Wear Station Optimization for Knee Simulator Testing at Orthopaedic Innovation Centre

Final Project Report

MECH 4860 – Team 1

Submitted To:
Dr. Paul E. Labossiere, P.Eng

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Letter of Transmittal

December 6, 2017

Dr. Paul E. Labossiere, P.Eng
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Dear Dr. Labossiere,

The purpose of this report is to present the final redesigned reservoir and design process carried out by Team 1 for the Orthopaedic Innovation Centre artificial knee wear testing system.

This report contains an introduction to the problem, outlines the concept selection process, and concludes with a description of the final design and reflection on the project.

Sincerely,

Derek Calsbeck
Israel Hernandez
Mercy Onweni
Jeremy Smith

Executive Summary

The purpose of this report is to present the completed design of a system to minimize fluid loss and setup time of the knee wear simulator test at the Orthopaedic Innovation Centre (OIC). The OIC currently experiences a high frequency of low-fluid alarms in their closed-loop lubrication system, resulting in testing delays and missed deadlines. The primary objective of the project is to redesign the reservoir that contains the lubricant so that fluid loss due to evaporation from the reservoir is minimized. A secondary objective is to ensure that the reservoir is simple to set up and maintain.

An engineering design approach was used to develop a conceptual design based on six criteria: quality of seal, volume, ease of setup, overall simplicity, ease of manufacture, and fail-safe reliability. The design was optimized, and a manufacturing plan was developed for the reservoir.

The final design uses a threaded lid that compresses an O-ring to seal the container. The reservoir has inlet and outlet ports for the lubricant positioned on the top surface of the container. A vertical rod protruding upwards from the floor of the container serves as a guide for the magnetic level float. The entire design is made from 316 Stainless Steel and is compatible with the sterilizer used at the OIC. With the lid fully inserted, the reservoir has an overall height of 4.319”, an outer diameter of 4.75”, and a wall thickness of 3/16”. The reservoir volume has been increased to approximately 735 mL. The team is confident in the ability of the redesigned reservoir to perform as expected and meet the needs of the client, based on the systematic methodology used to arrive at the final design.

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1.0 Introduction

The study of the mechanical wear of artificial joints is crucial to the advancement of artificial joint technology to increase the lifetime of these products. This project focuses on improving a system used for artificial knee wear testing at the Orthopaedic Innovation Centre in Winnipeg, Manitoba. The purpose of this report is to present the completed design of a reservoir that contains the lubricant used in the artificial joint wear testing, as well as the process that was undertaken to develop this design. This introductory section defines the project background, problem statement, project objectives, project scope, assumptions and constraints. The sections that follow are the design process and optimization, a manufacturing plan, further recommendations for the project, and a project summary. Project planning details, the concept selection process, and supplemental details of the final design are presented in the three appendices following the report.

1.1 Project Background

The Orthopaedic Innovation Centre, or OIC, is an interdisciplinary organization consisting of engineers, technologists, scientists, and surgeons supporting the development of medical device technology [1], [2]. Among the many services that it provides for its customers, the OIC operates an orthopaedic clinic and provides testing of orthopaedic joints [1], [2].

One of the tests that the OIC conducts is wear testing on artificial knee joints. In these tests, which ordinarily run continually for six days, human joint conditions are simulated around the artificial joint – the lubricant used to simulate the synovial fluid of a knee joint is heated in a reservoir to 37°C before being circulated. The lubricant flows in a closed loop cycle from the reservoir, through a peristaltic pump, into the chamber where the joint is tested, and then back to the reservoir. The test setup, showing the closed loop circulation system, is shown in Fig. 1. The OIC has six of these lubricant circulation setups for knee simulator wear testing at their facility.

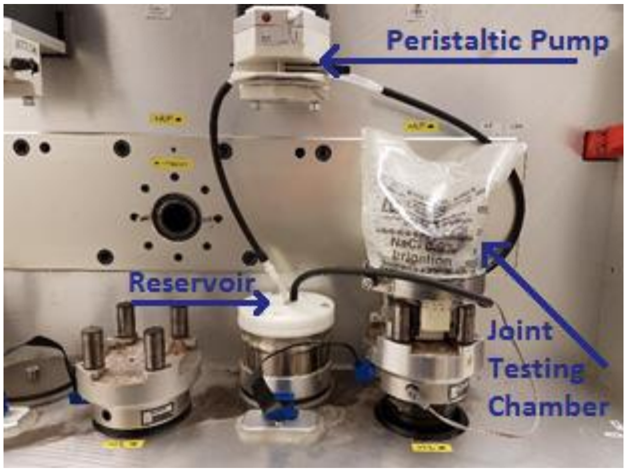


Figure 1. Closed circulation loop for lubricant used in knee simulator wear testing. The peristaltic pump is at the top, the joint testing chamber is on the right, and the reservoir is directly below the pump [3].

1.2 Problem Statement

The existing knee simulator wear testing system at the OIC routinely experiences unscheduled shutdowns due to low-fluid alarms in its closed-loop lubricant circulation systems. These testing delays result in missed deadlines for the customers of the OIC. It is suspected that lubricant is being lost from the closed loop by evaporation from the reservoir, shown in Fig. 2, as the reservoir lid does not seal the container properly. When the system shuts down due to the low-fluid alarm, the fluid must be replenished manually, which only happens on weekdays. Particularly significant delays are incurred if a test, which would have normally run over a weekend, is shut down by an alarm during the weekend and sits stagnant until it is started again on Monday.

Figure 2. Reservoir for lubricant in the closed-loop. The reservoir is suspected of allowing lubricant to evaporate [4].

In addition to the high frequency of low fluid alarms, the client has identified several other problems with the current reservoir design:

- The groove in the rim of the reservoir that is intended to hold the O-ring for sealing the container does not match a standard O-ring size, so the closest size of O-ring is difficult to fit into place, leading to poor sealing and more evaporation.
- The reservoir lid fastens to the rim of the reservoir using small screws that are cumbersome to manage.
- The reservoir is not made of materials that can withstand the 80°C temperatures it would experience in the sterilizer at the OIC.

1.3 Project Objectives

The primary objective of this project is to minimize the downtime experienced by the knee simulator wear testing system by redesigning the reservoir that contains the lubricant. The volume of synovial fluid (acting as the lubricant) in the circulation system must not drop below 100 mL over the course of a test. The reservoir, which is heated, is where the majority of the fluid evaporation occurs during testing. The customer has specified that an evaporation rate of 2 mL/hour or less of synovial fluid from the reservoir is the desired target. In addition to minimizing fluid loss from the system, the circulation of the lubricant must be reliable. This is to ensure that fresh lubricant is constantly replacing used lubricant at the knee joint, where protein degradation in the synovial fluid increases the friction between the moving parts and skews the test results if the lubricant is not circulated.

A secondary objective of the project is to decrease the amount of time and effort that is required to prepare the system for testing and maintain its components. The customer has specified five minutes as the target setup time for an improved design. Additionally, this objective includes the implementation of standard sizes of consumable components, such as the O-ring, the elimination of the use of cumbersome parts, like Allen keys and screws, and the selection of materials for the reservoir that are biocompatible and that can withstand temperatures of 80°C.

1.4 Scope

The scope of the project is limited to the redesign of the reservoir to eliminate fluid loss due to evaporation, and to improve the efficiency of the setup process by reducing the setup time. It is assumed that the reservoir is the cause of fluid loss; should the cause of fluid loss be determined to be something else, the scope will be modified accordingly to focus on the necessary components. However, no processes or equipment beyond the knee simulator wear testing system is considered.

1.5 Assumptions

The following assumptions are based on the most accurate information available.

- All team members are available to contribute to the project, especially in busy times leading up to project deadlines. Appendix A contains documents used for planning the project to anticipate busy periods in the schedule and to distribute work between team members.
- The major source of fluid loss from the circulation loop is evaporation from the reservoir.

1.6 Constraints

Several constraints on the project have been identified by the team. These constraints are listed below.

- The redesigned system components must fit within the current available space, be compatible with pre-existing equipment at the OIC, and meet safety requirements. This includes having the reservoir sit on top of the existing heating pad used for testing, using a magnetic float in the reservoir and magnetic sensor built into the heating pad for low fluid detection, ensuring that all materials in contact with the circulating synovial fluid are biomedical grade, and ensuring that all materials can withstand the 80°C temperatures experienced in the sterilizer.
- The components for the reservoir and any other parts of the system must be able to be either manufactured in-house (at Precision ADM, a division of the OIC) or sourced from a supply company.
- The team has a budget of $400 dedicated to internal costs associated with the course.

2.0 Design Process

Based on customer statements about the original design and the project objectives, needs and target specifications for the product are identified by the team to facilitate the concept generation process. The design process described in this section outlines the transition from customer statements about the existing product to the concept selection for a redesigned product.

2.1 Original Design

The original design consists of both stock parts and parts manufactured in-house. A 316 SS container from Polarware is used for the body, with an inner diameter of 4.029" and a wall thickness of 0.046". Underneath the container is a 1" thick by 4.31" diameter counter-bored aluminum base, into which the container is fitted. Two delrin pieces fasten to the top of the container body: a flange and a lid. The flange is silicone sealed inside the rim of the container, with a groove machined at the top to fit an O-ring. The lid has an outer diameter of 4.50" and is secured to the flange with three equally spaced 1/8" hex head screws. A steel outlet tube for the lubricant has an outer diameter of 0.148" and protrudes through the center of the lid. This outlet tube also serves as the guide pole for the magnetic level float. The inlet to the container is adjacent to the outlet but has a larger outer diameter and is made of delrin. The overall height of the original reservoir is 3.21", with a maximum diameter of 4.50" and maximum volume of just over 400 mL. The low fluid alarm is activated when 100 mL of fluid remains in the container, corresponding to the fluid level being 1.17" above the heating element. Fig. 3 and Fig. 4 show the features of the original reservoir.

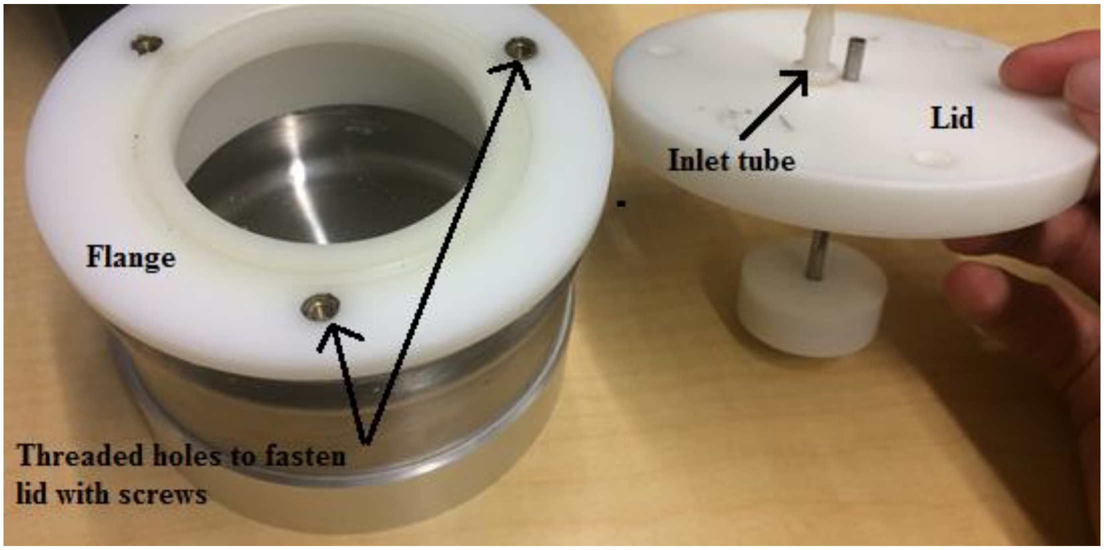


Figure 3. Photo of the original reservoir

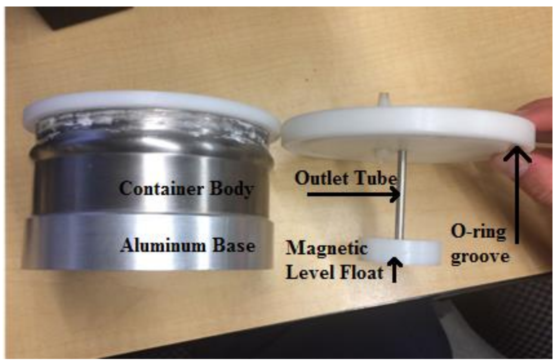


Figure 4. Side view of the original reservoir

2.2 Customer Statements and Needs

Table I records problems identified by the customer in the current system, and the corresponding basic need identified by the project team.

TABLE I
CUSTOMER STATEMENTS AND NEEDS REGARDING THE KNEE SIMULATOR WEAR TESTING STATION

Customer Statements and Needs			
Need #	**Statement**	**Need**	**Category**
1	The low-fluid sensor often goes into alarm and stops the testing	System runs consistently and reliably with minimal loss of fluid	reliability
2	Lubricant is necessary to prevent the test parts from being destroyed during testing	The system circulates lubricant	operation
3	The circulation path may accumulate proteins, causing clogs and shutdowns	Circulation path remains clear of obstructions	reliability
4	Inlet and outlet in knee-testing compartment should not use 90° elbows because they get clogged	The system allows lubricant to flow without obstruction	reliability
5	Current reservoir holds 400 mL and usually requires topping up during testing	Reservoir contains at least the same volume as the original reservoir	operation
6	Inlet tube slides up and down undesirably in the lid	Apparatus setup is reliable during testing and between tests	setup
7	Inlet and outlet from the reservoir are too close together	The system is simple to set up and use	setup
7	The screws to fasten the lid to the reservoir are cumbersome	The system is simple to set up and use	setup
8	The system takes a long time to set up	The system setup time is decreased	setup
9	Current setup cannot be cleaned in the sterilizer because of the high temperature	System can be cleaned using current equipment	maintenance
10	Precision ADM can manufacture most of the necessary components	Major components are simple to manufacture at Precision ADM	manufacture
11	The magnetic sensor shuts down the testing if the fluid level gets too low	A failsafe is in place to prevent a dry run if the fluid depletes	safety
12	The magnetic float can get stuck on the vertical tube	The failsafe system functions reliably	safety
13	Microbial contamination is a problem to be avoided	Materials comply with medical standards	safety, compatibility

CUSTOMER STATEMENTS AND NEEDS REGARDING THE KNEE SIMULATOR WEAR TESTING STATION (CONTINUED)

Customer Statements and Needs			
Need #	**Statement**	**Need**	**Category**
13	316SS is used since it is closer to medical grade, but medical grade is best	Materials comply with medical standards	safety, compatibility
14	Space is limited for the reservoir	Reservoir is compatible with current test setup	compatibility
14	The reservoir sits on the sensor base	Reservoir is compatible with current test setup	compatibility
15	Inlet and outlet from the reservoir should have the same diameter	System uses standard fittings and components	compatibility
15	The O-ring doesn't fit into the groove on the lip of the reservoir under the lid	System uses standard fittings and components	compatibility

In Table I, wherever multiple statements result in the same need being identified, the rows containing those statements are given the same need number. This way, the needs are more easily translated into metrics in Section 2.3.

2.3 Specifications and Metrics

Based on the needs identified in Table I in Section 2.2, metrics are developed which are used to define concept evaluation criteria. These metrics, along with the estimated target values for each one, have been presented to the customer and adjusted as per their requests to ensure that these proposed metrics align with their priorities. Table II presents these metrics and makes note of the needs fulfilled by each metric.

TABLE II
METRICS AND TARGET SPECIFICATIONS OF THE KNEE WEAR TESTING WORKSTATION

Target Specifications						
Metric #	**Metric # in HOQ**	**Need #s**	**Metric**	**Importance (max. 5)**	**Units**	**Estimated Target**
1	1	1	Rate of evaporation from reservoir	5	mL/ hour	< 2 mL/hour
2	N/A	1, 2, 3, 4	Flow rate of fluid through the system	3	mL/ min	TBD
3	2	5	Volume of reservoir	4	mL	> 400 mL (500 mL preferred)
4	3	6, 7, 8	System setup time	4	min.	5 min
5	4	6, 7, 8	Simplicity of the set-up process	3	subj.	subj.
6	5	9	Max. temperature the reservoir can withstand in sterilizer	3	°C	> 80 °C
7	6	10	Manufacturability	4	subj.	subj.
8	N/A	11	Fluid volume in reservoir at which system shuts down for safety	4	mL	100 mL

METRICS AND TARGET SPECIFICATIONS OF THE KNEE WEAR TESTING WORKSTATION (CONTINUED)

Target Specifications						
Metric #	**Metric # in HOQ**	**Need #s**	**Metric**	**Importance (max. 5)**	**Units**	**Estimated Target**
9	7	12	Ease with which magnetic float slides on tube for failsafe	3	subj.	subj.
10	8	13	The materials used comply with medical standards	5	true/ false	true
11	9	14	Diameter of reservoir	2	mm	= current dia.
12	10	15	Standard size of reservoir inlet and outlet (ID/OD)	1	inch	standard size
13	11	15	Standard seal size (diameter)	4	inch	standard size

2.4 Concept Selection Methodology

A high-level description of the concept selection process is presented in this section, while the details of the concept selection process are presented in Appendix B.

The first step of the concept selection is to identify the major concerns raised by the client with the current design. The method for the selection process is known as TRIZ 40: The Theory of Inventive Problem Solving. One of the 40 methods is segmentation, in which the design problem is broken into segments. This approach is adopted to redesign the reservoir.

First, concept evaluation criteria are developed from the metrics in Section 2.3. A weighting matrix is then used to prioritize the criteria according to their relative importance. Solutions are brainstormed by each team member and are subject to group evaluation and screening. When screening the concepts, each one is given a rating between 1 and 5 for every selection criterion. These ratings are then multiplied by the weight of the corresponding criterion, and the rating are summed for each component to produce an overall score. The concepts for each reservoir component with the highest overall score proceeds to the final design stage.

3.0 Final Design Details

The final design optimization is performed by communicating with the client to clarify their preferences for the design, consulting individuals with expertise in different manufacturing processes, and making changes to the design in accordance with the feedback from the client and the advisors. This process is repeated over the course of the final design phase to transform the conceptual design into a final design that satisfies the needs of the client. Section 3.1 contains a summary of the redesigned reservoir and a discussion of the extent to which it satisfies customer requirements, expressed as metrics. In Section 3.2 the clearance between the reservoir and the constraining elements in the environment is checked. Finally, Section 3.3 contains renders of the final design.

3.1 Design Overview

The redesigned reservoir consists of six components: the container body, flange, lid, inlet tube, outlet tube, and level float. The flange is welded onto the body, and the inlet and outlet tubes protrude through small holes in the flange and are welded or brazed in place. The level float slides vertically on a guide pole that protrudes out of the floor of the container, and the lid, with an octagonal grip and external threads, screws into the flange, which has internal threads in a central hole. Table III presents overall dimensions for the redesigned reservoir.

TABLE III
FINAL OVERALL DIMENSIONS OF THE REDESIGNED RESERVOIR

Measurement	**Value**
Total reservoir height (to top of lid, when lid is fully inserted)	4.319 in.
Lid height	0.5 in.
Flange height	0.5 in.
Container and flange OD	4.75 in.
Flange ID	1.759 in.
Container wall thickness	0.188 in.
Max. width of the lid handle	2.875 in.
Approximate volume, with lid fully inserted	735 mL
Remaining volume at low fluid alarm	215 mL

The redesigned reservoir is compared to the original reservoir in Table IV, indicating how each feature fulfills the target metrics and improves on the original reservoir design. Overall, it is seen that the redesigned reservoir minimizes evaporation of the fluid out of the container during testing and reduces set-up time.

TABLE IV
COMPARISON OF ORIGINAL AND REDESIGNED RESERVOIR

Component/ Quality	**Original Reservoir**	**Redesigned Reservoir**		
		Features	**Function**	**Metric # Satisfied**
Lid	Delrin; Fastened to container with screws.	316SS; Octagonal grip; Hanging portion with external threads.	Screws into flange to compress O-ring; Inhibits fluid from escaping.	1,4,5
Container Body	Cylinder; 316SS with aluminum base for sensor.	Cylinder; 316SS with chamfers and an indent in the base for sensor.	Compatible with the existing testing system.	5,6,7
Reservoir Volume	Can contain ~400 mL of lubricant.	Can contain up to 735 mL of lubricant.	Has larger buffer volume before alarm.	3,7,8,10
Sealing	Uses an O-ring and three small screws. O-ring does not fit groove.	Uses an O-ring compressed by a threaded lid.	The O-ring groove fits a standard O-ring size to seal the reservoir.	1,4,5,12,13
Inlet and Outlet Ports	Inlet and outlets ports are close together, and are positioned on the lid.	More separation between the tubes; Tubes protrude through flange, and are welded; Hoses connect to tubes with clamps.	Clamps ensure seal between tube and hose. Weld or braze ensures seal around tubes.	2,4,5,11
Magnetic Sensor	Guide pole protrudes through lid; Sensor detects low fluid at 100 mL.	Guide pole built into the floor of the container; Level sensor slides on and off from the top.	Sensor detects low fluid at 215 mL.	7,8,9

The actual rate of evaporation from the reservoir is difficult to predict with precision, due to the complex nature of the problem. However, a comparison of overall expected performance between that of the original reservoir and the redesigned reservoir is simple to effectuate. In the original reservoir, with a capacity of approximately

400 mL, the OIC could only afford to have 300 mL of fluid evaporate over the course of a test, or else the low fluid alarm would go off. However, the redesigned reservoir, with a maximum volume of 735 mL and a low fluid volume of 215 mL, can afford 520 mL to evaporate before experiencing a shutdown. This represents an increase in effective reservoir volume of over 70%.

In addition to the larger buffer volume of the redesigned reservoir, its sealing design is also improved from that of the original reservoir. The original design had an O-ring groove that was not sized to fit a standard size of O-ring, and screws that inadequately mated the lid to the container flange. In the redesigned reservoir, the groove for the O-ring fits a standard, predetermined size of O-ring, and all connecting points through the flange on the top of the container have welded connections to provide a reliable barrier between the interior and exterior of the container.

In the redesigned reservoir, the guide pole for the magnetic float has a 0.5 in. fillet at its base for structural reasons. This restricts the magnetic float from descending to the very base of the pole. At its lowest allowable position, the magnetic float can be 1.078 in. above the surface of the heating element, corresponding to the aforementioned volume of 215 mL of lubricant in the container. In contrast, the original reservoir would go into alarm with 100 mL of lubricant remaining, corresponding to a height of 1.00 in. above the heating element. The fillet therefore necessitates the recalibration of the low fluid sensor to be triggered at a height of 1.078 in. above the heating element instead of the original 1.00 in.

3.2 Dimensional Validation

The lack of available space around the location where the reservoir will operate imposes restrictions on the dimensions of the redesigned container. A photo sent to the team by the client, showing some dimensions around the test setup, is shown in Fig. 5.

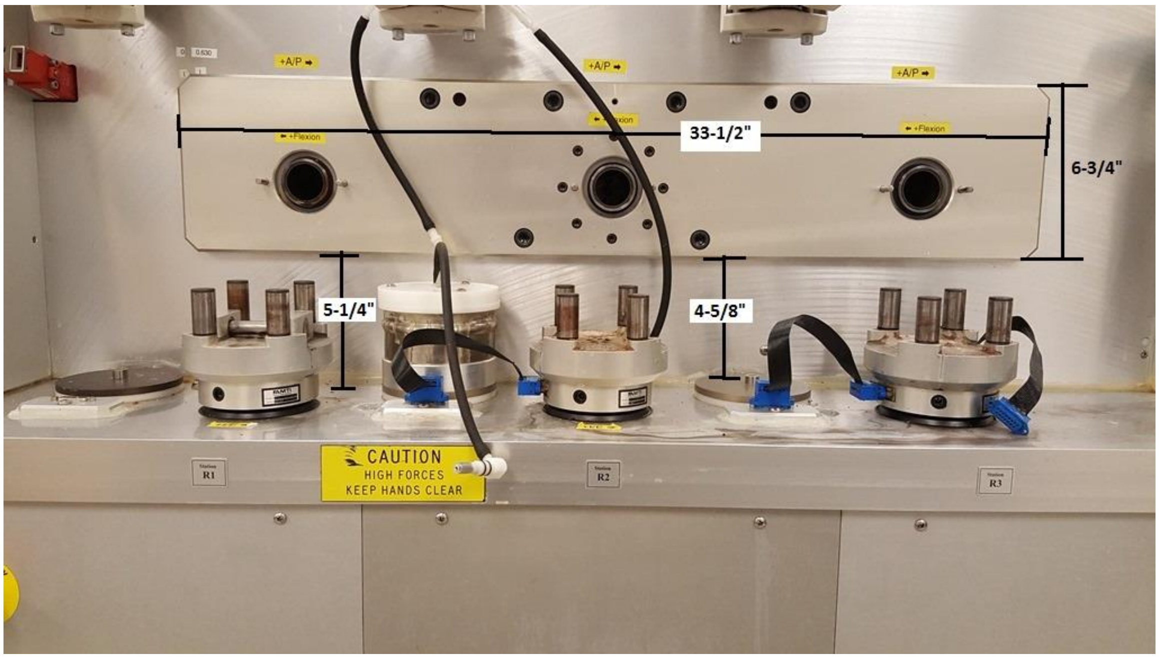


Figure 5. Dimensions of components around the test setup

The A/P actuator plate is the plate of length 33-1/2” mounted on the back wall. In addition to the dimensions indicated in Fig. 5, more relevant dimensions were obtained from the client in separate correspondence. Table V summarizes the environmental dimensions provided by the client that are useful for calculating the minimum clearance between the reservoir and other components of the test setup.

TABLE V
ORIGINAL CLEARANCE DIMENSIONS WITH THE ENVIRONMENT

Measurement	Value
Vertical distance between top of heating element and bottom of A/P actuator plate	4.625 in.
Thickness of A/P actuator plate	0.625 in.
Diameter of heating element	4.31 in.
Distance from edge of heating element to back wall	0.2335 in.

Using the dimensions tabulated in Tables III and V, along with dimensions of other features of the lid and container, the minimum clearances between reservoir components and the environment are obtained to validate that there are no interference issues with the redesigned reservoir. The calculated minimum clearances are summarized in Table VI, while the calculation details are found in Appendix C.

TABLE VI
MINIMUM CLEARANCES BETWEEN THE REDESIGNED RESERVOIR AND THE TEST SETUP

Distance to Calculate	Minimum Clearance
Distance from outside of container to back wall	0.0135 in.
Vertical clearance between top of flange and bottom of A/P actuator plate	0.806 in.
Horizontal clearance between outside of lid handle and A/P actuator plate	0.326 in.
Horizontal clearance between outlet (suction) tube and magnetic float	0.906 in.
Clearance between container wall and outlet (suction) tube	0.3435 in.
Clearance between ID of magnetic float and OD of its vertical guide pole	0.0125 in.
Vertical clearance between top of float guide tube and underside of lid	0.5 in.
Horizontal clearance between top of float guide tube and lid	0.425 in.

Fig. 6 shows an engineering drawing of the completed reservoir design. The rest of the drawings are found in Appendix C.3.

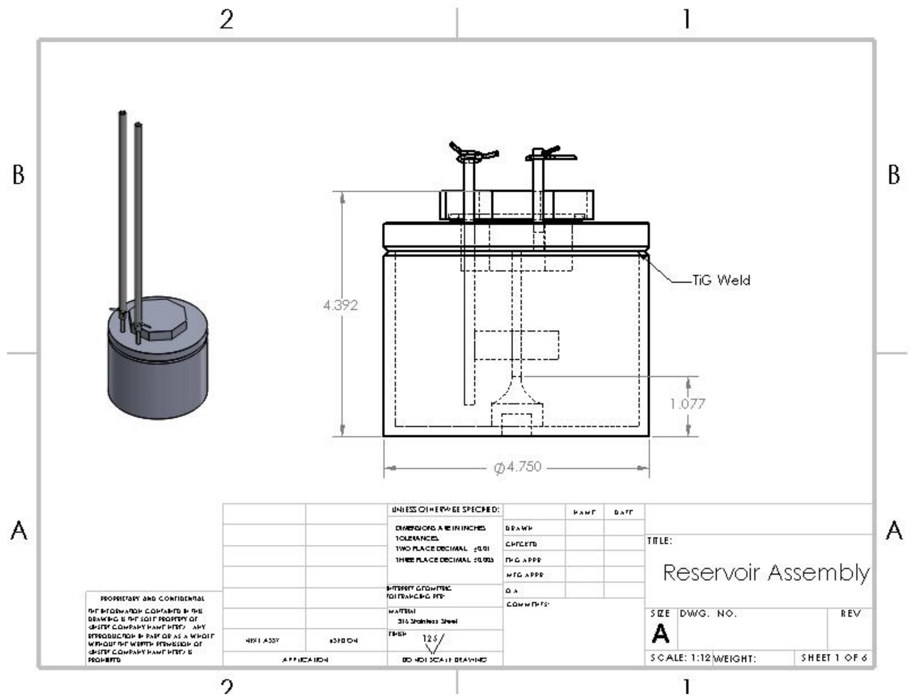


Figure 6. Engineering drawing of the redesigned reservoir assembly

3.3 Renders

Final renders of the redesigned reservoir are presented in Fig. 7 through Fig. 12, both in assembled form and as individual components.

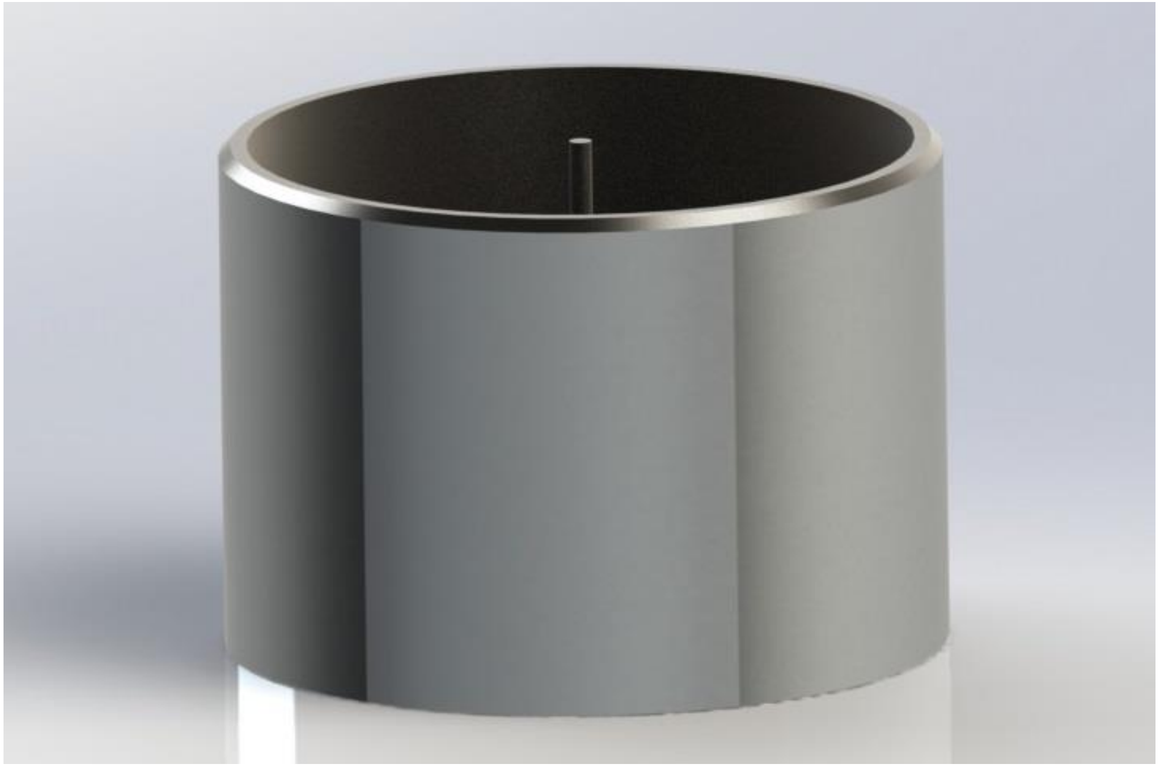


Figure 7. Render of final container body

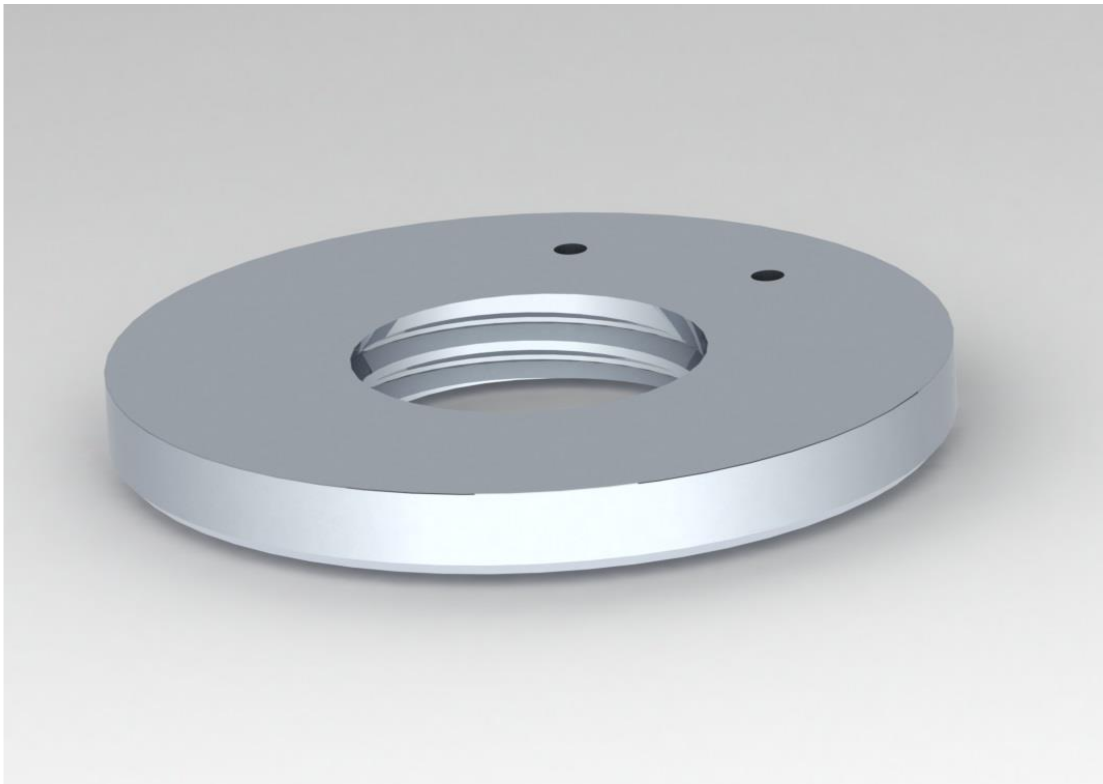


Figure 8. Render of final flange design

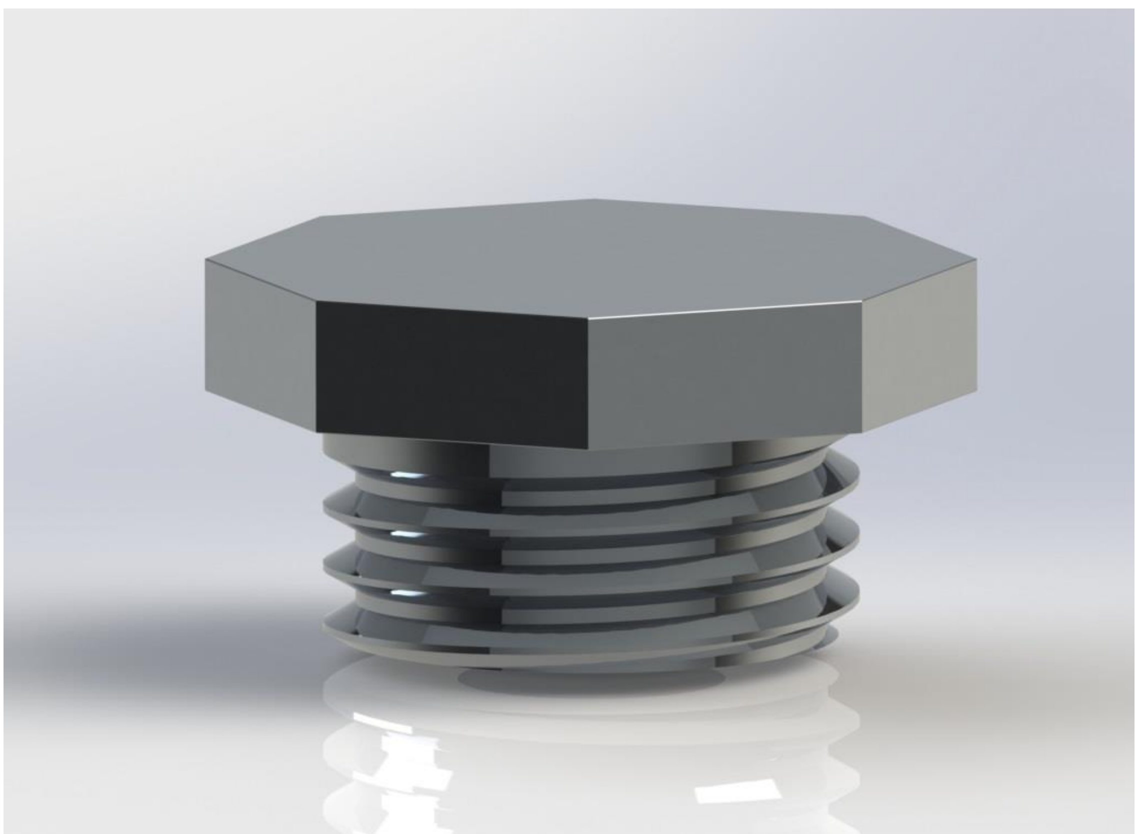


Figure 9. Render of final lid design

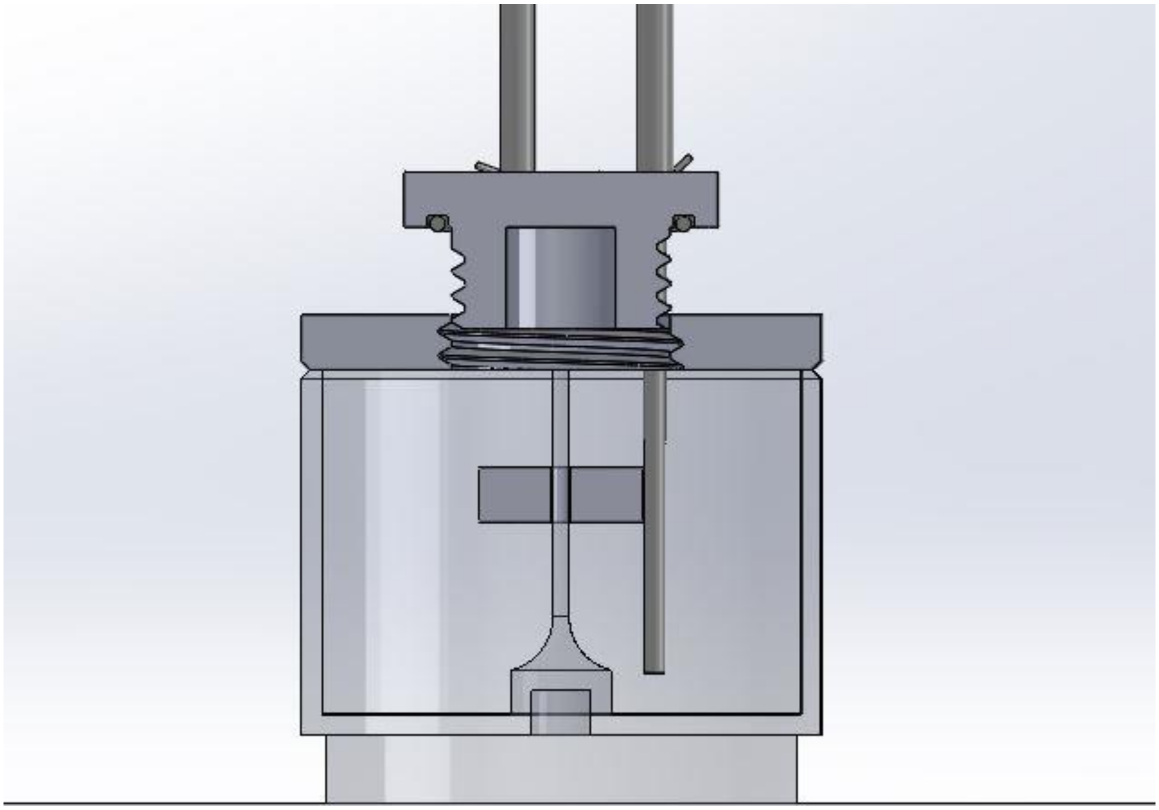


Figure 10. Section view in 3D of redesigned reservoir

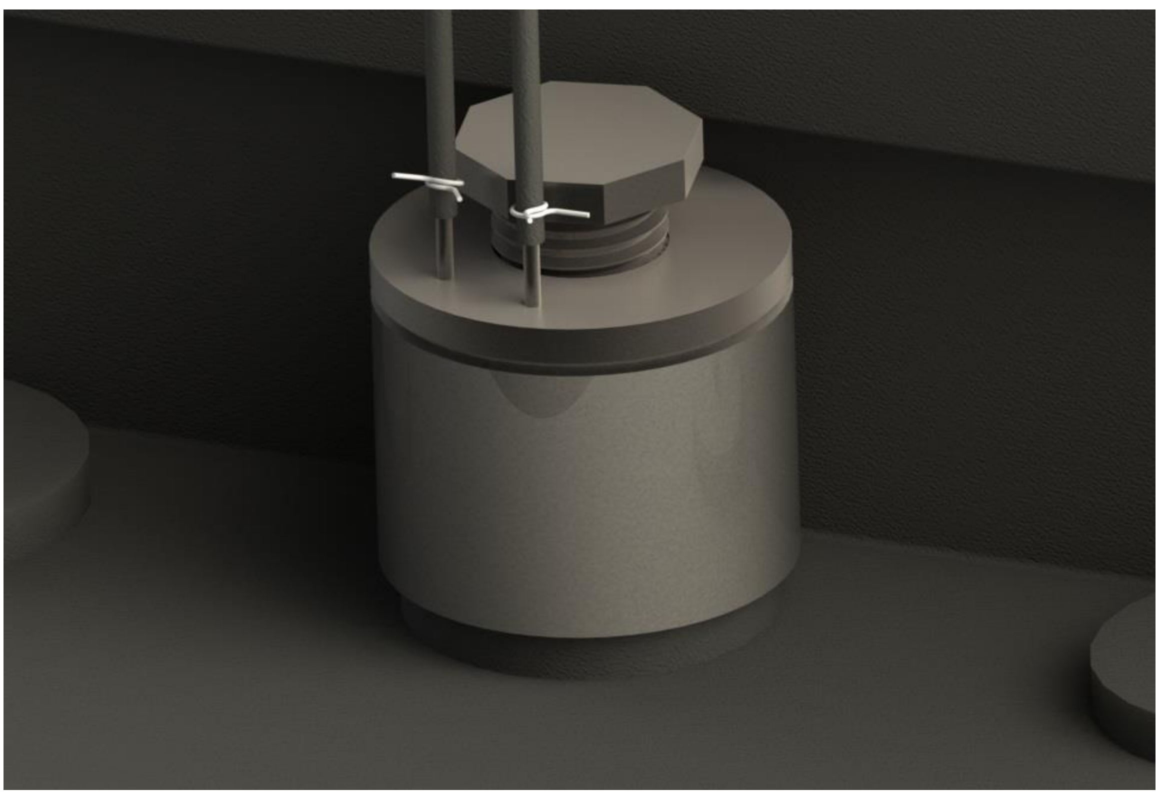


Figure 11. Close-up render of the redesigned reservoir

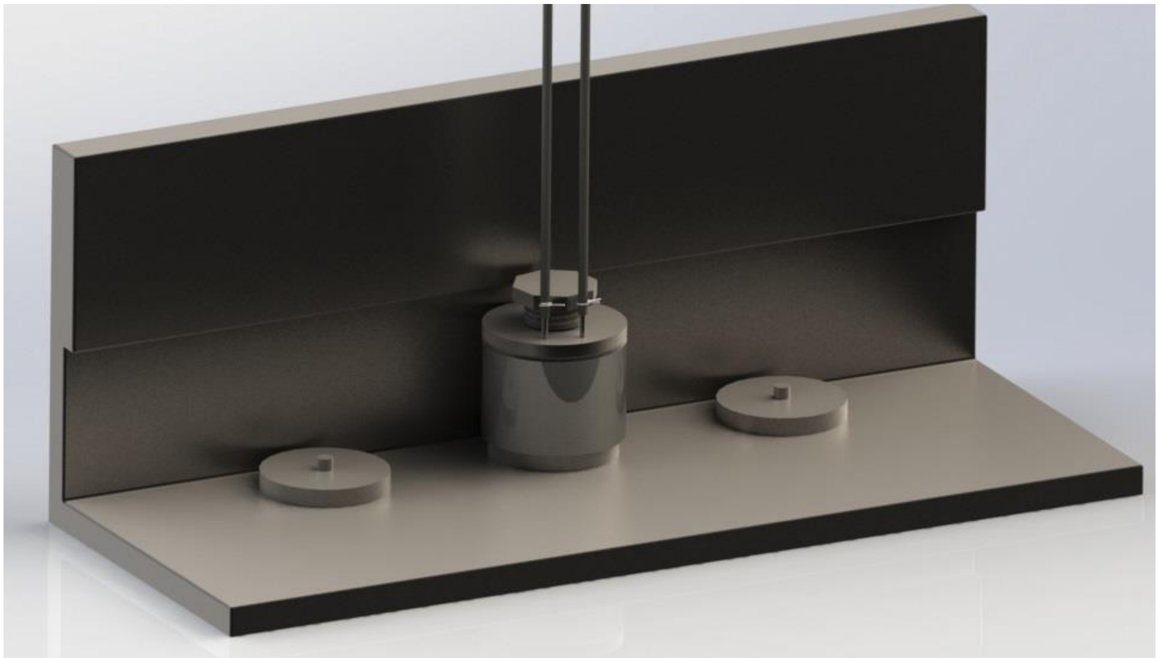


Figure 12. Render of the positioning of the reservoir in the test setup under the A/P actuator plate

4.0 Manufacturing Plan

This section of the report outlines all raw materials and processes required for the manufacturing of the reservoir, as well as the costs and companies associated with manufacturing.

4.1 Bill of Materials and Product Cost

The Bill of Materials (BOM) is given in Table VII below. The total cost of the raw material required for one container is $283.73.

TABLE VII
BILL OF MATERIALS

Inventory List					
Inventory ID	**Name**	**Description**	**Unit Price**	**Qty.**	**Inventory Value**
1800T251	316 Stainless Steel Tubing Precision	0.188" OD, 0.005" Wall Thickness, 1 ft. Length	$15.54	1	$15.54
9260K6	Highly Corrosion-Resistant 316 Stainless Steel Disc	5" Diameter, 5" Length	$196.67	1	$196.67
9260K3	Highly Corrosion-Resistant 316 Stainless Steel Disc	3" Diameter, 2" Length	$49.51	1	$49.51
9452K650	Oil-Resistant Buna-N O-Ring	1/8 Fractional Width, Dash Number 227. Actual: OD 2.387", ID 2.109". 100 per pack.	$14.21	1	$14.21
5324K52	Constant-Tension Spring Clamps	Zinc Plated Steel, for 5/16" OD Firm Hose and Tube. Per pack of 100	$7.80	1	$7.80
Total per container	-	-	-	1	$283.73
Total	-	-	-	6	$1,702.38

4.2 Procedures

To manufacture the reservoir, several components must be made from the raw materials outlined in the BOM and then assembled together to create the final product. These steps are not intended to be followed or given to a machinist, but are merely to provide the client with an idea of how the team intends the redesigned reservoir to be made using conventional machining methods.

The first component to be made is the container body from a billet of 316 SS 5” OD x 5” L. This will be made from the following steps on lathe:

1. Part the billet to make the overall length 3.32 in.
2. Turn down the outer diameter to 4.75 in.
3. Drill a hole of diameter 0.544” to a depth of 0.403”.
4. Flip the workpiece.
5. Using a boring tool, remove material from the inside, to a depth of 2.73”. Turn down the inside diameter from 4.375” to .148”. This will create the guide for the magnetic sensor.
6. Bore further to a depth of 3.132” and turn down to a diameter 4.375” to 0.925”. This will create the step.
7. Make a 45° chamfer of depth 0.079” son the top edge of the container.

Next, make the lid from a billet of 316 SS 3” OD x 2” L. Use the following steps to create the part on a lathe:

1. Turn down the OD of the workpiece to 2.875”.
2. Turn down the diameter of the workpiece from 2.875” to 2.00” by 0.925” length.
3. Make a 2 – $4^{1/2}$ UNC 2A thread along the minor diameter.
4. Bore out a hole to a depth of 0.925” and a diameter of 1.00”.
5. Machine the groove for the O-ring to a depth of 0.106” and a width of 0.189”.
6. On a mill, machine the octagon shape such that each side is 1.10” long.

Next, make the flange from the piece parted in step 1 of the container. The first step in creating the flange must be done on lathe.

1. Turn down to a diameter of 4.75” and a thickness of 0.50”. Put a 45° to a depth of 0.079” on one side.
2. Drill 2 holes of diameter 7/32”.
3. Install 2 3/16” SS tubes in the newly made holes, ensuring that the inlet tube and outlet tube are sticking out 1.25” above the flange.
4. Weld or braze the tubes around their OD on both sides of the flange to ensure a complete seal.

Next, assemble the reservoir. Align the OD of the flange with the OD of the container. Weld the 2 components together along the 45° chamfers, ensuring the weld beads through to the inside of the container.

The container must then be put back on the lathe to create the threaded opening. This can be accomplished from the following steps:

1. Bore a thru-hole in the flange 1.7594” in diameter. Ensure the hole is square so that lid aligns with the container hole.
2. Make a 2 – $4^{1/2}$ UNC 2A thread along the newly created bore hole.
3. Touch up the weld bead by turning or grinding to match the surface finish of container.
4. Apply a small 45° chamfer of depth 0.005” on all the outer edges so they are not sharp.

The raw materials and off-the-shelf components can all be purchased through the McMaster-Carr website. All machining can be done at Precision ADM, the sister company of the OIC. Any welding that cannot be done at Precision ADM can be contracted to several local welding specialists, such as Anything Custom or Specialloy.

5.0 Recommendations

Design recommendations that were considered but not implemented into the redesigned reservoir are presented in this section, as well as future plans for the team regarding the project.

5.1 Design Recommendations

For this project, the team focused exclusively on the reservoir used to store the synovial fluid during the wear testing. However, there are other components within and beyond the testing station that can be evaluated to further optimize the knee wear testing station. One component of the station that may be a source of evaporation during testing is the bag used to house the knee joint. The method by which the bag is installed around the knee joint is cumbersome. In past tests, small amounts of fluid have tended to escape the bag containing the artificial knee joint. Given more time, a more reliable method of housing the joint should be explored. Another task that merits further attention is the creation of a prototype. This will allow for the functionality of the final design to be entirely validated.

Another issue that could be further explored is the effect of degraded proteins gathering inside the reservoir. This has been responsible for causing the magnetic sensor to stick and has the potential to block the outlet tube. While the team took this into consideration during the concept generation phase, preventing the accumulation of proteins was not critical to the success of the final design. Given more time, further investigation into this problem could be explored so that this problem could be reduced or eliminated. One possible solution would be to give the magnetic float a larger bore diameter to increase clearance between the float and its guide shaft. An additional benefit of this change would be that the float could descend lower on the float guide shaft. In the final design presented in this report, the low fluid sensor is activated with approximately 215 mL of lubricant remaining in the container. If the float could descend lower on the shaft and fit around the top of the fillet, the sensor could be made to detect a low-fluid alarm at a volume less than 200 mL, giving the redesigned reservoir a greater functional volume.

5.2 Future Plans

After the requirements of this design course are fulfilled, including developing engineering drawings, bill of materials and analysis of the final design of the reservoir, OIC has suggested that our team be present during the first knee wear test of the redesigned reservoir once manufactured. The team has decided to follow through with the fabrication of the redesigned reservoir with the OIC and other personnel involved in the manufacturing process.

6.0 Conclusion

This report outlines the optimization of the knee simulator wear testing project at the Orthopaedic Innovation Centre, focused on the redesign of a reservoir that contains lubricant for the testing. The problem is that lubricant is evaporating from the reservoir, resulting in low fluid alarms that shut down the tests.

Before starting the design process, objectives are identified and the customer needs are quantified using metrics. Then, design concepts are generated and evaluated to arrive at a final design concept. Finally, the design is optimized and a manufacturing plan is developed through consultation with the client, advisors, and experienced tradesmen.

The final design is composed of six components: container body, flange, lid, inlet and outlet tubes, and level float. The body, flange and tubes are all made from 316 medical-grade stainless steel and are welded together to provide sealed connections. Hoses can be fastened to the tubes using spring clamps. The container is sealed using a standard sized O-ring that is compressed by a small, threaded lid, also made of 316 SS, for easy assembly and a tight seal. The overall height of the redesigned reservoir is 4.319 in. and the diameter is 4.75 in. It can contain up to 735 mL of fluid. There is at least 0.326 in. of clearance between the container and the A/P actuator plate to avoid any interference. Additionally, the redesigned reservoir is now compatible with the sterilizer at the OIC for ease of maintenance. Overall, the team is satisfied with the reservoir design and is confident that all of the needs of the client have been met, based on the thorough concept generation, evaluation, selection and optimization processes that were undertaken.

7.0 References

[1] Orthopaedic Innovation Centre. (2016). *About the OIC | Orthopaedic Innovation Centre* [Online]. Available: http://www.orthoinno.com/about/about-oic/ [September 27, 2017].

This source is the "About the OIC" page on the OIC's website. It was used in this report for its list of the various roles of team members who work at the OIC and for its description of the services that are offered there. It is particularly helpful when it summarizes the work of the OIC as "supporting the medical device industry." It is taken for granted the OIC describes their own identity accurately. (JS)

[2] Contact Canada. (n.d.) *Orthopaedic Innovation Centre Inc. « Canadian Medical Technologies Directory « Contact Canada* [Online]. Available: http://www.contactcanada.com/database/freesearch.php?portal=0a4&action=view_profile&id=11721 [September 27, 2017].

This website is a directory for Canadian medical technology companies. The database contains a summary of each company, and includes a profile for the Orthopaedic Innovation Centre. The website is useful for this report because of its summary of the wide scope of work done at the OIC. Its accuracy is validated by cross-checking its information with that given by the OIC website itself. (JS)

[3] J. Smith. "One Loop Setup.jpg." Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Sept. 14, 2017.

This photograph was taken at the Orthopaedic Innovation Centre during a site visit, and is used in this report with their permission. It shows the complete closed loop cycle that circulates the synovial fluid, used as the lubricant in knee simulator wear testing. The reservoir for the lubricant is centred at the bottom of the photograph, while the peristaltic pump is directly above the reservoir. The knee simulator testing chamber is seen to the right of the other components. (JS)

[4] J. Smith. “Reservoir setup.jpg.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Sept. 14, 2017.

This photograph was taken at the Orthopaedic Innovation Centre during a site visit, and is used in this report with their permission. It is a close-up shot of the reservoir for the lubricant. The black tube is the lubricant inlet, while the white tube is the outlet, through which lubricant is drawn by the pump (not shown in this photograph). (JS)

[5] Hi-Tech Seals Inc., "O-ring Design Guide," Hi-Tech Seals Inc., [Online]. Available: http://www.hitechseals.com/includes/pdf/o-ring_brochure.pdf. [Accessed Nov. 10, 2017].

Hi-Tech Seals is a company that sells a variety of different seals and information on how to determine the correct specifications for a particular seal setup. The online O-ring design guide provided information required to specify the dimensions of the groove to fit the standard O-rings used at the OIC so the team could correctly model the groove in SolidWorks. (DC)

[6] D. Dunn, "Solid Mechanics Dynamics: Tutorial - Forced Vibrations," [Online]. Available: http://www.freestudy.co.uk/dynamics/forced%20vibrations.pdf. [Accessed Nov. 9, 2017].

This source is from an online tutorial about forced vibrations in solid mechanics models. This document contained several equations and examples for various vibration models such as cantilever, simply supported, and fixed end supports. The cantilever model was used to determine the speed at which whirling would occur when creating the magnetic sensor guide shaft. This was crucial for verifying the team’s manufacturing plan. (DC)

Appendix A: Project Management

Contents

List of Figures

List of Tables

Appendix A contains documents that were developed in the first stage of the project, which is known as the Project Definition Phase, in order to clearly define the tasks required to complete the project, the timeline to complete the tasks, and the resources available to the team.

A.1 Project Planning

To organize the work required to complete the project, the project work has been divided into three phases: Project Planning (Phase I), Design (Phase II) and Final Development (Phase III). Within each phase are specific tasks, some of which are subsequently divided further into more specific tasks. These individual tasks are listed in the Work Breakdown Structure, or WBS (Section A.2). The WBS tasks are then scheduled in a Gantt Chart (Section A.3), and have team members assigned to each one in a Responsibility Assignment Matrix (Section A.4). The primary resources available to the team are listed in Section A.5.

The Project Planning phase focuses on the development of the plan to execute the project. This consists of the preparation of project management elements to be used over the course of the project, and the identification of project requirements in conjunction with the client. The Design phase is focused on the selection and design of the best concept for a solution. The Final Development phase of the project includes the optimization of the selected concept to arrive at the final design. This final design includes engineering drawings and set-up process that would be used to manufacture the reservoir including criteria to validate its fulfillment of the design requirements. The Final Development phase also consists of the compilation of the final design and procedure used along the way into one final report, as well as presentations to display the results.

A.2 Work Breakdown Structure

The Work Breakdown Structure (WBS) lists all major tasks and sub-tasks required for completion of the project in the three phases. As the WBS is a “living document,” some tasks may be adjusted as necessary over the course the project.

Work Breakdown Structure

1. **Phase I – Project Planning**
    - 1.1. Meeting with Team and Client
        - 1.1.1. Stakeholder Registry
        - 1.1.2. Resource Registry
    - 1.2. Outline Team Roles and Responsibilities
    - 1.3. Identify Customer Needs
    - 1.4. Create Gantt Chart
    - 1.5. Identify specifications, constraints and limitations
    - 1.6. Relate needs to specifications and create HOQ
    - 1.7. Project Definition Report
        - 1.7.1. Project Charter
        - 1.7.2. Hand in Report
    - 1.8. Oral Presentation
2. **Phase II – Design**
    - 2.1. Confirm Design Specifications
    - 2.2. Concept Generation
        - 2.2.1. SCAMPER
        - 2.2.2. 5 Step Brainstorming Method (Clarify, External/Internal Search, Systematic Exploration, Reflect on Process)
        - 2.2.3. Group Brainstorming
        - 2.2.4. External search, patents, etc.
    - 2.3. Concept Selection
        - 2.3.1. House of Quality
            - 2.3.1.1. Determine Top Metrics
            - 2.3.1.2. Determine Relationship Between Metrics
        - 2.3.2. Selection
            - 2.3.2.1. Weighting Matrix
            - 2.3.2.2. Scoring Matrix
    - 2.4. Modelling
        - 2.4.1. CAD Model
        - 2.4.2. Preliminary Drawings

2.5. Concept Design Report
2.6. Optimization

3. Phase III – Final Development

3.1. Final Design
3.1.1. Drawings
3.1.2. BOM
3.1.3. FMEA
3.2. Draft Report
3.3. Final Report
3.3.1. Compile Sections
3.3.2. Team Reflection
3.4. Oral Presentation
3.5. Poster Presentation
3.6. Exit Program Survey

A.3 Gantt Chart

The Gantt Chart shown below in Fig. A-1 gives a visual representation of the anticipated schedule for the project. Some tasks from the WBS are compressed together or are omitted for clarity in the Gantt Chart.

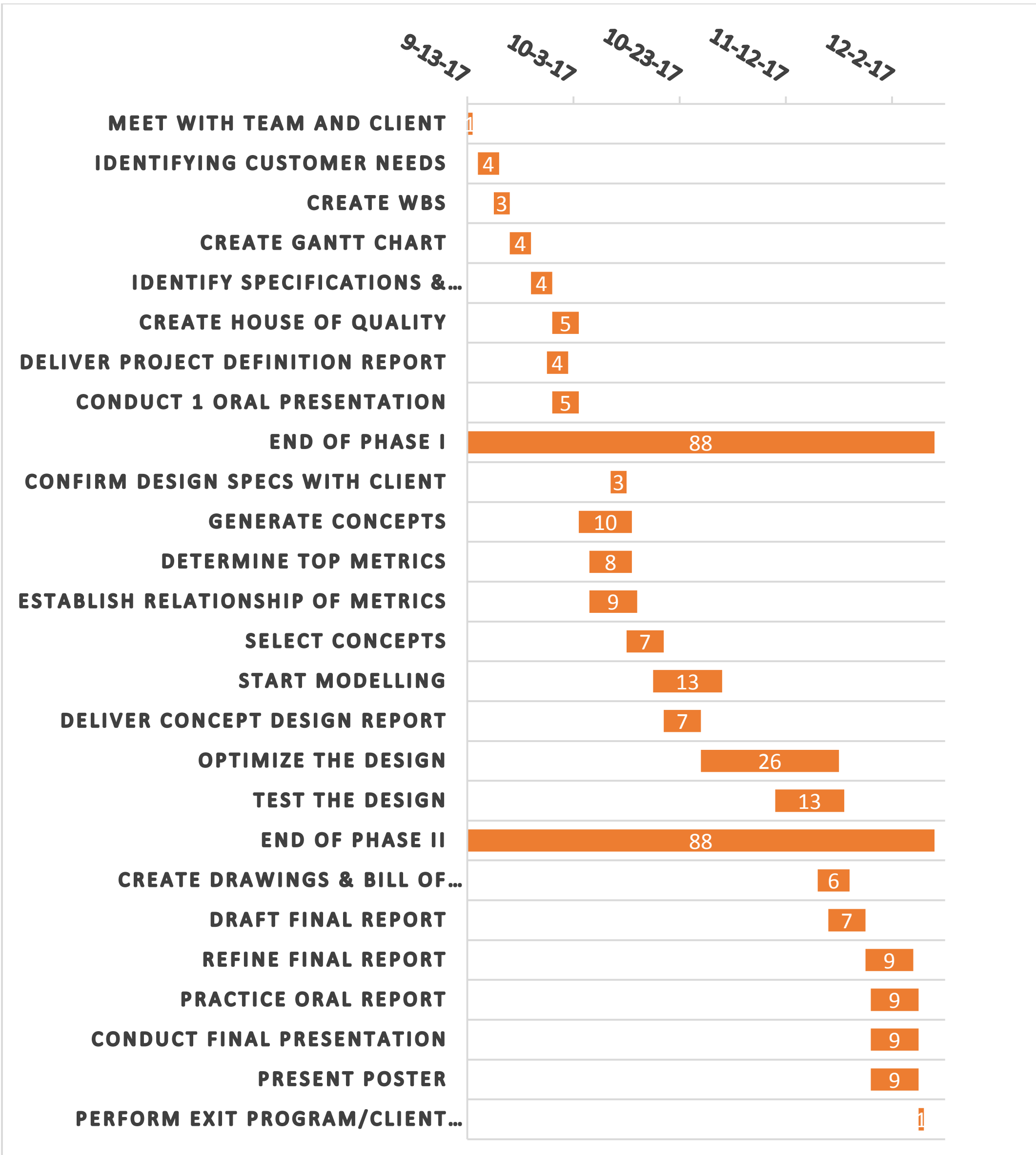


Figure A-1. Project gantt chart

A.4 Responsibility Assignment Matrix

Table A-I below outlines the responsibilities of different stakeholders, as evaluated by the project team members. The purpose of this table was to help the team gain a better understanding at the beginning of the project as to the extent of the responsibilities that are in the jurisdiction of the team. The Project team members consist of Mercy Onweni (M.O.), Derek Calsbeck (D.C.), Israel Hernandez (I.H.) and Jeremy Smith (J.S.). The other stakeholders consist of Paul Labossiere (P.L.), Leah Guenther (L.G.), Lawrence Cruz (L.C.) and Meaghan Coates (M.C.).

TABLE A-I
RESPONSIBILITY ASSIGNMENT MATRIX

WBS Element	**R** - Responsible; **A** - Accountable; **C** - Consulted; **I** - Informed							
	Project Team Members				**Other Stakeholders**			
	M.O	D.C	I.H	J.S	P.L	L.G	L.C	M.C
1. Phase I - Project Planning								
1.1. Meeting with client								
1.1.1. Stakeholder Register				R	C			
1.1.2. Resource Register			R		C			
1.2. Team Roles /Responsibilities	R	R	R	R	I			
1.3. Identify Customer Needs	R	R	R	R		C	C	C
1.4. Identify specification, constraints and limitations	A	A	R	A				
1.5. Relate needs to specifications and create HOQ	A	R	A	R		C	C	C

RESPONSIBILITY ASSIGNMENT MATRIX (CONTINUED)

WBS Element	**R** - Responsible; **A** - Accountable; **C** - Consulted; **I** - Informed							
	Project Team Members				**Other Stakeholders**			
	M.O	D.C	I.H	J.S	P.L	L.G	L.C	M.C
1.6. Project Definition								
1.6.1. Project Charter	R	R	R	R	C	C	C	C
1.6.2. Hand in Report	R	R	R	R	I			
1.7. Gantt Chart	A	R	A	A		I	I	I
1.8. Oral Presentation	R	R	R	R	C			
2. Phase II - Design								
2.1. Confirm design specification	R	R	R	R	C	C	C	C
2.2. Concept Generation								
2.2.1. SCAMPER Brainstorming	R	R	R	R				
2.2.2. 5-step Brainstorming (outlined in WBS)	R	R	R	R				
2.2.3. Group Brainstorming	R	R	R	R				
2.2.4. External search, patents, etc.	R	R	R	R	C			
2.3. Concept selection								
2.3.1 House of Quality	R	R	R	R				
2.3.2 Decision Matrix (Concept screening and concept scoring)	R	R	R	R		C	C	C

RESPONSIBILITY ASSIGNMENT MATRIX (CONTINUED)

WBS Element	**R** - Responsible; **A** - Accountable; **C** - Consulted; **I** - Informed							
	Project Team Members				**Other Stakeholders**			
	M.O	D.C	I.H	J.S	P.L	L.G	L.C	M.C
2.4. Modeling								
2.4.1. CAD Modeling	R	R	R	R				
2.4.2. FEA, Thermal Analysis, etc.		R			C			
2.4.3. Prototyping and Testing	A	A	A	A	C	R	R	C
2.5. Concept Design Report	R	R	R	R	C			
3. Phase III- Final Development								
3.1. Final Design								
3.1.1. BOM	R	R	R	R		I	I	I
3.1.2. Optimization	R	R	R	R	C	I	I	I
3.1.3. Drawings	R	R	R	R	C	I	I	I
3.1.4. Proof-of-Concept	R	R	R	R		C	C	C
3.2. Final Report	R	R	R	R		I	I	I
3.3. Oral Presentation	R	R	R	R		I	I	I
3.4. Poster Presentation	R	R	R	R		I	I	I

A.5 Available Resources

Table A-II shows the main project resources needed to determine success. The table also provides the type of resources as well as the quantity needed, the type of quantity and a brief description of the resources.

TABLE A-II
PROJECT RESOURCES

	Category	QTY Required	Units	Description
Raw Material	Material	TBD	Number	Material needed for project assembly and design
Power Tools	Material	TBD	Number	Tools necessary for building the container
Project Manager	Manpower	1	Person	Responsible for running the project
Team Members	Manpower	4	Person	Persons responsible for project plan, research, documentation and build
Team Scheduler	Manpower	1	Person	Person responsible for scheduling, and obtaining resources
Sponsor(s)	Vendor	2 (including Precision ADM)	Person	Vendors that support and help supply materials and supplement cost

Table A-III below lists two additional resources which may be useful over the course of the project.

TABLE A-III
RESOURCE REGISTER

	Contact Information	Description
Sean O'Brien	204-474-9876 sean.obrien@umanitoba.ca	His thesis was in orthopaedic wear simulations. He could be a helpful resource to understand the project and limitations
McMaster Carr	https://www.mcmaster.com/	Tools necessary for building the container

Appendix B: Concept Selection Details

Contents

List of Figures

List of Tables

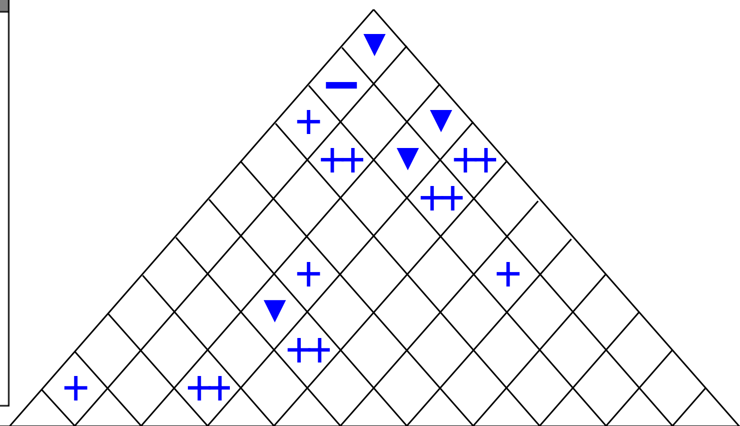
Appendix B contains a detailed description of the process used to develop a final concept during the Concept Design Phase of the project. The first step is the creation of the House of Quality, shown in Section B.1. Next, the brainstorming process has team members developing several designs for each major component of the reservoir, described in Section B.2. The development of concept evaluation criteria and the subsequent evaluation of all concepts are presented in Sections B.3 and B.4, respectively. Finally, the selection of a final reservoir concept is found in Section B.5.

B.1 House of Quality

The House of Quality (HOQ) in Fig. B-1 provides a visual representation of the relationships between the product metrics and customer needs, as well as relationships between individual metrics. Metric number 2 (flow rate of fluid through the system) and number 8 (fluid volume in reservoir at which system shuts down for safety) are not included in the HOQ. These metrics were removed from the HOQ retroactively during the concept evaluation process, as they were completely satisfied by all concepts evaluated by the team and so did not impact the proposed designs.

Legend

- Θ — Strong Relationship
- O — Moderate Relationship
- ++ — Strong Positive Correlation
- \+ — Positive Correlation
- — — Negative Correlation
- ▼ (blue) — Strong Negative Correlation
- ▼ — Objective Is To Minimize
- ▲ — Objective Is To Maximize
- X — Objective Is To Hit Target



Row #	Column #	1	2	3	4	5	6	7	8	9	10	11
	Direction of Improvement: Minimize (▼), Maximize (▲), or Target	▼	▲	▼	▲	▲	▲	▲	x		x	x
	Engineering Characteristics / Customer Requirements	Rate of evaporation from reservoir	Volume of reservoir	System setup time	Simplicity of the set-up process	Max. temperature the reservoir can withstand in sterilizer	Manufacturability	Ease with which magnetic float slides on tube for failsafe	The materials used comply with medical standards	Diameter of reservoir	Standard size of reservoir inlet and outlet (ID/OD)	Standard seal size (diameter)
1	System runs consistently and reliably with minimal loss of fluid	Θ										
2	Reservoir contains at least the same volume as the original reservoir		Θ									
3	The system setup time is decreased			Θ	O							
4	The system is simple to set up and use			O	Θ							
5	System can be cleaned using current equipment					Θ						
6	Major components are simple to manufacture at Precision ADM						Θ					
7	The failsafe system functions reliably							O				
8	Materials comply with medical standards								O			
9	Reservoir is compatible with current test setup									O		
10	System uses standard fittings and components										O	Θ
	Target or Limit Value	< 2mL/hour	> 400 mL (500 mL preferred)	< 5 min	subj.	> 80°C	subj.	subj.	true	= current diameter	standard size	standard size
	Importance (out of 5)	5	4	4	3	3	4	3	5	2	1	4

Figure B-1. House of Quality

B.2 Concept Generation

Different components of the original reservoir design cause different issues with the current test setup. One of the 40 TRIZ principles for brainstorming, called segmentation, is therefore used to separate the problem into independent parts, so that a solution can be found for each part [1B]. The solutions for each component of the reservoir are then combined to create an overall reservoir concept. Effectuating this plan, each team member brainstorms five concepts for redesigned components and presents a rough sketch of each concept to the group. A master list is then compiled to summarize the concepts and group them according to component. Section B.4 presents the most notable of these components, along with sketches. The main components of the reservoir and the number of concepts developed for each component are shown in Table B-I.

TABLE B-I
NUMBER OF CONCEPTS GENERATED FOR EACH COMPONENT

Component	**Number of Concepts Developed**
Container Body	7
Lid	3
Low Fluid Sensor	5
Inlet and Outlet Connections	8
Sealing Configuration	11

In total, there are 34 conceptual designs developed for the components of the reservoir, with multiple concepts in each category.

B.3 Development of Concept Evaluation Criteria

The criteria to evaluate the concepts are developed by identifying the most important metrics to achieve from the House of Quality. The HOQ shows that some metrics are very dependent on other metrics for their fulfillment, and so can be grouped together to form selection criteria. For example, “System Setup Time” and “Simplicity of the Setup Process” are combined to form the evaluation criterion “Ease of System Setup.” Overall, there are six main evaluation criteria:

- Quality of Seal
- Volume of Reservoir
- Ease of System Setup
- Simplicity of Design
- Ease of Manufacture
- Fail-safe Reliability

The evaluation criteria are then compared in a weighting matrix to determine the relative importance of each one, so that they can be used in concept scoring. The weighting matrix and the results are shown in Table B-II.

TABLE B-II
WEIGHTS OF CRITERIA TO BE USED FOR CONCEPT EVALUATION

Top Criteria		**A**	**B**	**C**	**D**	**E**	**F**	**Score**
Quality of Seal	**A**		A	A	A	A	A	**0.333**
Volume of reservoir	**B**			C	B	E	F	**0.067**
Ease of System Setup	**C**				C	C	F	**0.2**
Simplicity of Design	**D**					E	F	**0**
Ease of manufacture	**E**						F	**0.133**
Fail-Safe Reliability	**F**							**0.267**

In Table B-II, each criterion is compared directly to the other criteria in a series of pairings, where the result of each comparison is simply the identification of the more important criterion. The winner of each pairing is listed in main portion of the table and the total number of wins for each criterion is summed and divided by the total number of pairings, resulting in a final score for each criterion.

The result is that the quality of seal is the most heavily-weighted evaluation criterion. Simplicity of design is given a score of zero, not because it is not relevant, but because of its strong relationship with ease of manufacturing, as is seen in the HOQ. Therefore, this criterion is ignored, since in general, the simpler the design, the simpler the manufacturing process.

B.4 Concept Evaluation

As there are thousands of different combinations of complete reservoir concepts that can be produced from the 34 component concepts, a method to quickly eliminate concepts is employed where each team member rates each concept “good” or “bad” based on the perceived likelihood of that concept meeting the customer requirements in the HOQ. Table B-III shows an example of this screening for the container body concepts.

TABLE B-III
EXAMPLE PRELIMINARY CONCEPT FILTERING

Concept Name	**MO (good/bad)**	**IH (good/bad)**	**DC (good/bad)**	**JS (good/bad)**	**Team Decision**
Container					
Wavy Cylinder	bad	bad	bad	bad	bad
Taller Cylinder	good	good	good	good	good
Removed-base Cylinder	good	good	good	good	good
Erlenmeyer flask Cylinder	good	bad			bad
Cone-shape Cylinder	good	good	good		good
Tall, thin, wide-base Cylinder	bad	good	good		good
Secondary stacked Cylinder		bad		bad	bad

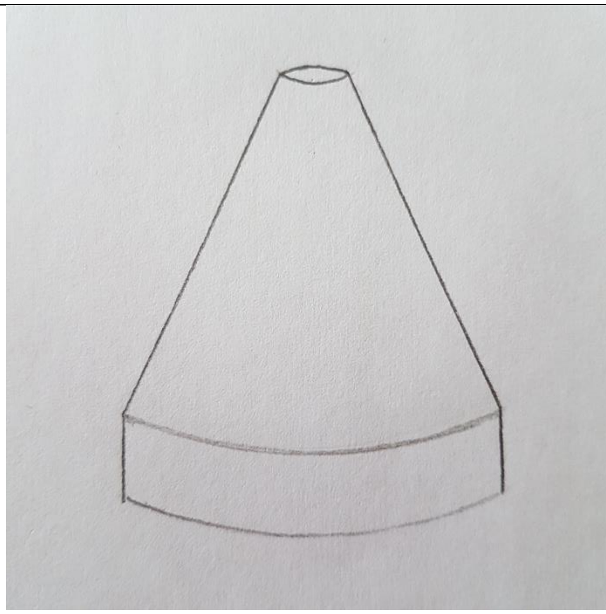
In this way, concepts that the team agrees are low-quality are eliminated from consideration early on, and the remaining concepts are left to be evaluated using the concept evaluation criteria from Table B-II to arrive at a final concept.

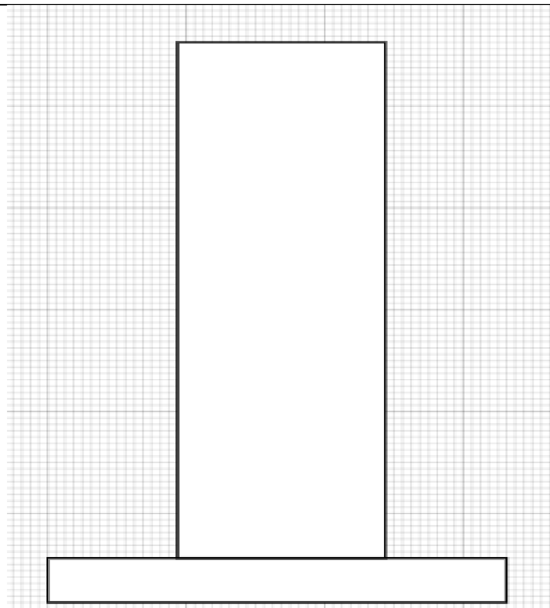
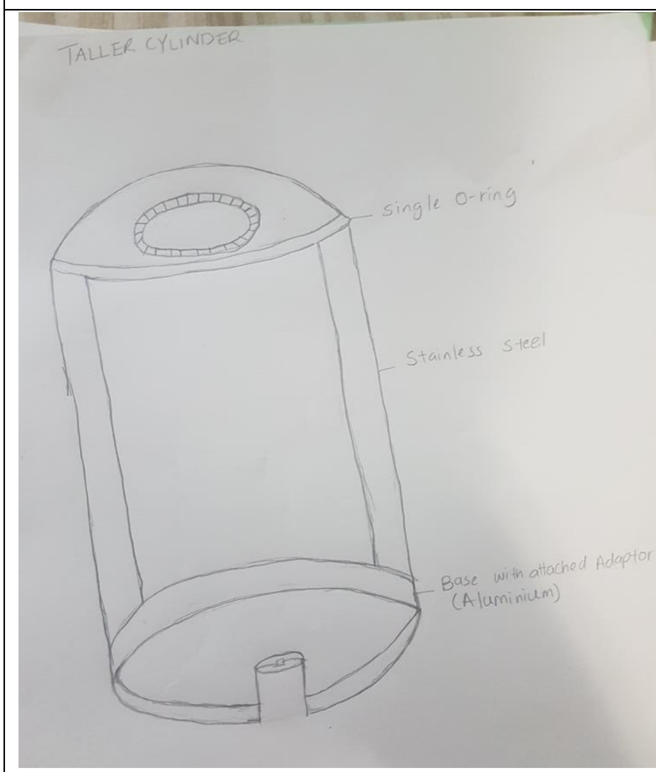
A different concept scoring matrix is developed for each type of reservoir component, with each concept receiving two results for each evaluation criterion: a rating from 1 to 5 (with 5 being the best) to judge the extent to which each concept satisfies each criterion, and a score indicating the relative importance of the satisfaction of each criterion. The relative score is obtained by multiplying the rating from 1 to 5 by the relative weight of the corresponding criterion. The relative scores for the satisfaction of each criterion are summed for each concept, and the concept with the highest total score is deemed the best concept.

B.4.1 Evaluation of Containers

Table B-IV shows drawings for three of the seven container concepts.

TABLE B-IV
CONTAINER CONCEPT DRAWINGS

 Figure B-2. Cone Shape with Removed Base [2B]	A cone shaped container that would reduce the amount of area from which fluid can evaporate and has better clearances within current setup. This sketch also shows a base that is integrated into the container, instead of being made of aluminum and fastened to the container separately.

 Figure B-3. Graduated Cylinder [3B]	A container resembling a graduated cylinder that could fit the original heating plate but allow the container to be taller.
 Figure B-4. Taller Cylinder [4B]	This concept has a smaller circumference than the original, and increased height to create more volume within the current setup.

In the concept scoring matrix for the container, shown in Table B-V, the quality of seal and fail-safe reliability are not considered to be selection criteria because they do not depend on features of the container. The concepts that are analysed in this selection process are the taller cylinder, removed base, cone shape, and graduated cylinder. The concepts with the highest overall score are the taller cylinder and the removed base with scores of 1.93 while the concept with the lowest score is the cone shape, with a final score of 1.07. As the removed-base and taller cylinder concepts are not mutually exclusive, they are combined to allow the container to have the greatest volume possible.

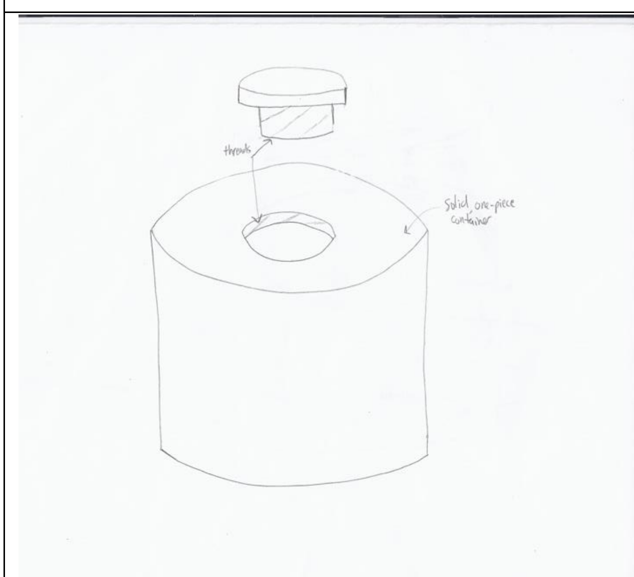
TABLE B-V
CONCEPT SCORING MATRIX FOR THE CONTAINERS

Attributes	Weighting	Taller Cylinder		Removed Base		Cone Shape		Graduated Cylinder	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score
Quality of Seal	0.333	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Volume of Reservoir	0.067	4	0.27	4	0.27	3	0.2	5	0.34
Ease of System Set Up	0.2	5	1	5	1	3	0.6	4	0.8
Ease of Manufacturing	0.133	5	0.67	5	0.67	2	0.27	3	0.4
Fail-Safe Reliability	0.267	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Score			**1.93**		**1.93**		**1.07**		**1.53**

B.4.2 Evaluation of Lids

Table B-VI displays concepts that were developed during the brainstorming phase of the project for possible lid designs.

TABLE B-VI
LID CONCEPT DRAWINGS

 Figure B-5. Skirted Lid [5B]	This skirted lid uses external threads and an encompassing skirt to help seal around the outer diameter of the container.
 Figure B-6. Small Lid [6B]	A small diameter lid relative to the container diameter with external threads should allow for easy installation into the container and create more room to install the inlet/outlet.

The concept selection process for the lid does not require considering the volume of the reservoir or the fail-safe reliability, as they are not related to the lid. The three concepts that are evaluated in this matrix are the small lid, large lid and skirted lid. The concept with the highest score is the small lid, which is reasonable because of the small size of the opening to minimize opportunity for fluid to escape and to simplify the installation of the lid. The results of this evaluation are shown in Table B-VII.

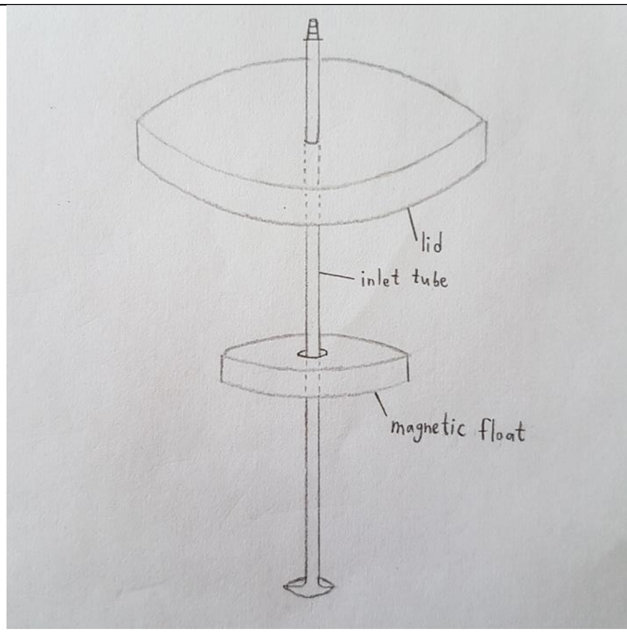
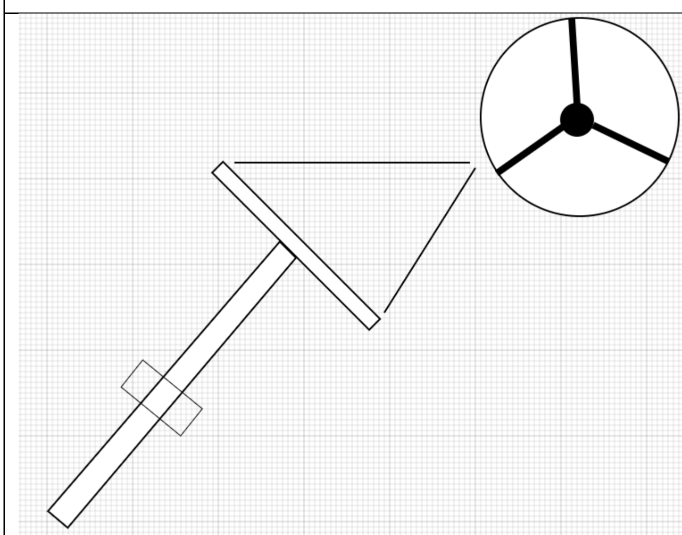
TABLE B-VII
CONCEPT SCORING MATRIX FOR THE LIDS

Attributes	Weighting	Small Lid		Large Lid		Skirted Lid	
		Rating	Score	Rating	Score	Rating	Score
Quality of Seal	0.333	5	1.665	4	1.33	5	1.67
Volume of Reservoir	0.067	N/A	N/A	N/A	N/A	N/A	N/A
Ease of System Set Up	0.2	5	1	4	0.8	4	0.8
Ease of Manufacturing	0.133	5	0.665	5	0.67	5	0.67
Fail-Safe Reliability	0.267	N/A	N/A	N/A	N/A	N/A	N/A
Total Score			**3.33**		**2.8**		**3.13**

B.4.3 Evaluation of Low Fluid Sensors

Table B-VIII shows concepts that were developed for the improvement of the magnetic sensor.

TABLE B-VIII
MAGNETIC SENSOR

 Figure B-7. Wider Bore [7B]	This concept uses the same sensor setup as the original with a wider clearance around the inlet tube to prevent from making the sensor stick.
 Figure B-8. Upside-down Hanger [8B]	This sensor would be detachable from the overall setup. It can be fitted around the container and then secured to it by the lid similar to a modern French press coffee filter.

In the concept selection for the low fluid sensor, the quality of seal and volume of reservoir do not contribute to the scoring matrix because those criteria do not influence the operation of the low fluid sensor. Therefore, the remaining criteria, namely ease of system setup, manufacturability and reliability are used to evaluate the low fluid sensor concepts. The scoring matrix is shown in Table B-IX. The upside-down hanger concept, with a score of 2.53, was selected in conjunction with the wider bore concept since they can both be implemented into the design.

TABLE B-IX
CONCEPT SCORING MATRIX FOR THE LOW FLUID SENSOR

Attributes	Weighting	Upside-down Hangar		Wider Bore		Inlet as Guide		Guide Tube on Bottom	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score
Quality of Seal	0.333	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Volume of Reservoir	0.067	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ease of System Set Up	0.2	4	0.8	5	1	4	0.8	3	0.6
Ease of Manufacturing	0.133	3	0.4	5	0.67	4	0.53	4	0.53
Fail-Safe Reliability	0.267	5	1.34	5	1.34	2	0.53	3	0.8
Total Score			**2.53**		**3**		**1.87**		**1.93**

B.4.4 Evaluation of Inlet and Outlet Ports

For the inlet and outlet concept selection, the quality of seal of the reservoir is not computed in the scoring analysis because it does not impact the design of the inlet and outlet. Therefore, volume of reservoir, ease of system setup, ease of manufacturing and fail-safe reliability are used in the concept selection process. The “same size diameter off the lid” concept has the highest score at 2.8, while the lowest score is 1.27 for the side chamber filtering concept. Table B-X shows the scoring matrix. With a score of 2.74, the bent outlet concept is selected alongside the “same size off lid” concept in the final conceptual design.

TABLE B-X
CONCEPT SCORING MATRIX FOR THE INLET AND OUTLET PORTS

Attributes	Weighting	Side Chamber Filtering		Rounded Bottom		Bent Outlet		Same Size on Lid		Same Size off Lid	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Quality of Seal	0.333	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Volume of Reservoir	0.067	3	0.2	3	0.2	5	0.34	5	0.34	5	0.34
Ease of System Set Up	0.2	2	0.4	5	1	4	0.8	3	0.6	5	1
Ease of Manufacturing	0.133	1	0.13	4	0.53	4	0.53	4	0.53	5	0.67
Fail-Safe Reliability	0.267	2	0.53	3	0.8	4	1.07	3	0.8	3	0.8
Total Score			**1.27**		**2.53**		**2.74**		**2.27**		**2.8**

B.4.5 Evaluation of Sealing Configurations

Table B-XI contains drawings of concepts for sealing the container.

TABLE B-XI
SEAL CONCEPT DRAWINGS

 Figure B-9. Single O-ring and External Thread [9B]	This concept uses the skirted lid with a seal that fits around the outside of the lid, similar to the mason jar lid shown here.

REDACTED Figure B-10. Latch and Hinge [10B]	A latch and hinge, similar to the preserving jar shown, would provide a quick, easy seal that allows the user to access the inside of the jar. An O-ring would be installed the outside of the lid and mate with the inner diameter of the container.

In this selection process for the best sealing concept, all of the selection criteria are considered in weighing the concepts. The concepts that are evaluated are the latch and hinge, double latch, single O-ring, double O-ring, internal thread and external thread, as are shown in Table B-XII. The internal and external thread concepts both have overall scores of 2.86, the single O-ring and double O-ring have scores of 2.8, and the latch and hinge concept has the lowest score at 2. The O-ring concepts and the internal and external thread concepts are not mutually exclusive, so the single O-ring and internal thread concepts are selected to be combined to provide the sealing for the reservoir.

TABLE B-XII
CONCEPT SCORING MATRIX FOR THE SEALING CONFIGURATION

Attributes	Weighting	Latch & Hinge		Double Latch		Single O-ring		Double O-ring		Internal Thread		External Thread	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Quality of Seal	0.333	3	1	4	1.33	4	1.332	5	1.67	4	1.33	4	1.33
Volume of Reservoir	0.067	0	0		0	0	0		0		0		0
Ease of System Set Up	0.2	3	0.6	2	0.4	4	0.8	3	0.6	5	1	5	1
Ease of Manufacturing	0.133	3	0.4	3	0.4	5	0.665	4	0.53	4	0.53	4	0.53
Fail-Safe Reliability	0.267	0	0		0	0	0		0		0		0
Total Score			**2**		**2.13**		**2.797**		**2.8**		**2.86**		**2.86**

B.5 Final Concept Selection

The first complete reservoir concept is formed by selecting the top concepts for each component, which includes the upside-down hanger for the low fluid sensor. However, the upside-down hanger significantly increases the complexity of the design in order to avoid interference with the threaded lid, which is not accounted for in the concept evaluation process. For this reason, the upside-down hanger concept is abandoned, and is replaced by a guide pole for the sensor mounted either from the floor of the container or hung from the lid, possibly doubling as the inlet tube. Thus, a complete concept, except for the low-fluid sensor configuration, is compiled into a final concept and is sent to the client to receive their feedback. Fig. B-11 shows the sketch sent to the client to communicate the first complete concept.

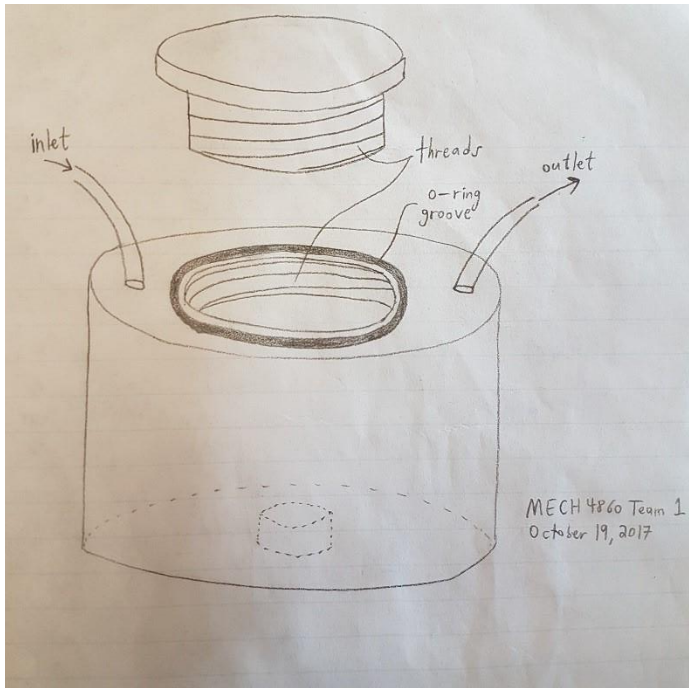


Figure B-11. First complete concept emailed to the client

The client recommended several minor changes to this first concept. Their recommendations were to increase the reservoir opening diameter to facilitate pouring into the container without spilling, to bring the inlet and outlet ports closer together for ease of setup, and to mount a single O-ring on the lid instead of on the reservoir body. However, a compromise is required between enlarging the lid and placing the inlet and outlet on the rim of the container. The preference of the client is to avoid having the inlet and outlet protrude through the lid, and instead to place the inlet and outlet beside the lid. Their recommendations are taken into account, and the final reservoir concept is illustrated in Fig. B-12 through Fig. B-16.

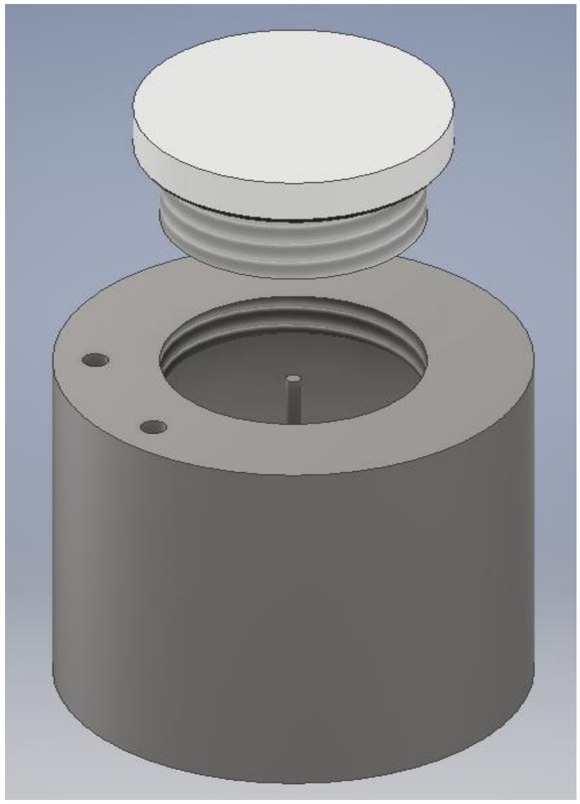


Figure B-12. Overall reservoir concept

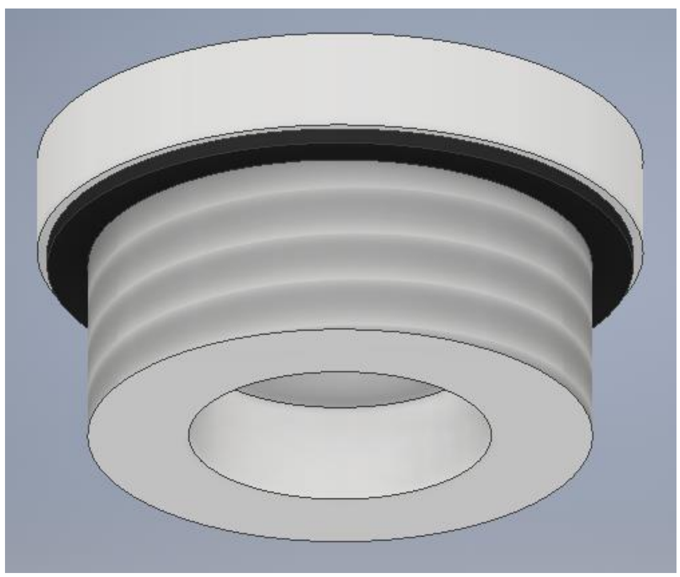


Figure B-13. Selected lid and sealing concept for the reservoir

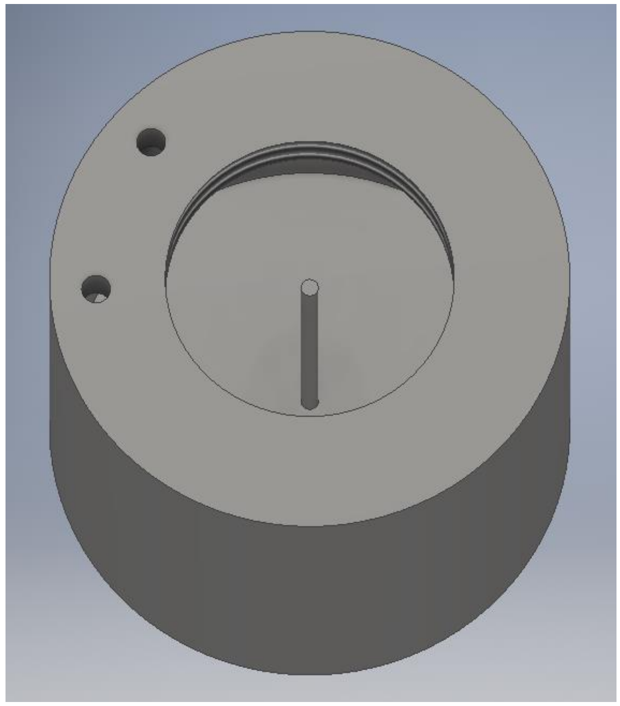


Figure B-14. Close-up view of the conceptual reservoir body, showing the inlet and outlet ports and a proposed guide pole for the floating sensor, mounted from the floor

Figure B-15. Redesigned reservoir concept showing a partially inserted lid

Figure B-16. Fully inserted lid compressing the O-ring to seal the container-ring to seal the container

The concepts in Fig. B-12 and Fig. B-14 show the use of a guide for the magnetic sensor that is attached to the floor of the container. The client recommends that the guide pole be mounted to the container floor rather than mounted below the lid, so this feature is included in the final concept.

B.6 References

[1B] Solid Creativity, "The 40 TRIZ Principles," Solid Creativity, 2017. [Online]. Available: http://www.triz40.com/aff_Principles_TRIZ.php. [Accessed 22 October 2017].

This website breaks down the 40 different methods that comprise the TRIZ approach to problem solving. The site was informative to describing our approach to the concept generation process in which segragation was used to break down the problem into smaller components. (DC)

[2B] J. Smith. “Cone Shape with Removed Base.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 14, 2017.

This photo was taken from the journal of Jeremy Smith. It is needed to convey one of our potential concepts to the reader. (JS)

[3B] I. Hernandez. “Graduated Cylinder.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 14, 2017.

This photo was taken from the journal of Israel Hernandez. It is needed to convey one of our potential concepts to the reader. (IH)

[4B] M. Onweni. “Taller Cylinder.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 14, 2017.

This photo was taken from the journal of Mercy Onweni. It is needed to convey one of our potential concepts to the reader. (MO)

[5B] M. Onweni. “Skirted Lid.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 14, 2017.

This photo was taken from the journal of Mercy Onweni. It is needed to convey one of our potential concepts to the reader. (MO)

[6B] D. Calsbeck. “Small Lid.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 14, 2017.

This photo was taken from the journal of Derek Calsbeck. It is needed to convey one of our potential concepts to the reader. (DC)

[7B] J. Smith. “Wider Bore.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 14, 2017.

This photo was taken from the journal of Jeremy Smith. It is needed to convey one of our potential concepts to the reader. (JS)

[8B] I. Hernandez. “Upside-down Hanger.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, Oct. 14, 2017.

This photo was taken from the journal of Israel Hernandez. It is needed to convey one of our potential concepts to the reader. (IH)

[9B] Mason Jar Lifestyle. (n.d.). “stainless-steel-storage-lid-cap-regular-mouth-mason-ball-jars-bottom-silicone-seal-out.jpg,” in *Stainless Steel Storage Lids Caps with Silicone Seals for Mason Jars 5 Pack* [Online].
Available: https://masonjarlifestyle.com/product/stainless-steel-storage-lids-caps-with-silicone-seals-for-mason-jars/ [Accessed Oct. 10, 2017].

This photo of a mason jar lid from masonjarlifestyle.com shows the concept for both the skirted lid and an O-ring inside the lid to seal a container.

[10B] Etsy, Inc., "12 WHITE PET Plastic Empty Kilner Latch Bail Jars 12 Oz UPSCALE 350mL Hinge Top Mason Jar Bale Salt Scrub Bath Salts Lotion Conditioner," Etsy, Inc., 2017. [Online]. Available: https://www.etsy.com/listing/236502382/12-white-pet-plastic-empty-kilner-latch [Accessed 24 October 2017].

This photo is from an online store and is used to explain the latch and hinge concept for sealing the reservoir. This image served as an inspiration for the design concept. (DC)

[11B] Sandvik Coromant, "Threading Design," Sandvik Coromant, [Online]. Available: https://www.sandvik.coromant.com/sitecollectiondocuments/downloads/global/technical%20guides/en-gb/c-2920-031.pdf [Accessed Oct. 27, 2017].

Sandvik Coromant is a company that specializes in cutting inserts and metal removal techniques. They are a reputable company that is very popular in the machining industry. The team used one of their online brochure to thoroughly research how to machine threads, thread types, and thread design parameters.

Appendix C: Design Validation

Contents

List of Figures

List of Tables

Appendix C gives tables and calculations that support the qualitative and quantitative analyses of the redesigned reservoir found in Section 3.0 of the report.

C.1 Summary of Target Metrics

Table C-I is a condensed version of the original list of metrics.

TABLE C-I
SUMMARY OF METRICS AND TARGET SPECIFICATIONS OF THE KNEE WEAR TESTING WORKSTATION

Target Specifications				
Metric #	**Metric**	**Importance (max. 5)**	**Units**	**Estimated Target**
1	Rate of evaporation from reservoir	5	mL/ hour	< 2 mL/hour
2	Flow rate of fluid through the system	3	mL/ min	TBD
3	Volume of reservoir	4	mL	> 400 mL (500 mL preferred)
4	System setup time	4	min.	5 min
5	Simplicity of the set-up process	3	subj.	subj.
6	Max. temperature the reservoir can withstand in sterilizer	3	°C	> 80 °C
7	Manufacturability	4	subj.	subj.
8	Fluid volume in reservoir at which system shuts down for safety	4	mL	100 mL
9	Ease with which magnetic float slides on tube for failsafe	3	subj.	subj.
10	The materials used comply with medical standards	5	true/ false	true
11	Diameter of reservoir	2	mm	= current dia.
12	Standard size of reservoir inlet and outlet (ID/OD)	1	inch	standard size
13	Standard seal size (diameter)	4	inch	standard size

C.2 Calculation Details for Clearance Checks

This section gives the calculation details for the calculation of clearance between reservoir components and its environment in which it operates. Table C-III summarizes the calculated clearances.

Table C-II below presents all of dimensions required to complete the clearance calculations, grouped by component.

TABLE C-II
OVERALL DIMENSIONS OF THE REDESIGNED RESERVOIR

Measurement	**Symbol**	**Value [in.]**
Environment		
Distance from back wall to heating plate	BWo	0.2335
Heating plate diameter	Dhp	4.31
Total available height	H	4.625
A/P actuator plate thickness	APt	0.625
Container		
Container ID	Di	4.375
Container wall thickness	t	0.1875
Container OD	Do (= Di + 2*t)	4.75
Container body height (without flange)	Ho	3.319
Depth of indent in base for sensor nub on heating pad	hnb	0.403
Flange		
Flange thickness	Hfl	0.5
Radius of imaginary circle on flange, on which inlet and outlet holes lie	RCirThru	1.75
OD of inlet and outlet tubes	DThru	0.188
Lid		
Lid grip diameter	Dlg	2.875
Lid hanging portion ID	IDhl	1.00
Float		
Float OD	odfl	1.5
Float ID	idfl	0.175
Float guide pole diameter	dgp	0.15
Float guide pole height	hgp	2.7285

Distance from Outside of Container to Back Wall

The first clearance to be calculated is the clearance between the outside of the container and the back wall. The equation used to calculate this clearance is

$$BWcl = BWo - Roh \qquad \textit{(eq. C1)}$$

where *BWcl* is the clearance between container and the back wall,

BWo is the distance from the back wall to the outside of the heating plate,

and *Roh* is the distance of the overhang of the container over the edge of the heating element (on one side of the element).

The overhang distance, Roh, is calculated by

$$Roh = (Do - Dhp)/2 \qquad \textit{(eq. C2)}$$

where *Do* is the outer diameter of the container,

and *Dhp* is the diameter of the heating plate.

Combining *(eq. C1)* and *(eq. C2)*, and substituting values from Table C-II:

$$BWcl = 0.2335 \text{ in.} - (4.75 - 4.31) \text{ in.} / 2$$

$$BWcl = 0.0135 \text{ in.} \qquad \textit{(Calculation 1)}$$

Vertical Clearance Between Top of Flange and Bottom of A/P Actuator Plate

To calculate the clearance between the flange and the A/P actuator plate, the following equation is used:

$$Hcl = H – Hfl – Ho \qquad \textit{(eq. C3)}$$

where *Hcl* is the clearance in question,

H is the total available height between the surface of the heating element and the bottom of the A/P actuator plate,

Hfl is the height of the flange,

and *Ho* is the height of the container alone.

The height of the lid is not considered in this calculation, since the projection of the A/P actuator plate onto the container does not overlap with the lid at all. Substituting values from Table C-II into *eq. C3*:

$$Hcl = 4.625\ in - 0.5\ in - 3.319\ in$$

$$Hcl = 0.806\ in. \qquad \textit{(Calculation 2)}$$

Horizontal Clearance Between the Outside of the Lid and the of the Wall of the A/P Actuator Plate

The clearance that is calculated between the outside of the lid and the walls of the A/P actuator plate represents the minimum clearance available for fingers wrapped around the lid as it is unscrewed out of the flange.

The basic equation for calculating this clearance is:

$$APcl = BWcl + (Do - Dlg)/2 - APt \qquad \textit{(eq. C4)}$$

where *APcl* is the horizontal clearance between the A/P actuator plate and the lid,

BWcl is the clearance between the container and the back wall (which was calculated in the first clearance calculation),

Do is the outside diameter of the container,

Dlg is the diameter of the part of the lid that is gripped when turning,

and *APt* is the thickness of the actuator plate, or the furthest distance of the plate away from the back wall.

The grip for the lid used in the final design has a regular octagonal shape, so the “diameter” used as the lid grip diameter is in fact the diameter of the circumscribed circle defined by the octagon.

Substituting the values provided in Table C-II into *eq. C4*:

$$APcl = 0.0135 \text{ in.} + (4.75 - 2.875) \text{ in.} / 2 - 0.625 \text{ in.}$$

$$APcl = 0.326 \text{ in.} \qquad \text{(Calculation 3)}$$

Clearance Between Float and Outlet Tube

The equation used to calculate the horizontal clearance between the outside of the magnetic float and the outlet tube (protruding into the container through the flange) is

$$CLflot = RCirThru - odfl/2 - DThru/2 \qquad \text{(eq. C5)}$$

where *CLflot* is the clearance between the float and the outlet tube,

RCirThru is the radius of the imaginary circle on the flange that defines the positions of the inlet and outlet tube on the flange,

odfl is the the outer diameter of the magnetic float,

and *DThru* is the outer diameter of the outlet tube.

Substituting the known values into *eq. C5*:

$$CLflot = 1.75 \text{ in.} - 1.5 \text{ in.} / 2 - 0.188 \text{ in.} / 2$$

$$CLflot = 0.906 \text{ in.} \qquad \text{(Calculation 4)}$$

Clearance Between Container Wall and Outlet Tube

The equation used to calculate the clearance between the inside of the container wall and the outlet tube protruding through the flange into the container is

$$CLotwall = Di/2 - RCirThru - Dthru/2 \qquad \text{(eq. C6)}$$

where *CLotwall* is the clearance between the outlet tube and the container wall,

RCirThru is again the radius of the imaginary circle on the flange that defines the positions of the inlet and outlet tube on the flange,

and *Dthru* is the outer diameter of the outlet tube.

Substituting the values from Table C-II into *eq. C6*:

$$CLotwall = 4.375\ in.\ /\ 2 - 1.75\ in. - 0.188\ in.\ /\ 2$$

$$CLotwall = 0.3435\ in. \qquad \textit{(Calculation 5)}$$

Clearance Between the Magnetic Float and the Float Guide Pole

The magnetic float slides up and down freely on a guide pole. The equation to calculate the clearance between the inner diameter of the float and the diameter of the pole is:

$$CLflgp = (idfl - dgp)/2 \qquad \textit{(eq. C7)}$$

where *CLflgp* is the clearance between the float and its guide pole,

idfl is the inner diameter of the float,

and *dgp* is the diameter of the guide pole.

Substituting *idfl* and *dgp* from Table C-II into *eq. C7*:

$$Clflgp = (0.175 - 0.15)\ in.\ /\ 2$$

$$CLflgp = 0.0125\ in. \qquad \textit{(Calculation 6)}$$

Vertical Clearance Between the Top of the Guide Pole and the Underside of the Lid

The threaded portion of the lid has a cylindrical section bored out of its centre so that the lid does not interfere with the float guide pole as the lid is screwed into the flange. The vertical clearance between the top of the pole and the "floor" of the bored-out section of the lid is given by *eq. C8* as:

$$CLvergplid = Ho + Hfl - hnb - t - hgp \qquad \textit{(eq. C8)}$$

where *CLvergplid* is the vertical clearance between the guide pole and the lid,

Ho is the total height of the container (without the flange), *hnb* is the height of the indent in the base of the container to accommodate the sensor nub on the heating element,

t is the thickness of the floor of the container,

and *hgp* is the height of the guide pole.

However, the height of the float guide pole is given by the equation

$$hgp = Ho - (hnb + t) \qquad (eq.\ C9)$$

where each of *Ho*, *hnb* and *t* have the same definitions as in *eq. C8*.

Substituting *eq. C9* into *eq. C8* yields the result:

$$CLvergplid = Hfl \qquad (eq.\ C10)$$

This is a consequence of two decisions that were made in selecting dimensions:

1. The guide pole height was intentionally selected so as to have the top surface of the guide pole be flush with the bottom surface of the flange.
2. The depth of the depression into the hanging portion of the lid was selected such that the “floor” of the depression would lie on the same horizontal plane as the top of the flange.

Thus, *eq. C10* simplifies to give

$$CLvergplid = 0.5\ in. \qquad (Calculation\ 7)$$

Horizontal Clearance Between the Top of the Guide Pole and the Lid

When the lid is fully screwed into the flange, the bored-out portion of the hanging section of the lid lowers deep enough into the container to encircle the top of the sensor guide pole. The equation for the clearance between the pole and the hanging walls is:

$$CLhorgplid = IDhl/2 - dgp/2 \qquad (eq.\ C11)$$

where *CLhorgplid* is the horizontal clearance between the top of the guide pole and the walls of the lid,

IDhl is the inner diameter of the bored-out portion of the lid,

and *dgp* is the diameter of the guide pole.

Substituting values into *eq. C11*:

$$CLhorgplid = 1.00\ in. / 2 - 0.15\ in.$$

$$CLhorgplid = 0.425\ in. \qquad \text{(Calculation 8)}$$

Table C-III summarizes the calculated clearances.

TABLE C-III
CALCULATED CLEARANCES BETWEEN THE REDESIGNED RESERVOIR AND THE ENVIRONMENT

Calculation Number	**Distance to Calculate**	**Symbol**	**Minimum Clearance**
1	Distance from outside of container to back wall	BWcl	0.0135 in.
2	Vertical clearance between top of flange and bottom of A/P actuator plate	Hcl	0.806 in.
3	Horizontal clearance between outside of lid handle and A/P actuator plate	APcl	0.326 in.
4	Horizontal clearance between outlet (suction) tube and magnetic float	CLflot	0.906 in.
5	Clearance between container wall and outlet (suction) tube	CLotwall	0.3435 in.
6	Clearance between ID of magnetic float and OD of its vertical guide pole	CLflgp	0.0125 in.
7	Vertical clearance between top of float guide pole and underside of lid	CLvergplid	0.5 in.
8	Horizontal clearance between top of float guide pole and lid	CLhorgplid	0.425 in.

Fig. C-1 shows the main portion of the spreadsheet that was used to organize the calculations of the redesigned reservoir volume and clearances.

Measurement	Symbol	Variable	Unit	Equation
Heights				
Total Available Height	H	4.625	inch	-
Clearance	Hcl	0.806	inch	= H - Hfl - Ho
Lid Grip Height	Hlg	0.5	inch	-
Flange Height	Hfl	0.5	inch	-
Height of container body (without flange)	Ho	3.319	inch	-
Height of Nub	hnb	0.403	inch	-
Overall Height	HH	4.319	inch	= Hlg + Hfl + Ho
Wall thickness	t	0.1875	inch	
Thickness of AP Actuator Plate	APt	0.625	inch	
Diameters				
Diameter of Heating Plate	Dhp	4.31	inch	
Distance from back wall to heating plate	BWo	0.2335	inch	
ID of Container	Di	4.375	inch	
OD of Container	Do	4.75	inch	= Di + 2*t
Radius overhang of container off plate	Roh	0.22	inch	= (Do - Dhp)/2
Clearance between container and back wall	BWcl	0.0135	inch	= BWo - Roh
Diameter of Nub	dnb	0.544	inch	
Horiz. clearance between AP Actuator plate and lid	APcl	0.326	inch	= BWcl + (Do - Dlg)/2 - APt
Flange				
Flange height	Hfl	0.5	inch	
Flange OD	ODfl	4.75	inch	= Do
Flange ID	IDfl	1.7594	inch	
Float				
Float height	hfl	0.5	inch	
Float OD	odfl	1.5	inch	
Float volume	Vfl	14.48	mL	= hfl * pi/4 * odfl^2
Float ID	idfl	0.175	inch	
Float guide pole				
Float guide pole height	hgp	2.7285	inch	= Ho - (hnb + t)
Float guide pole diameter	dgp	0.15	inch	
Float guide pole volume	Vgp	0.79	mL	= hgp * pi/4 * dgp^2 * (2.54 cm/in)^3
Clearance between ID of float and OD of float guide	CLflgp	0.0125	inch	= (idfl - dgp)/2
Radius of circle on flange to define the thru holes	RCirThru	1.75	inch	
OD of tubing for inlet/outlet	DThru	0.188	inch	
Clearance between outlet (suction) tube and float	CLflot	0.906	inch	= RCirThru - odfl/2 - DThru/2
Clearance between outlet (suction) tube and wall	CLotwall	0.3435	inch	= Di/2 - RCirThru - DThru/2
Vert. clearance between top of guide pole and lid	CLvergplid	0.5	inch	= Ho + Hfl - hnb - t - hgp = Hfl
Horiz. clearance between top of guide pole and lid	CLhorgplid	0.425	inch	= IDhl/2 - dgp/2
Lid				
Lid grip diameter	Dlg	2.875	inch	
Lid grip height	Hlg	0.5	inch	
Lid hanging OD	ODhl	2.00	inch	= IDfl
Lid hanging ID	IDhl	1.00	inch	
Lid hanging wall thickness	thl	0.5	inch	= (ODhl - IDhl)/2
Lid hanging height	hhl	0.925	inch	
Overall lid height	hlo	1.425	inch	= Hlg + hhl
Volume cut out around nub in container	Vbelow	94.90	mL	=hnb*pi*[(1/2*Do-t)^2-(1/2*dnb+t)^2]*(2.54cm/in)^3
Volume above nub in container	Vabove	656.89	mL	=(Ho-hnb-t)*pi/4*(Do-2*t)^2*(2.54cm/in)^3-Vfl-Vgp
Volume of container	Vmain	751.79	mL	= Vbelow + Vabove
Volume (available) inside flange	Vinflange	19.92	mL	= Hfl * pi/4 * IDfl^2 * (2.54cm/in)^3
Volume (occupied) by hanging lid portion	Vhanglid	35.72	mL	= hhl * pi/4 * (ODhl^2 - IDhl^2) * (2.54cm/in)^3
Volume of container with lid	Vfinal	735.99	mL	= Vmain + Vinflange - Vhanglid

Figure C-1. Truncated version of the spreadsheet used to calculate redesigned reservoir volume and clearances

C.3 Engineering Drawings

The following Fig. C-2 through C-6 provide engineering drawings for the redesigned reservoir.

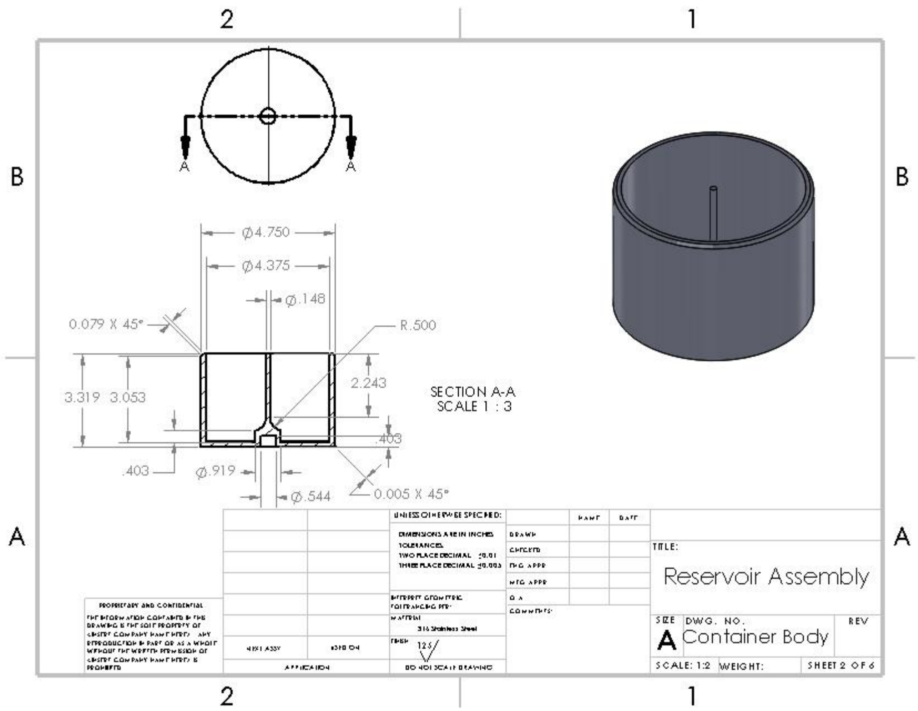


Figure C-2. Engineering drawing of the container body

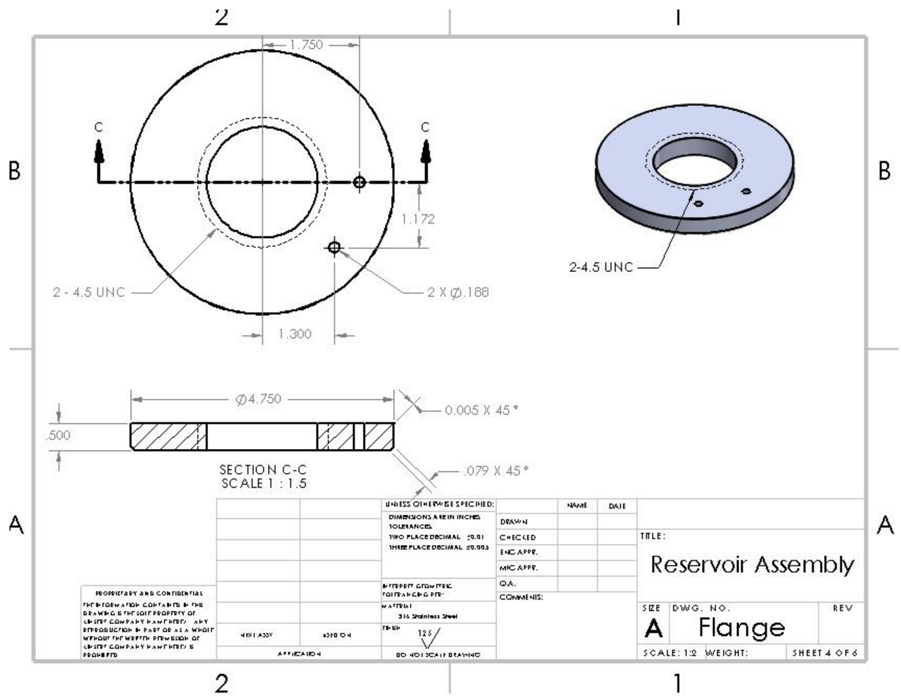


Figure C-3. Engineering drawing of the flange

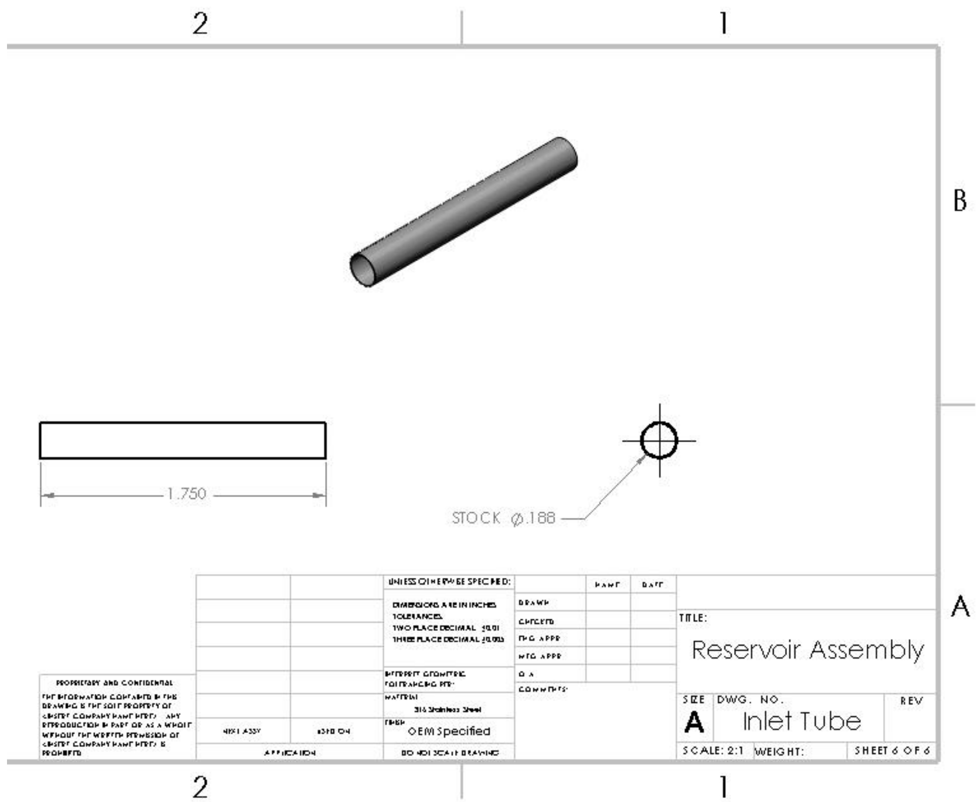


Figure C-4. Engineering drawing of the inlet tube

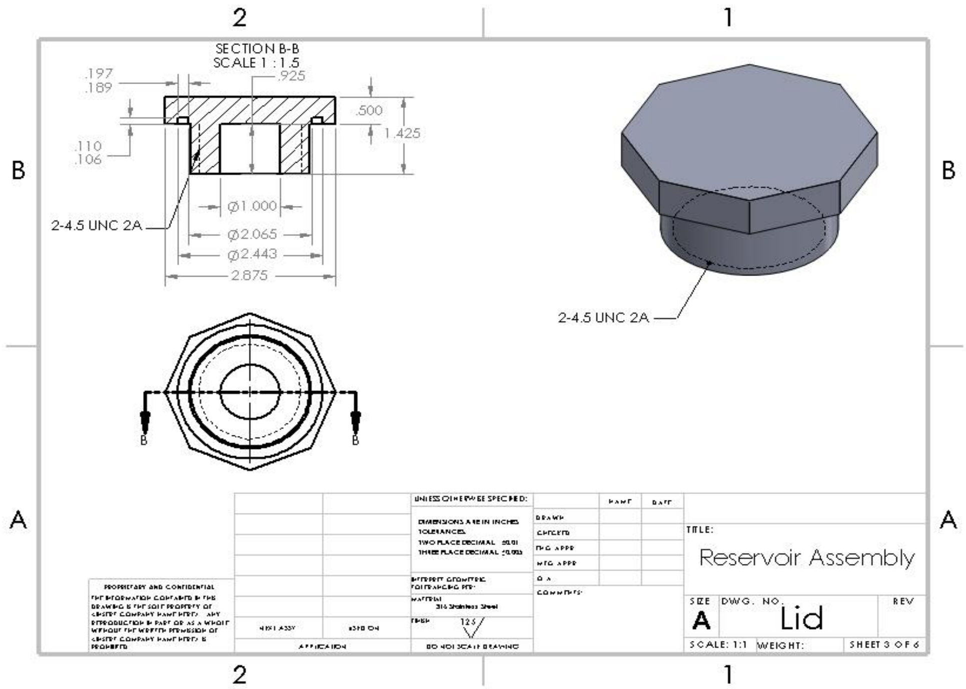


Figure C-5. Engineering drawing of the lid

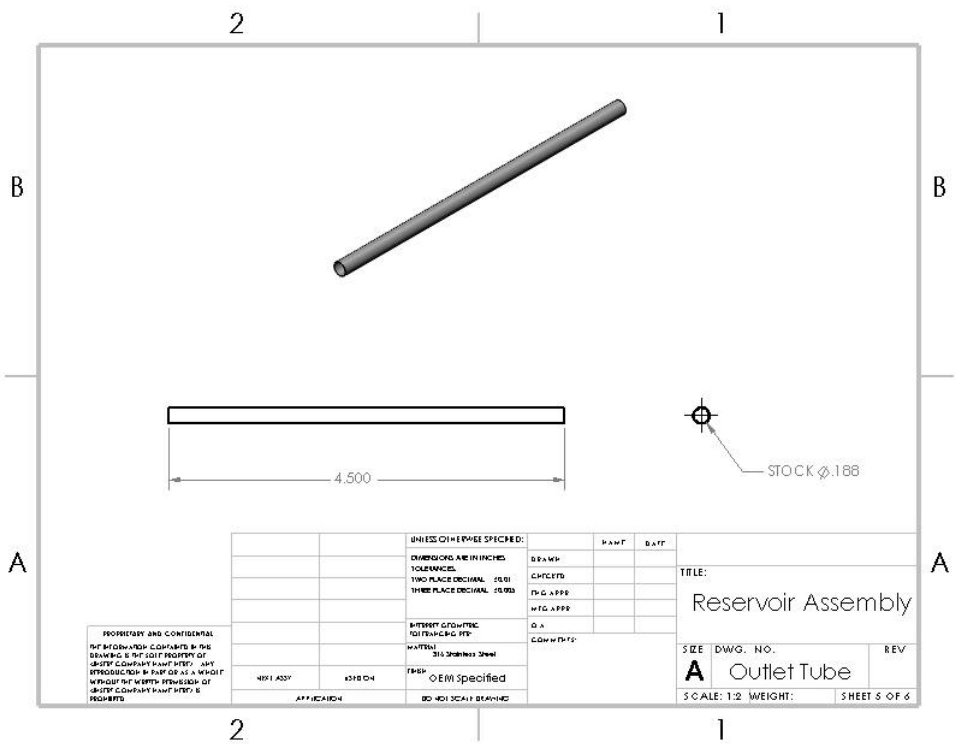


Figure C-6. Engineering drawing of the outlet tube