fixed constraint 1 bare no_refine color blue // large end outline

// Initial Geometry
```

```
 9  6  7 constraint 2 3 4
10  7  8 constraint 2 3 4
// 11  8  6 constraint 2 3 4

12 11 10 constraint 2 4
13 10  9 constraint 2 4
// 14  9 11 constraint 2 4

// 15  9  6 constraint 2
// 16  8 11 constraint 2

//Large Ellipse
17 12 14 fixed constraint 5 bare no_refine color blue // large end outline
18 14 13 fixed constraint 5 bare no_refine color blue // large end outline
19 13 15 fixed constraint 5 bare no_refine color blue // large end outline
20 15 12 fixed constraint 5 bare no_refine color blue // large end outline

// Initial Geometry
21 8 16 constraint 2 3 4
22 16 6 constraint 2 3 4

23 9 17 constraint 2 4
24 17 11 constraint 2 4

25 18 19 constraint 4
26 19 20 constraint 4
27 20 21 constraint 4
28 21 18 constraint 4

29 22 23 constraint 4
30 23 24 constraint 4
31 24 25 constraint 4
32 25 22 constraint 4

33 18 6 constraint 4
34 7 19 constraint 4
35 8 20 constraint 4
36 16 21 constraint 4

37 9 22 constraint 4
38 23 10 constraint 4
39 24 11 constraint 4
40 25 17 constraint 4

41 22 18 constraint 4
42 19 23 constraint 4
43 20 24 constraint 4
44 25 21 constraint 4

face
1 9 34 -25 33 // constraint 4
2 10 35 -26 -34 // constraint 4
3 21 36 -27 -35 // constraint 4
4 22 -33 -28 -36 // constraint 4

5 13 37 29 38 // constraint 4
6 12 -38 30 39 // constraint 4
```

```
7 24 -39 31 40 // constraint 4
8 23 -40 32 -37 // constraint 4

9 41 25 42 -29 // constraint 4
10 26 43 -30 -42 // constraint 4
11 27 -44 -31 -43 // constraint 4
12 -41 -32 44 28 // constraint 4

body
1 1 2 3 4 5 6 7 8 9 10 11 12 density 0 volume 0.3

read
{refine edge where on_constraint 1}5  // make outline look smooth
{refine edge where on_constraint 5}5  // make outline look smooth
lh:={histogram(edge where not fixed, length)}
ah := histogram(face, area)
vug := {{V 3; u 3; g3}3;}
showq
set face backcolor red
k 10
rcl := refine edge where on_constraint 2
```

Surface Evolver 1.1 Ratio Test section, Plug

```
// Surface Evolver 1.1 Ratio Test section, Plug
// Trevor Jahn

SYMMETRIC_CONTENT
gravity_constant 0  // start with gravity off

PARAMETER cang = 30  // contact angle in degrees
#define WALLT  (-cos(cang*pi/180))  // virtual tension of facet on plane

// Ellipse Large
PARAMETER Ra1 = 0.815 // side to side
PARAMETER Rb1 = 0.741 // up and down
PARAMETER Rz1 = Ra1/((Ra1-0.5)/2.78) // height of the cone

PARAMETER AlphaA = atan(Ra1/Rz1) // cone half angle // angle of the semi
major axis
PARAMETER AlphaB = atan(Rb1/Rz1) // cone half angle // angle of the semi
minor axis

// Ellipse Small
PARAMETER Rz = Rz1-2.78 // height of the cone
PARAMETER Ra = Rz*tan(AlphaA) // side to side
PARAMETER Rb = Rz*tan(AlphaB) // up and down

// Initial Geometry
PARAMETER Rz2 = Rz+2 // height of the cone
PARAMETER Ra2 = Rz2*tan(AlphaA) // side to side
PARAMETER Rb2 = Rz2*tan(AlphaB) // up and down

#define TERM1 sqrt( (x^2) + (y^2) + (z^2) ) // L

#define tt (atan2(y*Ra,x*Rb))
#define T2 sqrt((Rb^2)*((cos(tt))^2)+(Ra^2)*((sin(tt))^2))

#define dSx ((-Ra*sin(tt))/T2) // dx
#define dSy ((Rb*cos(tt))/T2) // dy

constraint 1 // outline only for only the post // Small Ellipse
formula: (x^2)/(Ra^2) + (y^2)/(Rb^2) - 1 = 0

constraint 2 convex // contact line
formula: (x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2) -  1 = 0
energy:
e1: 0.5*TERM1*dSx*WALLT/((Ra1*Rb1)^2)
e2: 0.5*TERM1*dSy*WALLT/((Ra1*Rb1)^2)
e3: 0

constraint 3  nonnegative// in plane of waist
formula: z - Rz

constraint 4 nonnegative // inside of cone
formula: 1 - ((x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2)) = 0

constraint 5 // outline only for only the post // Large Ellipse
```

```
formula: (x^2)/(Ra1^2) + (y^2)/(Rb1^2) - 1 = 0

vertex
1 0 0 0 fixed // origin

// Small Ellipse
2 0 Rb Rz fixed // Up (y)
3 0 -Rb Rz fixed // Down (-y)

4 Ra 0 Rz fixed // Right (x)
5 -Ra 0 Rz fixed // Left (-x)

// Initial Geometry
 6   0   rb  Rz constraint 2 3 // (y)
 7  Ra    0  Rz constraint 2 3 // (x)
 8   0  -rb  Rz constraint 2 3 // (-y)

 9   0  rb2 Rz2 constraint 2 // (y)
10 Ra2    0 Rz2 constraint 2 // (x)
11   0 -rb2 Rz2 constraint 2 // (-y)

// Large Ellipse
12 0 Rb1 Rz1 fixed // Up (y)
13 0 -Rb1 Rz1 fixed // Down (-y)

14 Ra1 0 Rz1 fixed // Right (x)
15 -Ra1 0 Rz1 fixed // Left (-x)

// Initial Geometry
16  -Ra    0  Rz constraint 2 3 // (-x)
17 -Ra2    0 Rz2 constraint 2 // (-x)


edge
// outline of the wall of the cone
1 2 12 fixed bare no_refine color red
2 3 13 fixed bare no_refine color red
3 4 14 fixed bare no_refine color red
4 5 15 fixed bare no_refine color red

//Small Ellipse
5 2 4 fixed constraint 1 bare no_refine color blue // large end outline
6 4 3 fixed constraint 1 bare no_refine color blue // large end outline
7 3 5 fixed constraint 1 bare no_refine color blue // large end outline
8 5 2 fixed constraint 1 bare no_refine color blue // large end outline

// Initial Geometry
 9  6  7 constraint 2 3 4
10  7  8 constraint 2 3 4
// 11  8  6 constraint 2 3 4

12 11 10 constraint 2 4
13 10  9 constraint 2 4
// 14  9 11 constraint 2 4

// 15  9  6 constraint 2
// 16  8 11 constraint 2
```

```
//Large Ellipse
17 12 14 fixed constraint 5 bare no_refine color blue // large end outline
18 14 13 fixed constraint 5 bare no_refine color blue // large end outline
19 13 15 fixed constraint 5 bare no_refine color blue // large end outline
20 15 12 fixed constraint 5 bare no_refine color blue // large end outline

// Initial Geometry
21 8 16 constraint 2 3 4
22 16 6 constraint 2 3 4

23 9 17 constraint 2 4
24 17 11 constraint 2 4


face
1 9 10 21 22 constraint 4
// 1 10  11   9 constraint 4
2 12 13 23 24 constraint 4
//2 12  13  14 constraint 4
// 3 16 -14  15 -11 constraint 4

body
1 1 2 density 0 volume 2

read
{refine edge where on_constraint 1}5  // make outline look smooth
{refine edge where on_constraint 5}5  // make outline look smooth
lh:={histogram(edge where not fixed, length)}
ah := histogram(face, area)
vug := {{V 3; u 3; g3}3;}
showq
set face backcolor red
k 10
rcl := refine edge where on_constraint 2
```

Surface Evolver 1.5 Ratio Test section, Plug

```
// Surface Evolver 1.5 Ratio Test section, Plug
// Trevor Jahn

SYMMETRIC_CONTENT
gravity_constant 0  // start with gravity off

PARAMETER cang = 30  // contact angle in degrees
#define WALLT  (-cos(cang*pi/180))  // virtual tension of facet on plane

// Ellipse Large
PARAMETER Ra1 = 0.815 // side to side
PARAMETER Rb1 = 0.543 // up and down
PARAMETER Rz1 = Ra1/((Ra1-0.5)/2.78) // height of the cone

PARAMETER AlphaA = atan(Ra1/Rz1) // cone half angle // angle of the semi
major axis
PARAMETER AlphaB = atan(Rb1/Rz1) // cone half angle // angle of the semi
minor axis

// Ellipse Small
PARAMETER Rz = Rz1-2.78 // height of the cone
PARAMETER Ra = Rz*tan(AlphaA) // side to side
PARAMETER Rb = Rz*tan(AlphaB) // up and down

// Initial Geometry
PARAMETER Rz2 = Rz+2 // height of the cone
PARAMETER Ra2 = Rz2*tan(AlphaA) // side to side
PARAMETER Rb2 = Rz2*tan(AlphaB) // up and down

#define TERM1 sqrt( (x^2) + (y^2) + (z^2) ) // L

#define tt (atan2(y*Ra,x*Rb))
#define T2 sqrt((Rb^2)*((cos(tt))^2)+(Ra^2)*((sin(tt))^2))

#define dSx ((-Ra*sin(tt))/T2) // dx
#define dSy ((Rb*cos(tt))/T2) // dy

constraint 1 // outline only for only the post // Small Ellipse
formula: (x^2)/(Ra^2) + (y^2)/(Rb^2) - 1 = 0

constraint 2 convex // contact line
formula: (x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2) -  1 = 0
energy:
e1: 0.5*TERM1*dSx*WALLT/((Ra1*Rb1)^2)
e2: 0.5*TERM1*dSy*WALLT/((Ra1*Rb1)^2)
e3: 0

constraint 3  nonnegative// in plane of waist
formula: z - Rz

constraint 4 nonnegative // inside of cone
formula: 1 - ((x^2)/((Ra*(z/Rz))^2) + (y^2)/((Rb*(z/Rz))^2)) = 0

constraint 5 // outline only for only the post // Large Ellipse
```

```
formula: (x^2)/(Ra1^2) + (y^2)/(Rb1^2) - 1 = 0

vertex
1 0 0 0 fixed // origin

// Small Ellipse
2 0 Rb Rz fixed // Up (y)
3 0 -Rb Rz fixed // Down (-y)

4 Ra 0 Rz fixed // Right (x)
5 -Ra 0 Rz fixed // Left (-x)

// Initial Geometry
 6   0   rb  Rz constraint 2 3 // (y)
 7  Ra    0  Rz constraint 2 3 // (x)
 8   0  -rb  Rz constraint 2 3 // (-y)

 9   0  rb2 Rz2 constraint 2 // (y)
10 Ra2    0 Rz2 constraint 2 // (x)
11   0 -rb2 Rz2 constraint 2 // (-y)

// Large Ellipse
12 0 Rb1 Rz1 fixed // Up (y)
13 0 -Rb1 Rz1 fixed // Down (-y)

14 Ra1 0 Rz1 fixed // Right (x)
15 -Ra1 0 Rz1 fixed // Left (-x)

// Initial Geometery
16  -Ra    0  Rz constraint 2 3 // (-x)
17 -Ra2    0 Rz2 constraint 2 // (-x)


edge
// outline of the wall of the cone
1 2 12 fixed bare no_refine color red
2 3 13 fixed bare no_refine color red
3 4 14 fixed bare no_refine color red
4 5 15 fixed bare no_refine color red

//Small Ellipse
5 2 4 fixed constraint 1 bare no_refine color blue // large end outline
6 4 3 fixed constraint 1 bare no_refine color blue // large end outline
7 3 5 fixed constraint 1 bare no_refine color blue // large end outline
8 5 2 fixed constraint 1 bare no_refine color blue // large end outline

// Initial Geometry
 9  6  7 constraint 2 3 4
10  7  8 constraint 2 3 4
// 11  8  6 constraint 2 3 4

12 11 10 constraint 2 4
13 10  9 constraint 2 4
// 14  9 11 constraint 2 4

// 15  9  6 constraint 2
// 16  8 11 constraint 2
```

```
//Large Ellipse
17 12 14 fixed constraint 5 bare no_refine color blue // large end outline
18 14 13 fixed constraint 5 bare no_refine color blue // large end outline
19 13 15 fixed constraint 5 bare no_refine color blue // large end outline
20 15 12 fixed constraint 5 bare no_refine color blue // large end outline

// Initial Geometry
21 8 16 constraint 2 3 4
22 16 6 constraint 2 3 4

23 9 17 constraint 2 4
24 17 11 constraint 2 4


face
1 9 10 21 22 constraint 4
// 1 10  11   9 constraint 4
2 12 13 23 24 constraint 4
//2 12  13  14 constraint 4
// 3 16 -14  15 -11 constraint 4

body
1 1 2 density 0 volume 2

read
{refine edge where on_constraint 1}5  // make outline look smooth
{refine edge where on_constraint 5}5  // make outline look smooth
lh:={histogram(edge where not fixed, length)}
ah := histogram(face, area)
vug := {{V 3; u 3; g3}3;}
showq
set face backcolor red
k 10
rcl := refine edge where on_constraint 2
```

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