GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

Trabajo Fin De Grado

CAMbox - Compact Autonomous Microbioreactor

Autor
Pelayo Urrios Gomendio

Director
Dr Matthew J. Traum

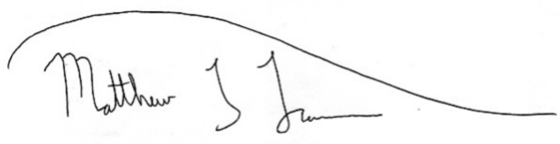
Madrid
Julio 2020

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título CAMbox en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el curso académico 2020/21 es de mi autoría, original e inédito y no ha sido presentado con anterioridad a otros efectos. El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada de otros documentos está debidamente referenciada.

Fdo: Pelayo Urrios Gomendio

Autorizada la entrega del proyecto

Director Del proyecto
Fdo: Dr Matthew J. Traum



I. Autorización Para La Digitalización, Depósito Y Divulgación En Red De Proyectos Fin De Grado, Fin De Máster, Tesinas O Memorias De Bachillerato

1. **Declaración de la autoría y acreditación de la misma**
   El autor D.Pelayo Urrios Gomendio DECLARA ser el titular de los derechos de propiedad intelectual de la obra: CAMbox, que ésta es una obra original, y que ostenta la condición de autor en el sentido que otorga la Ley de Propiedad Intelectual.

2. **Objeto y fines de la cesión**
   Con el fin de dar la máxima difusión a la obra citada a través del Repositorio institucional de la Universidad, el autor **CEDE** a la Universidad Pontificia Comillas, de forma gratuita y no exclusiva, por el máximo plazo legal y con ámbito universal, los derechos de digitalización, de archivo, de reproducción, de distribución y de comunicación pública, incluido el derecho de puesta a disposición electrónica, tal y como se describen en la Ley de Propiedad Intelectual. El derecho de transformación se cede a los únicos efectos de lo dispuesto en la letra a) del apartado siguiente.

3. **Condiciones de la cesión y acceso**
   Sin perjuicio de la titularidad de la obra, que sigue correspondiendo a su autor, la cesión de derechos contemplada en esta licencia habilita para:

   (a) Transformarla con el fin de adaptarla a cualquier tecnología que permita incorporarla a internet y hacerla accesible; incorporar metadatos para realizar el registro de la obra e incorporar "marcas de agua" o cualquier otro sistema de seguridad o de protección.
   (b) Reproducirla en un soporte digital para su incorporación a una base de datos electrónica, incluyendo el derecho de reproducir y almacenar la obra en servidores, a los efectos de garantizar su seguridad, conservación y preservar el formato.
   (c) Comunicarla, por defecto, a través de un archivo institucional abierto, accesible de modo libre y gratuito a través de internet.
   (d) Cualquier otra forma de acceso (restringido, embargado, cerrado) deberá solicitarse expresamente.
   (e) Asignar por defecto a estos trabajos una licencia Creative Commons.
   (f) Asignar por defecto a estos trabajos un HANDLE (URL persistente).

4. **Derechos del autor**
   El autor, en tanto que titular de una obra tiene derecho a:

   (a) Que la Universidad identifique claramente su nombre como autor de la misma.
   (b) Comunicar y dar publicidad a la obra en la versión que ceda y en otras posteriores a través de cualquier medio.
   (c) Solicitar la retirada de la obra del repositorio por causa justificada.
   (d) Recibir notificación fehaciente de cualquier reclamación que puedan formular terceras personas en relación con la obra y, en particular, de reclamaciones relativas a los derechos de propiedad intelectual sobre ella.

5. **Deberes del autor.**
   El autor se compromete a:

   (a) Garantizar que el compromiso que adquiere mediante el presente escrito no infringe ningún derecho de terceros, ya sean de propiedad industrial, intelectual o cualquier otro.
   (b) Garantizar que el contenido de las obras no atenta contra los derechos al honor, a la intimidad y a la imagen de terceros.
   (c) Asumir toda reclamación o responsabilidad, incluyendo las indemnizaciones por daños, que pudieran ejercitarse contra la Universidad por terceros que vieran infringidos sus derechos e intereses a causa de la cesión.

(d) Asumir la responsabilidad en el caso de que las instituciones fueran condenadas por infracción de derechos derivada de las obras objeto de la cesión.

6. **Fines y funcionamiento del Repositorio Institucional.**

   La obra se pondrá a disposición de los usuarios para que hagan de ella un uso justo y respetuoso con los derechos del autor, según lo permitido por la legislación aplicable, y con fines de estudio, investigación, o cualquier otro fin lícito. Con dicha finalidad, la Universidad asume los siguientes deberes y se reserva las siguientes facultades

   (a) La Universidad informará a los usuarios del archivo sobre los usos permitidos, y no garantiza ni asume responsabilidad alguna por otras formas en que los usuarios hagan un uso posterior de las obras no conforme con la legislación vigente. El uso posterior, más allá de la copia privada, requerirá que se cite la fuente y se reconozca la autoría, que no se obtenga beneficio comercial, y que no se realicen obras derivadas.

   (b) La Universidad no revisará el contenido de las obras, que en todo caso permanecerá bajo la responsabilidad exclusive del autor y no estará obligada a ejercitar acciones legales en nombre del autor en el supuesto de infracciones a derechos de propiedad intelectual derivados del depósito y archivo de las obras. El autor renuncia a cualquier reclamación frente a la Universidad por las formas no ajustadas a la legislación vigente en que los usuarios hagan uso de las obras.

   (c) La Universidad adoptará las medidas necesarias para la preservación de la obra en un futuro.

   (d) La Universidad se reserva la facultad de retirar la obra, previa notificación al autor, en supuestos suficientemente justificados, o en caso de reclamaciones de terceros.

   Madrid a 21 de Julio de 2021

   ACEPTA

FDO:

Contents

List of Figures

List of Tables

II. Diseño y Analisis De Un Microbiorreactor

Autor: Pelayo Urrios Gomendio
Director: Dr Matthew J. Traum

Resumen del proyecto
La invención que se da a conocer es un microbiorreactor semiautónomo que puede cultivar las células al mismo tiempo que es capaz de monitorizar sus constantes vitales. El biorreactor será capaz de proporcionar un entorno controlado para promover el crecimiento y la producción de cultivos celulares, medir las constantes vitales, acomodar varias placas de cultivos y tubos cónicos, gestionar los residuos celulares y manejar los gases y líquidos durante los períodos de incubación.

1. **Introducción:**

   El proyecto fue desarrollado durante un periodo de 3 meses por 7 compañeros y yo.

   Está dividido en tres secciones, correspondientes a los tres periodos de desarrollo del proyecto.El objetivo principal del microbiorreactor es automatizar el proceso de cultivo de celulas. Este dispositivo es capaz de cultivar microbioorganismos en compartimentos totalmente sellados, intercambiables y que permiten el cambio de medios. El CAMbox mide continuamente la densidad óptica y la intensidad fluorescente del cultivo, la presión interna y la temperatura. El cliente (UF Bio Foundry) también incluyó algunos requisitos adicionales que debía cumplir el biorreactor.

   En la primera fase del CAMbox (CDR), mi equipo y yo nos centramos en investigar los diferentes componentes que conforman un microbiorreactor y en desarrollar prototipos que pudieran realizar las tareas requeridas y satisfacer las necesidades del cliente.

   En la segunda fase del CAMbox (PDR), nos centramos en desarrollar el prototipo que mejor respondiera a las necesidades del cliente y al "concepto de erizo" (objetivo del proyecto). Utilizamos estudios comerciales para asegurarnos de que cada subsistema satisfacía las necesidades del cliente.

   En la tercera fase del CAMbox (FDR), seguimos corrigiendo y desarrollando los prototipos elegidos. Para determinar los materiales, las geometrías y las dimensiones de los diferentes subsistemas del microbiorreactor tuvimos que realizar varios análisis e investigaciones.

2. **Definición del proyecto:**

   Desde la pandemia sufrida en marzo del 2020 debido al Covid-19 nos hemos visto obligados a investigar exhaustivamente y invertir en equipos de laboratorios, es por eso que este proyecto se va a centrar en diseñar un microbiorreactor que facilite la labor de investigación y reduzca el riesgo de contaminación de los experimentos, dando lugar a una bajada del presupuesto necesario para desarrollar medicamentos y/o vacunas. El CAMbox esta pensado para ser un microbiorreactor asequible y al alcance de laboratorios/universidades pequeñas de tal manera que no solo las grandes entidades sean capaces de aportar nuevos avances en el mundo de la investigación.

3. **Descripción del microbiorreactor:**

   Durante el proceso de diseño, la CAMbox se dividió en varios subsistemas para promover una mayor atención a los detalles. Los subsistemas clave de la CAMbox son la cubierta, el subsistema de control de gases, el subsistema de manipulación de líquidos, la interfaz de usuario, el subsistema de control climático, el lector OD/FI y el subsistema de agitación. La cubierta es de acero y aísla el entorno de cultivo del mundo exterior. El recinto está aislado térmicamente y es resistente a la corrosión para permitir una limpieza sin preocupaciones y promover la longevidad.

   El subsistema de control de gas utiliza válvulas de solenoides para regular la entrada de gas y, en última instancia, proporciona al usuario final la capacidad de cultivar células en un entorno con opciones ilimitadas en cuanto a la composición atmosférica.

   El subsistema de manipulación de líquidos utiliza un pórtico prefabricado que se mueve en tres dimensiones para depositar los nutrientes y eliminar los residuos de los cultivos de desecho sin necesidad de intervención humana, lo que minimiza el riesgo de contaminación. Además, este sistema es capaz de añadir y retirar fluidos de los cultivos celulares con un grado de precisión extremadamente alto: se tomaron medidas adicionales para garantizar que no se crearan aerosoles durante la adición o retirada de líquidos.

El interfaz de usuario ofrece al usuario final el control de la temperatura, la composición atmosférica y el patrón de agitación, a la vez que proporciona información del sistema de monitorización OD/FI incorporado.

El subsistema de control climático permite al usuario controlar la temperatura a la que se cultivan las células y mitiga la condensación en la superficie de los contenedores de cultivo, ofreciendo un rango de temperatura marcable de 4 a 70 grados celsius, y la capacidad de alcanzar estas temperaturas en menos de 15 minutos utilizando la convección forzada para calentar y enfriar los cultivos celulares.

El agitador de placas proporciona al usuario la capacidad de agitar automáticamente los cultivos celulares en patrones lineales, orbitales y dobles orbitales utilizando motores pequeños y eficientes de alta velocidad y resortes de larga duración.

El CAMbox también utiliza un sistema de monitorización celular personalizado capaz de realizar mediciones de densidad óptica e intensidad de fluorescencia. Uno de los requisitos mas indispensable fue asegurar que la lectura de la densidad óptica y la intensidad de fluorescencia sea rápida, eficiente y no dañina para los cultivos celulares.

4. **Resultado y conclusión:**
El resultado final es un microbiorreactor compacto y ligero capaz de desempeñar las funciones mencionadas anteriormente. Los siete subsistemas trabajando en armonia son capaces de llevar a cabo un experimento totalmente automatizado y con riesgo de contaminación del cultivo practicamente nulo.

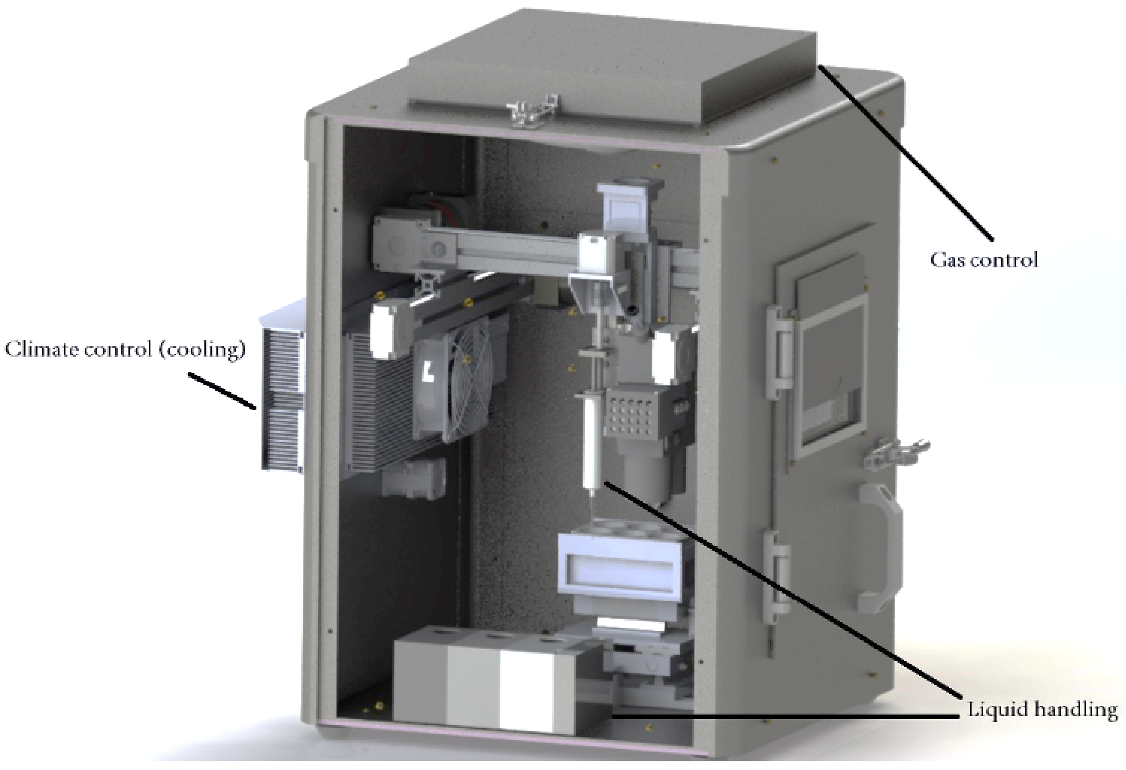


Figure 1: Vista Interna 1 del CAMbox.

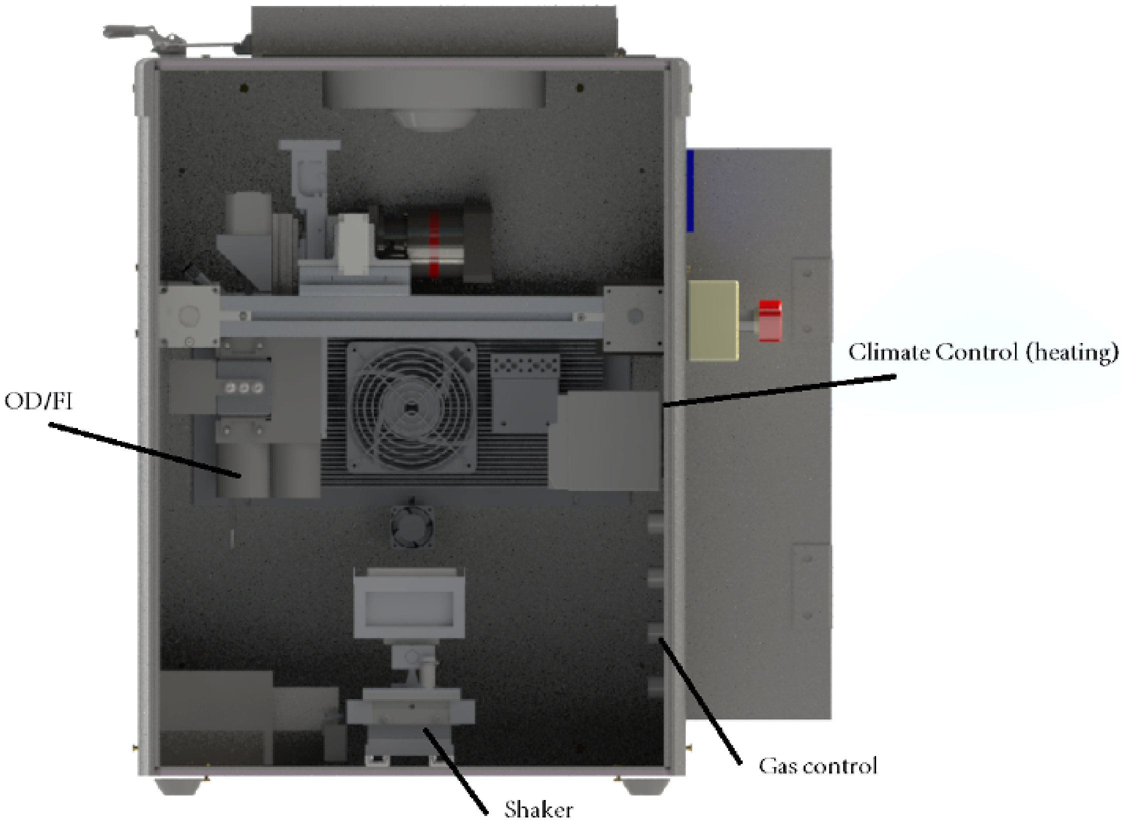


Figure 2: Vista Interna 2 del CAMbox.

III. Design and Analysis Of A Microbioreactor

Author: Pelayo Urrios Gomendio
Director: Dr Matthew J. Traum

A. Project Summary

The invention disclosed is a semi-autonomous microbioreactor that can grow cells while being able to monitor their vitals. The bioreactor will be capable of providing a controlled environment to promote cell culture growth and production, measure vitals, accommodate various culture plates and conical tubes, manage cell waste, and handle gases and liquids during incubation periods.

1. **Introduction:**

   The project was developed over a period of 3 months by 7 colleagues and myself. It is divided into three sections, corresponding to the three periods of project development.The main purpose of the microbioreactor is to automate the process of culturing.This device is able of culturing microbes in compartments fully enclosed, interchangeable and allow media exchange. The CAMbox is continuously measuring culture optical density and fluorescent intensity, internal pressure, and temperature. The customer (UF Bio Foundry) also included some additional requirements that the bioreactor must meet.

   In the first phase of the CAMbox (CDR), my team and I focused on researching the different components that make up a microbioreactor and developing prototypes that could perform the required tasks and meet the customer needs.

   The second phase of the CAMbox (PDR), we focused on developing the prototype that best met the customer needs and the hedgehog concept (project goal). We used trade studies to make sure each subsytem was meeting the customer needs.

The third phase of the CAMbox (FDR), we continue to correct and develop the chosen prototypes. In order to determine materials, geometries, dimensions of the different subsystems of the microbioreactor we had to carry out several analyses and investigations.

2. **Proyect Definition:**

   Since the pandemic suffered in March 2020 due to Covid-19 we have been forced to research extensively and invest in laboratory equipment, that is why this project will focus on designing a microbioreactor that eases the research work and reduces the risk of contamination of experiments, resulting in a lowering of the budget needed to develop medicines and / or vaccines. The CAMbox is intended to be an affordable microbioreactor within the reach of small laboratories/universities so that not only large entities are able to bring carry out new advances.

3. **Microbioreactor description:**

   During the design process, the CAMbox was broken down into several subsystems to promote a greater attention to detail. The key subsystems of the CAMbox are the enclosure, the gas control subsystem, the liquid handling subsystem, the user interface, the climate control subsystem,the OD/FI reader, and the shaker subsystem. The enclosure is made from steel and isolates the culturing environment from the outside world. The enclosure is thermally insulated and corrosion-resistant to allow for worry free cleaning and to promote longevity. The gas control subsystem uses solenoid valves to regulate gas input and ultimately provides the end user with the ability to culture cells in an environment with unlimited options concerning atmospheric composition.

   The liquid handling subsystem uses a prefabricated gantry that moves in three dimensions to deposit nutrients and remove waste from the cull cultures without any need for human intervention, minimizing the risk of contamination. Additionally, the liquid handling system is capable of adding and removing fluid from cell cultures with an extremely high degree of accuracy – extra steps were taken to ensure that no aerosols are create during liquid addition or removal. The user interface gives the end user control over the temperature, atmospheric composition, shaking pattern, while providing feedback from the in built OD/FI monitoring system. The climate control subsystem allows the end user to control the temperature at whicht he cells are cultured and mitigates condensation on the surface of culture containers, offering are markable temperature range of 4 Celsius to 70 Celsius, and the ability to achieve these temperatures in under 15 minutes by using forced convection to heat and cool cell cultures. The well plate shaker provides the end user with the ability to automatically shake the cell cultures in linear, orbital, and double orbital patterns using small, efficient, high-speed motors and long-lasting springs. The CAMbox also uses a custom cell monitoring system capable of both optical density and fluorescence intensity measurements. The designers behind the CAMbox to care to ensure that OD/FI reading is fast, efficient, and not harmful to cell cultures.

4. **Result and conclusion:**
   The end result is a compact and lightweight microbioreactor capable of performing the functions mentioned above. The seven subsystems working in harmony are capable of carrying out a fully automated experiment with virtually no risk of contamination of the culture.

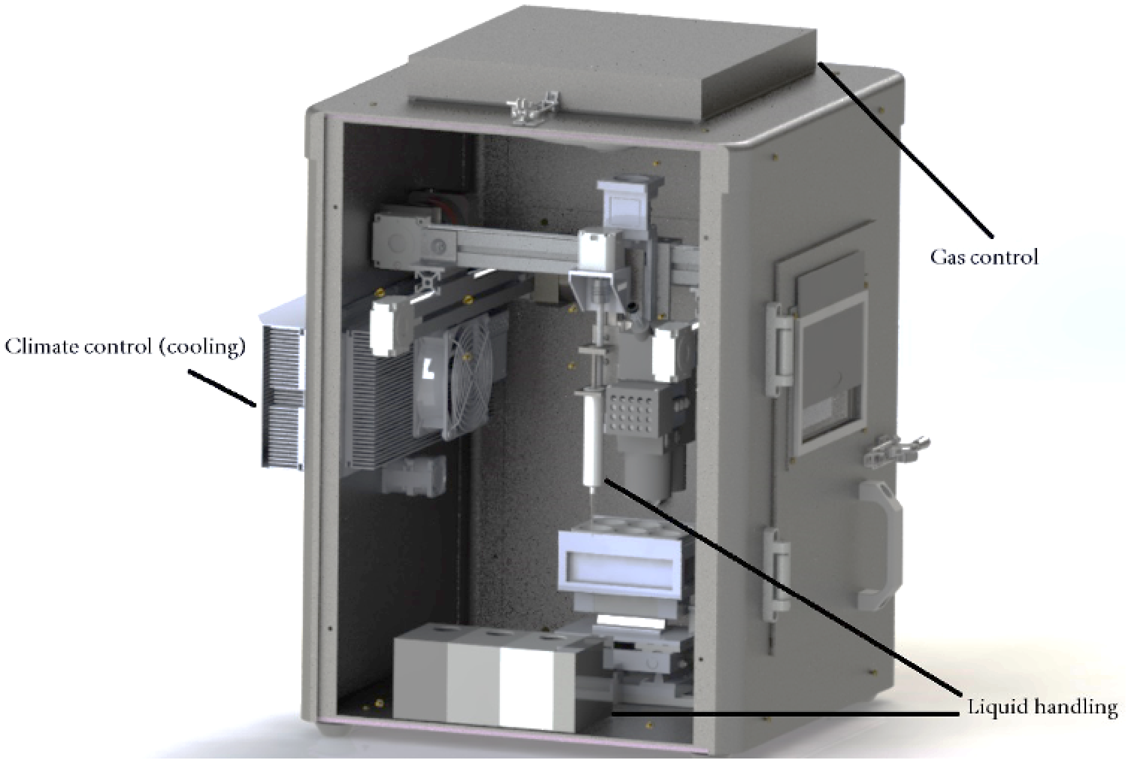


Figure 3: Internal View 1 del CAMbox.

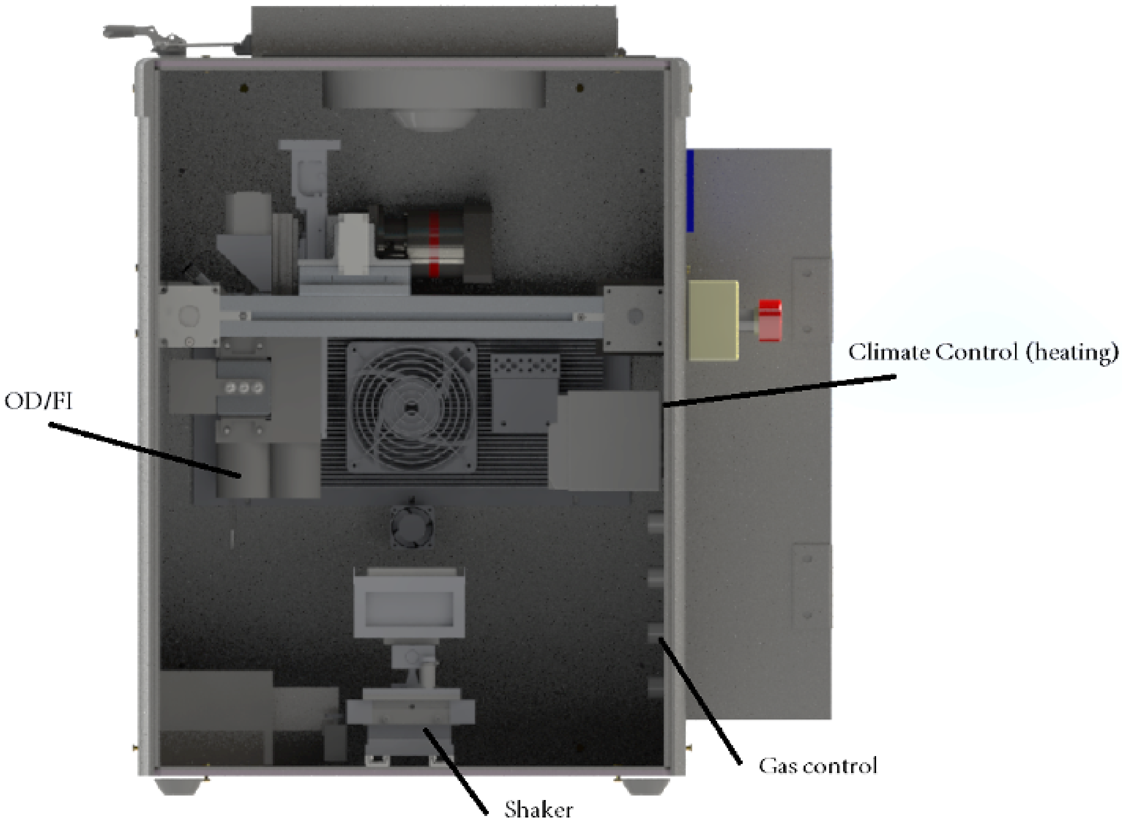


Figure 4: Internal View 2 del CAMbox.

A. Introduction

The project was developed over a period of 3 months by 7 colleagues and myself. It is divided into three sections, corresponding to the three periods of project development.The main purpose of the microbioreactor is to automate the process of culturing.This device is able of culturing microbes in compartments fully enclosed, interchangeable and allow media exchange. The CAMbox is continuously measuring culture optical density and fluorescent intensity, internal pressure, and temperature. The customer (UF Bio Foundry) also included some additional requirements that the bioreactor must meet.

In the first phase of the CAMbox (CDR), my team and I focused on researching the different components that make up a microbioreactor and developing prototypes that could perform the required tasks and meet the customer needs.

The second phase of the CAMbox (PDR), we focused on developing the prototype that best met the customer needs and the hedgehog concept (project goal). We used trade studies to make sure each subsytem was meeting the customer needs.

The third phase of the CAMbox (FDR), we continue to correct and develop the chosen prototypes. In order to determine materials, geometries, dimensions of the different subsystems of the microbioreactor we had to carry out several analyses and investigations.

B. Literature Review

A. Problem Statement

There are no affordable autonomous bioreactor devices which feature built-in culture monitoring. The customer desires a device that offers a wider selection of working volumes and condition control, as well as greater levels of automation compared to commercially-available micro-plate readers. The customer desires a device that can culture microbes in compartments or vessels that are fully enclosed, easily interchangeable, and allow for media exchange. The device must move cultures suspended in liquid between compartments or vessels, provide nutrients in media to cultures, dispose of waste, and sterilize itself. The device must also continuously measure culture optical density and fluorescent intensity, and provide control over internal temperature and pressure. During functional use, contamination must be avoided while also having a satisfactory liquid handling system that has no interaction with the local atmosphere/environment.

B. The State of the Art

This section will cover some of the existing devices and strategies which attempt to meet all the customer needs. However, none of the devices found in this section fully meet all of the customer needs. The sections following this one will break down state of the art strategies and devices within the subsystems that the final design will include.

Currently, the technology to meet the customer's needs has been applied in several segments. Processes performed manually that caused errors, delays, and losses are now replaced by agile and secure technological tools. The inclusion of automated, standardized and accurate methods in the laboratory routine, has significantly assisted researchers in completing studies quickly and accurately. Among the types of studies that have benefited the most from technological advancement, cell culturing is one of the most prominent.

Cell culturing is a technique for growing or preserving cells in a controlled environment, also known as bioreactor, in vitro [27]. The advancement of biotechnology has been aided by the invention of bioreactors. A bioreactor is a piece of equipment that is used to carry out a biological reaction or transition. Enzymes, microorganisms, animal cells, plant cells, and tissues are among the biological elements involved [34]. Bioreactors are mostly used in fermentation processes, on both laboratory and industrial scales. The device is used with an incubator that maintains the inside atmosphere at a controlled temperature, humidity, and gas content [27]. The device also allows pH, agitation, foam, and other parameters to be controlled. Among these parameters, the temperature ensures that the selected microorganism grows properly and can also be a form of induction to obtain a product of interest, such as a protein. The pH is also essential, as it interferes with cell growth and process yield and, therefore, it is ideal that it is well established. Stirring, on the other hand, has the role of ensuring good mass and heat transfer, keeping the medium homogeneous throughout the process. Each parameter can be adjusted according to the needs and characteristics of each specific study.

Regarding the current project, the Autonomous Microbioreactor requested by the UF Bio foundry will have three main functions: cell culturing, liquid handling, and culture monitoring. Thus, in addition to the cell growth analysis, the device will be able to transport the desired culture from one location to another and to measure its internal temperature and pressure, culture optical density (OD), and fluorescent intensity (FI). Most equipment currently available can perform only one of the above functions. For example, the BioProfile FLEX2, is an automated cell culture analyzer from Nova Biomedical. This device can monitor the progress of bioreactor runs, determine consumption and production of key metabolites, identify growth-limiting nutrients, design feeding strategies, calibrate bioreactor probes, measure cellular respiration, balance media electrolytes, and control levels of waste product [4].

Another example is the Assist Plus, which is a Pipetting Robot for full workflow automation, designed by Integra. The device reduces physical strain while also ensuring high reproducibility and error-free pipetting. It is well known for its versatility. First, an electronic multi-channel pipette needs to be mounted onto the pipette holder. Then, a pipetting protocol should be selected and a tip rack and labware added. Finally, the run button needs to be pressed and the Assist Plus will automatically carry out the pipetting task [10].

Therefore, the innovative idea of the microbioreactor is to combine multiple functions found in different equipment into a single device. Although certain concepts from existing products might work well with our vision for the customer's device, there are some key limitations to observe. For example, it would be very useful to use an electronic multi-channel pipette instead of dealing with motors and other electronic components, but the prototype production cost limit of 10,000 dollars makes such a feature prohibitively expensive. The final design will have similar functionality as the equipment currently available but will be synthesized to combine each of these functionalities into a single autonomous device.

C. Customer Needs

Customer Need Metrics			
Need Number	Customer Need	Quantification	Max/Min
1	Operational lifetime	10 years	Max
2	Prototype production cost	10,000	Max
3	Moveable by one person after disassembly	Each unassembled component weighs under 50 pounds	Max
4a	Fits on a research benchtop, Clearance through doors	Less than 36 inches wide	Max
4b	Fits on a research benchtop, Benchtop loadbearing capacity	load of assembly must be lower than 600 pounds	Max
4c	Fits on a research benchtop, Benchtop footprint	Bottom face dimensions must be smaller than 24 inches wide and 60 inches long.	Max
5	Runs from a single standard 120 VAC wall outlet	Operate with a 120V AC	Max
6	Has an easily accessible interior for cleaning	Access hole must allow two hands to fit through at least 20 inches long, 5 inches wide	Max
7	Includes an easily actuated emergency shut-off that safely that stops all functions	quantified by how long to takes to stop all function, a minimum of 0.5 seconds will be used and a maximum of 1 second	Max
8	Has an intuitive user interface	There will be a minimum of 1 setting per number of subassemblies of the system and a maximum of 2 settings per number of subassemblies, making the minimum settings on the interface 8 and the maximum 16	Max
9	Has a visual indicator that is easily seen by the user and nearby personnel	this need will be quantified by the brightness of the interface display or flashing of the buttons on a scale of 1-5, 1 being the dimmest and 5 being the brightest.	Min
10	Is programmable: control parameters can be changed by the user, and more complex processes can be added	Each subsystem can be controlled individually, quantified by the number of controls on the interface, a minimum of 8 to allow control of different subsystems.	Min
11	Only nonporous materials contact cell cultures	Disposable tips will be made of nonporous materials. 1 disposable tip per liquid being used.	Min

12	Only nonreactive materials contact lab chemicals	Signs will be posted to the device warning users about volatile materials and to keep them far from the reactor	Min
13	Appropriate for operation in a BSL-2 space	Waste will be stored and made safe until waste can be fully disposed of	Min
14	Has an exterior surface that is not too hot to comfortably touch	Exterior casing must always remain at a temperature under 44 Celsius or 111 Fahrenheit [11]	Min/Max
15	Is capable of sequestering and neutralizing its own liquid and solid waste	Waste will be neutralized by being placed in a reservoir containing 0.10 of the volume in bleach.	Min
16	Cultures microbes in fully enclosed compartments or vessels that are interchangeable	Every compartment is interchangeable	min
17	Maintains environmental conditions independently for each well plate or tube	Independently control at least 3 separate environments	Min
18	Is capable of safely injecting, measuring, and regulating the composition of the following gases in each compartment holding a well plate or tube: N2, O2, CO2, CH4, H2	Inject 5 gases	Max
19	Is capable of incubation periods long enough to permit 1,000 E. coli culture generations	2 weeks	Max
20	Maintains cultures in a well plate or tube at a constant temperature within a range from 4 to 70 degrees C	4-70 degrees Celsius	Min/Max
21	Maintains internal set point temperature with time and spatial variation less than ±2.5 degrees C	2.5 degree difference	Max
22	Uniformly heats/cools wells/tubes within the desired temperature range	5 degree difference	Max
23	Mitigates condensation on cooled well plate and tube surfaces	covers less than .10 of surfaces on well plates or conical tubes	Max
24	Reaches set point culture temperature in less than 15 minutes	15 minutes	Max
25	Accommodates existing culture well plates of the following sizes: 6, 24, 48, 96, deep 96, 384	Hold well plates of 6,24,48,96, deep 96, 385	Max/Min

26	Accommodates existing conical tubes of the following sizes: 15mL and 50mL	Hold conical tubes of 15mL and 50mL	Min/Max
27	Includes a photobioreactor mode to illuminate photosynthesis-capable cell cultures(e.g., cyanobacteria) with white light	Illuminate from 400nm-640nm at 1kW/cm3	Min/Max
28	Shakes well plates and tubes in Linear, Orbital, and Double Orbital patterns	Capable of three shaking patterns	Max
29	Has shaking patterns that are independent for each well plate or tube	Adaptable to shake well plates and tubes	Min
30	Measures optical density (OD)in all individual wells and conical tubes	Measure OD at 600nm	Max
31	Measures fluorescent intensity (FI)in all individual wells and conical tubes	Excite fluorescence up to 640nm and detect emission up to 740 nm	Max
32	For OD/FI measurement, sustains adequate light intensity to make measurements at wavelengths not lethal to cells	Maintain Light intensity of 640nm	Max
33	Processes a 384 well plate through OD/FI measurements in less than 6.5 minutes	6.5 Minutes	Max
34	Is capable of automated liquid handling with fluid addition/subtraction from each well or tube	Quantified by the number of steps the subsystems require to complete the process of adding or subtracting liquid. The number of steps this subsystem takes will be between 3 and 6.	Min/Max
35	Dispenses fluid without creating aerosols	To determine whether aerosols will be created the Reynolds number will be calculated. The Reynolds number will have a maximum of 2300 in order to avoid creating aerosols.	Max
36	Achieves dispense rates from 225 uL/s to300 uL/s	Dispenses fluid from 225 uL/s to 300 uL/s	Min/Max
37	Deposits a minimum/maximum aliquot fluid volume from5–20,000 µL	Deposit from 5-20000 uL of aliquot fluid volume	Min/Max
38	Achieves dispensing volume accuracy of±0.1µL	volume accuracy 0.01 uL	Min/max
39	Achieves dispensing volume precision±0.01 µL	volume accuracy 0.01 uL	Min/Max

40	No cross contamination between individual wells/tubes during liquid handling	Cross contamination will be avoided by using disposable tips. The number of tips used will depend for the number of pipettes, a minimum of 1.	Min

D. Concept Design Report

A. Gantt Chart

The group allotted nearly 2 weeks starting from 2/22 to work on the Concept Design Report. It was anticipated that background research on bioreactors and each subsection were completed by 2/24 so that subsystem designs can be made. Eight subsections were divided amongst the eight group members. A large portion of time and effort was given towards concept and design development as shown in the figure below.

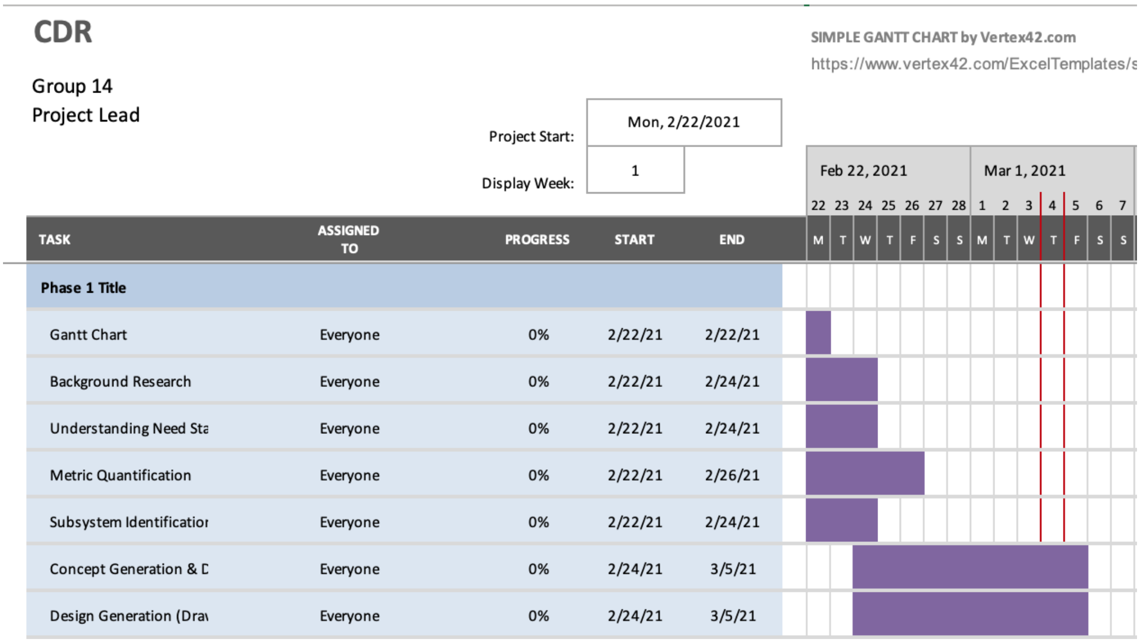


Figure 5: Gantt Chart.

B. Subsystem 1: Enclosure

Governing Equations		
Equation	Reason for Application	Design Applications
q $= U * A * dT$	This equation governs the conductive heat transfer based on thermal conductivity of materials, material thickness, and heat transfer area	All Enclosure Designs

Based on current research performed with other bioreactors, it appears that, while important for keeping a stable temperature throughout the environment, the actual type of insulation did not have a significant change in temperature. This led the design process to include as much insulation as possible while incorporating a design that promoted airflow and optimized consumption of space. The following designs have a few main variations like frame construction material, insulation installation, internal versus external heating and cooling, and a tower design compared to a more simple box design.

Concept Design 1: This first enclosure focuses on optimizing space while allowing the bioreactor to be in a singular package. The tower design has a cooling fan at the top that sucks air from the top, cooling the wiring and circuitry while allowing for a vent to open to allow the fan to assist with circulation of cool or warm air evenly throughout the entire reactor. This design has an external cooling unit meaning it is not as mobile and conservative with space as some of the other designs. This design also incorporates a layered design that could potentially have detachable layers for easier access and complete removal of certain sections.

Concept Design 2: This design is very similar to the previous design but incorporates the external cooling unit into another layer of the tower. Eliminating a large external cooling unit makes the entire design more streamlined but does bring up issues involving the actual construction and implementation of the cooling. Internal cooling with the tower design would allow for a very fast and efficient transferal of cool air throughout the tower. The insulation used throughout the lower section of the tower, where the well plates are stored, would most likely be a standard insulation foam.

Concept Design 3: The final tower-based design is very similar to the rectangular tower design but except for being a cylinder as opposed to a rectangular prism. This change was made specifically to accommodate a gantry that utilizes a loop system around the exterior of the enclosure. Similar to the previous design, the singular tower is more streamlined, but the actual creation and assembly of this design would be much more complex and increase the overall research and development time; however, it is worth investigating the potential benefits this design could yield.

Concept Design 4: This design is much simpler than the tower designs and utilizes a simple aluminum frame and features and external cooling unit like some of the previous designs. The panels on this design, clip on and can be removed easily to allow access to the internals of the enclosure. The gases, gantry, heating, shakers, well plates, and ODFI readers are all inside a single box.

Concept Design 5: This design is like the previous design but focuses on optimizes insulation by incorporating an inner layer of insulation within the metal framing itself. The design also features insulation pads and an external cooling unit.

Concept Design 6: This enclosure design focuses on the simplicity and availability of the materials it is made with. The frame itself is comprised of 80/20 beams and connection points with an external. The 80/20 design also allows for almost infinite adjustability in any direction. This design heavily borrows from some of the previous designs in that it also has an external cooling supply, slot for viewing, and box like shape that houses the heating unit.

Concept Design 7: This design is identical to the solid aluminum rod design from above except it does not have external cooling. This means that the overall volume of the box would have to be increased. This allows for a singular device that can fit on a table a one unit. This aligns very close with the customer needs that call for the device to fit on a single table; however, the overall complexity increases when dealing with the specific implementation of the cooling into the device itself. This design would be more difficult to manufacture because the sheer size.

C. Subsystem 2: Robot Motion

Governing Equations		
Equation	Reason for Application	Design Applications
$t_{xyz} = \frac{d_{xyz}}{V_{xyz}}$	This equation governs the time required for a linear robot motor to travel a determined linear distance.	All Robot Motion Designs
$t_{xyz} = \frac{\theta_{xyz}}{\omega_{xyz}}$	This equation governs the time required for a rotational robot motor to travel a determined angular distance.	Robot Motion Designs 3, 4, 5, and 6

With constant innovation within the robotics field, various types of robotic arms are becoming faster, stronger, more efficient, and more affordable for everyday consumers. Robotic arm systems come in various forms including Cartesian or Gantry robot arms, Cylindrical robot arms, and Selection Compliance Assembly Robot Arms (SCARA) [21]. Each of these types of robotic arms are widely used in a variety of real world industries including 3D-printing, industrial assembly, and load transportation. While these robotic arms come in wide ranges of sizes, smaller more compact robotic arm systems can be designed, built, and used in much smaller projects such as liquid handling and cell culture research.

Concept Design 1: The first Cartesian or gantry style robot design that is considered involves a three-motor system that will be connected to and supported by the enclosure inner walls. While most gantry style robot structures are supported by vertical columns, this design's wall attachment allows for a greater area of coverage by the robot arm since there is no vertical columns that prevent additional motion in the z direction. A large benefit of using gantry robots is their three linear axes of motion (x, y, z), precision, and accuracy of positioning. This design considers servo electric motors along with a belt system across each direction of motion to create the fast linear movement of the robot arm. All three motors can work simultaneously for faster and more efficient arm positioning. Servo motors are used instead of stepper electric motors due to their greater ability to achieve a higher speed, acceleration, and accuracy [20].

Concept Design 2: A second slightly altered design for a gantry type robot includes a similar three-motor design however now, the structure itself is attached to the ceiling of the enclosure interior. Similar to the first design, the removal of column supports allows for a greater area of coverage by the motor and belt system. The design choice of shifting the structure attachment to the ceiling was done to aid in the assembly, disassembly, cleaning, and inspection processes involved with the entire resulting system. With the robot's entire structure being connected to the one upper inner face of the casing, the top wall of the casing may be removed, and the robot arm can easily be taken out for any cleaning, transportation, or repair needs. In addition, with the top plate removed and large robot arm subsystem out of the way, it becomes much easier to access the remaining interior components of the entire system.

A critical component in understanding the differences across each robotic arm design and which design would better fit the required needs of the system, a governing equation is established to determine the time in seconds that it would take each robot subsystem to travel a designated distance in each direction of motion. A more efficient robot system would be able to perform the required tasks in a faster and more efficient manner. To derive this governing equation for Cartesian style designs, the velocities that the linear belts travel, and the distances needed to be traveled are considered. From an online source which spoke on similar servo and belt gantry style robots, the linear loaded velocities in the horizontal z and x directions as well as the vertical y direction can fall around 2000 mm/s, however at a maximum load of up to 30 kg, it can be assumed that the velocity falls to about 1200 mm/s or 60 percent of the maximum speed [12]. The distance needed to be traveled will consider the standard dimensions of the largest well plate that the system will use, a 384 well plate which has dimensions of approximately 127.76 mm long, 85.48 mm wide, with a well depth of 12.7 mm [31].

Concept Design 3: A different design also being considered is a cylindrical robot style design. This design considers the robot to stand vertically connected to the bottom inner face of the system casing. Three stepper motors and two belt systems are used within the design. Stepper motors are used in this design specifically for a slower arm motion due to the decreased overall robot arm strength and stability. The single rotational motor rotates the main robot arm column about the y axis while the two linear motor systems slide the robot arm up and down along the main column in the y direction and outward and inward along the x direction. The largest difference in using this style robot over the Cartesian system is the cylindrical area of coverage by the arm. Due to this, the governing equation must consider the angular velocity of the rotational motor. From an online source, similar cylindrical robot arms showed to have linear loaded velocities of 500 mm/s in the x and y directions and an angular velocity of 180 degrees/s about the y axis [35]. Once again, the dimensions of the large well plate are considered. For the time calculation of rotational motor z, the arc length equation is used to approximate the angle the robot must travel to cover the width of the well plate. The radius of the robot's arm reach for the rotational speed calculation was assumed to be the length of the well plate. Due to the robot's arm reach radius being significantly larger than the width of the well plate, the arc length can be assumed as equivalent to the width of the well plate.

$$\theta = \frac{s}{r} = \frac{w}{L} = \frac{85.48}{127.76} = 0.669rad^{*}\frac{180}{\pi} = 38.335degrees \tag{1}$$

$$t_z = \frac{38.335degrees}{180degrees/s} = 0.213seconds \tag{2}$$

$$t_x = \frac{127.76mm}{500mm/s} = 0.256seconds \tag{3}$$

$$t_y = \frac{12.7mm}{500mm/s} = 0.0254seconds \tag{4}$$

As expected, due to the stepper motors' slower speeds, the greater combined time of 0.4944 seconds of robot motion shows that the cylindrical robot design is not the fastest nor most efficient design.

Concept Design 4: Another different style of a robot arm that is being considered is a Selection Compliance Assembly Robot Arm (SCARA). This robot arm differs from previous design in that it makes use of two rotational motors as joints and a single linear vertical motor and belt system. SCARA robots also differ from previous designs in that their average angular and linear velocities are far greater. One source states that latest SCARA technology has allowed for angular speeds of up to 1700 degrees/s and linear speeds of up to 2300 mm/s [3]. To compute the time required for the robot to travel across the dimensions of the well plate, the same assumptions and equations were applied as before. This time however, the linear motor travels the depth of the well plate and the two rotational motors travel across the length and width of the well plate.

$$\theta_w = \frac{s}{r} = \frac{w}{L} = \frac{85.48}{127.76} = 0.669rad^{*}\frac{180}{\pi} = 38.335degrees \tag{5}$$

$$\theta_L = \frac{s}{r} = \frac{L}{L} = \frac{127.76}{127.76} = 1.0rad^{*}\frac{180}{\pi} = 57.296degrees \tag{6}$$

$$t_z = \frac{38.335degrees}{1700degrees/s} = 0.0226seconds \tag{7}$$

$$t_x = \frac{57.296degrees/s}{1700degrees/s} = 0.0337seconds \tag{8}$$

$$t_y = \frac{12.7mm}{2300mm/s} = 0.0055seconds \tag{9}$$

Due to the innovated technology of SCARA robot arms, the combined travel time across all directions resulted in 0.0618 seconds which shows to be the fastest moving robot arm of the analyzed designs.

Concept Design 5: The next design considered is a combination and alteration of the Cartesian and SCARA robot arm systems. In this design, the single z axis linear motor was taken from the Cartesian style robot arm and one of the rotational joints and vertical linear motor system were brought in from the SCARA model and attached to the bottom of the horizontal beam. This design makes use of the Cartesian system's ability to maximize area coverage by attaching the main robot structure to the ceiling of the inner casing as well as due to the Cartesian style's rectangular coverage area as opposed to the circular coverage area of the SCARA robot arm. The SCARA motors were then added to increase the maneuverability and speed of the design's liquid dispensing arm. Using the previously stated speeds of each representative robot motor, this designs travel time can be computed.

$$t_z = \frac{127.76mm}{1200mm/s} = 0.1065seconds \tag{10}$$

$$t_x = \frac{57.296degrees}{1700degrees/s} = 0.0337seconds \tag{11}$$

$$t_y = \frac{12.7mm}{2300mm/s} = 0.0055seconds \tag{12}$$

This customized combination design resulted in a total travel time of 0.1457 seconds. Although this speed is not as fast as the standard SCARA robot arm, this design shows greater benefits in stability, coverage area, and accuracy in terms of movement and positioning.

Concept Design 6: This design is very similar to that of the standard SCARA robot arm design however, the robots placement has now been shifted so that the base of the robot arm and main column is attached to the ceiling of the inner system casing. By doing so, the robots area coverage increases as the large bulky base of the robot structure no long stands in the way of the arm and well plates. In addition, due to inverted base, there is greater free inner space for potential additional well plates or system components to fit. Since this design uses the same motor types as the standard SCARA robot, the calculations for the travel times remain constant.

$$\theta_w = \frac{s}{r} = \frac{w}{L} = \frac{85.48}{127.76} = 0.669rad^* \frac{180}{\pi} = 38.335degrees \tag{13}$$

$$\theta_L = \frac{s}{r} = \frac{L}{L} = \frac{127.76}{127.76} = 1.0rad^* \frac{180}{\pi} = 57.296degrees \tag{14}$$

$$t_z = \frac{38.335degrees}{1700degrees/s} = 0.0226seconds \tag{15}$$

$$t_x = \frac{57.296degrees/s}{1700degrees/s} = 0.0337seconds \tag{16}$$

$$t_y = \frac{12.7mm}{2300mm/s} = 0.0055seconds \tag{17}$$

The resultant total travel time therefore is the same as the standard SCARA robot arm at 0.0618 seconds, matching the SCARA as the fastest robot arm design.

Concept Design 7: One final design that is being considered is a complete circular track style robot system. In this system, a complete circular track is attached to the ceiling of the inner casing similar to that of the Cartesian design previously discussed. This time however, the main motor and belt system is able to travel not in a linear fashion but in a full 360-degree circular track in either clockwise or counterclockwise direction. Along with this, two linear servo and belt motor systems are attached to the track cart and allow the robot arm to maximize the coverage area of the arm. For calculation purposes, the linear and track motors are the same as those used in the Cartesian designs. The same assumptions and well plate dimensions apply to the calculations as well.

$$t_y = \frac{85.48mm}{1200mm/s} = 0.0712seconds \tag{18}$$

$$t_x = \frac{127.76mm}{1200mm/s} = 0.1065seconds \tag{19}$$

$$t_z = \frac{12.7mm}{1200mm/s} = 0.0106seconds \tag{20}$$

While the direction labels for this design differed to that of the Cartesian designs, the overall motor types were the same and therefore the resulting travel time was the same at 0.1883 seconds. Once again, while this design is not the fastest, the advantages of coverage area may be worth considering over greater speed.

D. Subsystem 3: User Interface

This subsystem is made to allow the user to interact with the device intuitively and with minimal errors. The purpose of the user interface is to control the environment and other processes during the incubation period. Through the interface the user will be able to customize settings such as the temperature, and carry out other processes such as measuring optic density or a specific shaking pattern without taking the cell cultures out or interrupting the process. Furthermore, the user interface also takes into account safety. To ensure the safety of those in the lab when the device is working, an emergency off button has been implemented in all of the concepts for this subsystem. The governing equation that was determined for the user interface, along with all of the design concepts can be seen below.

Governing Equations		
Equation	Reason for Application	Design Applications
$R = \frac{C+S}{T}$	This equation will determine which interface better meets needs 8 and 10. C is the number of components, S is the number of settings, and T is the total subsystems. The more components and settings that are available to the user will make the system more customizable and reduce error.	All Designs

Concept Design 1: This concept utilizes a computer connected to the device through a USB as the user interface. All of the settings will be able to be changed and regularly checked on by keeping the device connected to the computer at all times. Additionally, the emergency off button is located on the enclosure of the device and will require the user to turn it in order to press it to cease function.

Concept Design 2: This concept utilizes an app that can be downloaded on a tablet or phone which will be connected to the device through a USB. When the app is opened and the device is connected the user will be able to customize various settings such as temperature, and carry out the necessary processes such as measuring fluorescent intensity or adding liquid. Furthermore, a window will be added in to allow the user to observe the processes being carried out. Lastly, the Emergency button is placed on the outside of the enclosure and requires the user to twist it in order to push.

Concept Design 3: This concept takes a widely different approach from the previous two. As opposed to using a separate device for the user to interact with, this interface is directly on the outside of the enclosure. It uses a variety of knobs, buttons and switches to customize the settings and set the controls. Additionally, a display is used to show the measurements for optic density and fluorescent intensity. Lastly, the emergency off button operates the same way as the in the previous concepts.

Concept Design 4: This concept has the user interface on the enclosure of the device. It uses a combination of a display, knobs and buttons. The knob would be used to adjust the temperature which could be checked on the display. The rest of the controls such as adding gas or removing waste would be customized through the display. Additionally, there is an on and off button and the emergency off button that functions the same as the previous concepts.

Concept Design 5: This concept does not use any buttons besides the emergency off, this would require the user to twist and then press done for the system to shut down. All of the settings and processes will be controlled through the interface placed directly on the device enclosure. This display will be touchscreen and the user will have a menu to choose the specific process they would like to adjust or to check on.

Concept Design 6: This concept utilizes more components than the other concepts shown until now. The interface used an Arduino that is wired to the device and also connected to the computer. All desired adjustments will be made by the user on the computer and sent to the device through the arduino. Lastly, the only component of the user interface that is directly on the enclosure is the emergency off button which functions the same as in other concepts.

Concept Design 7: This design utilizes its own controller to change the settings on the device. In addition to a controller, it also requires a display box. The controller will be used to select a specific setting which will be seen on the display box as selected. Then the buttons on the controller will be used to adjust this setting such as adding liquid or measuring optic density. The measurements and settings will always be available to check on the display. The controller connects to the display which then connects to the overall device. Lastly, the emergency off button is placed on the enclosure and requires the user to twist it and press down in order to cease all functions.

Concept Design 8: For this concept a combination of a display, nobs, button, and switches directly on the device enclosure were used. The buttons, knobs are used to adjust settings or carry out a specific process, the actual status of all the controls and settings will be seen on the display. In this concept the display is never used to change a setting or make a change, it is only used to see the status of each of the settings and ensure the desired processes are being carried out. Lastly, the emergency off button is placed on a side of the enclosure next to the interface, the button functions the same as in previous designs.

E. Subsystem 4: Climate Control

Governing Equations		
Equation	Reason for Application	Design Applications
$Q = MC\Delta T$	This equations governs the heat load required to change the temperature of a given mass of substance by a given amount	All climate control Designs
$q_c = h\left(T_h - T_c\right)A$	This equation governs the rate of convective heat transfer based on the temperature gradient, the area of heat transfer, and the substance used to transfer the heat	Climate control designs employing conductive heat transfer
$q_d = \frac{kA(T_h - T_c)}{L}$	This equation governs the rate of conductive heat transfer based on the temperature gradient, the length of heat transfer, and the material used to transfer the heat	Climate control designs employing conductive heat transfer
$q_r = \sigma\varepsilon\ A_i\ F_{ij}\ (T_i^4 - T_j^4)$	This equation governs the rate of heat transfer due to radiation using form factors	Climate control designs employing radiated heating

The customer desires a bioreactor with several climate control features. Key among these are the following, which are explicitly stated in the customer needs statement: - Bioreactor needs to maintain cell cultures at a constant temperature, and to be capable of doing so over a range of temperatures – from 4 to 70 Celsius. - Further, the difference in the desired and actual must be no greater than 2.5 Celsius at any time or location. - Needs to uniformly heat/cool wells/tubes. - Mitigates condensation on cooled well plate and tube surfaces. - Reaches desired culture temperature in under 15 minutes.

In view of the customer needs listed above, and the desire for a device that has an inbuilt ability to add or remove gaseous chemicals from its own chambers, it is apparent that the device is going to require an integrated HVAC system. Additionally, there are other critical features of the HVAC system which are not explicitly mentioned by the customer. Among these are the requirement that the HVAC system is neither prohibitively large nor prohibitively expensive.

There are four salient features to be considered when designing a climate control system for the customer's device. They are (1) temperature control of conical tubes, (2) temperature monitoring of conical tubes, (3) temperature control of well plates, and (4) temperature monitoring of well plates. An interesting opportunity which may be introduced by the requirement for gas flow/atmospheric control and shaking is a mechanism to evenly distribute heat and to increase the uniformity of the temperature within the cultures.

Finally, the customer's desire to mitigate condensation within the containers introduces additional challenges and further inquiries to the customer may be needed. At this time, it is unknown whether dehumidification is an acceptable method of reducing condensation within cultures.

Concept Design 1: Climate control design 1 assumes that the customer has access to an existing temperature controlled water system. This concept then uses a circulating water bath to distribute heat. It is assumed that temperature monitoring is available for the water existing water sources. This design uses a gas-permeable sealing membrane to mitigate condensation buildup in the cultures.

Concept Design 2: Climate control design 2 uses an electrically-heated insulated heating chamber and a conductive heating block to transfer heat to conical tubes and well plates. This design requires the use of different heating blocks for each of the different culture container geometries. This concept uses a temperature sensor placed inside the insulated heating chamber to monitor temperature. This design uses a gas-permeable sealing membrane to mitigate condensation.

Concept Design 3: Climate control design 3 uses a prefabricated heating and refrigeration unit with built-in fan for heat generation and distribution. Since this unit uses custom wire racks to support the conical tubes, a separate rack will likely be required for either different sized conical tubes or microwell plates. The prefab heating and refrigeration unit used in this design has built-in temperature monitoring capability. This design uses a gas-permeable sealing membrane to mitigate condensation.

Concept Design 4: Climate control design 4 uses a microwave oven to initially heat the cultures. Then, the design uses a prefab heating and refrigeration unit to maintain the ambient temperature and minimize heat transfer out of the cultures. For cooling, the design strictly uses the refrigeration unit – the insulated reverberation chamber assists in quick cooling and temperature stability. The design uses a gas-permeable sealing membrane to mitigate condensation.

Concept Design 5: Climate control design 5 is almost identical to design 3 aside from a couple of modifications. Design 5 uses a temperature probe to sense the temperature within conical tubes. However, it still uses a standard ambient temperature sensor for well plates. Additionally, this design utilizes a humidifier within the chamber to mitigate condensation, as the use of a probing thermometer negates the freedom to use sealing membranes without regular replacement.

Concept Design 6: Climate control design 6 is similar to designs 3 and 5 but with slight modifications. First, the design uses water for cooling and heating as opposed to air. Secondly, this design uses a microwave oven to rapidly heat water before supplying it to the insulated water-tight climate control chamber. This device also uses pre-fabricated water cooling unit and a cold water reservoir for instant cold water supply. Finally, this device uses indirect temperature monitoring by way of a temperature sensor present in the water – and a gas-permeable membrane to mitigate condensation.

Concept Design 7: Climate control design 7 improves on design 3. This concept uses a high-powered fan adapted to the heating and refrigeration unit to improve heat transfer rates, attempting to alleviate one of the primary shortcomings of air-cooling. The concept also uses the temperature monitoring strategy. This design also employs a unique strategy for condensation reduction, using warm air flow generated by a secondary heating unit passed through a defogger fan over the surface of the culture container to achieve this goal.

Concept Design 8: Climate control design 8 is like design 7 other than a few exceptions. First, concept 8 uses a dehumidifier unit instead of the gas-permeable membrane or de-fogger unit utilized in other designs. This design also uses the dual ambient and thermocouple temperature monitoring strategy employed by design 5. Finally, this design, like concept 7, uses a high-powered fan adapted to a pre-fabricated heating and cooling unit for superior heat transfer rates.

F. Subsystem 5: Gas Control

The gas handling system will be in charge of controlling the flow rate of each gas to the culture. In this way we can control the environment to which the cells will be exposed. There are two types of systems, systems with sealed chambers and open systems. The first type of system will be able to control the flow of each gas (N2, O2, CO2, CH4, H2) individually for each culture. The second system, only the flow rate of each gas can be controlled for the whole incubator, meaning that all the cultures will be exposed to the same gas conditions. To meet the customer needs, regulators and solenoid valves will be used. In the design, the priority will be the use of equipment that maximizes the homogenization and precision of the flow rate of the gases supplied.

Governing Equations		
Equation	Reason for Application	Design Applications
Q = V^*A	This equation will be used to determine the volumetric flow rate of the gases if it meets need 18 .	All Designs

Concept Design 1: The concept design 1, consists of two open well plates. The ventilation system consists of two pipes and two fans to distribute the gases homogeneously. The gas enters through small plastic tubes, then all the gases are collected in a larger PVC tube where it is distributed to the inside of the bioreactor. The outlet system consists of a fan and another PVC pipe parallel to the intake.

Concept Design 2: The concept design 2, utilizes regulators and solenoid valves to control the flow of gases into the interior. The outlet system is similar to concept design 1 but it is located in the upper part of the enclosure.

Concept Design 3: The concept design 3, consists of a vent pipe that surrounds the interior of the bioreactor and distributes the gas homogeneously. The gas enters the bioreactor through a series of valves and regulators to control the flow. The outlet system consists of a fan connected to the outside of the bioreactor.

Concept Design 4: The concept design 4, utilizes a triangular shaped tube placed between the well plates. The tube has outlets pointing towards the well plates for a more effective and efficient flow. The gas enters the bioreactor through a series of valves and regulators to control the flow. The outlet system consists of a fan connected to the outside of the bioreactor.

Concept Design 5: The concept design 5, consists of two isolated chambers with six different tubes connected. The entire tubing system is situated in the lower part of the enclosure. Each tube is in charge of supplying the desired gas to the chamber. The system also has regulators and valves to control the flow of gas being introduced. In this case the exhaust system is different as it is sealed and consists of a pipe connected to the chamber on one end and to the outside on the other. It also has regulators and valves to control the flow.

Concept Design 6: The concept design 6, is similar to the concept design 3 but instead of having one tube for each chamber, there is one for both chambers. Each chamber will have its own regulator and its own valve to control the flow. The exhaust system is different as it is sealed and consists of a pipe connected to the chamber on one end and to the outside on the other. It also has regulators and valves to control the flow.

Concept Design 7: The concept design 7, Similar to concept 3, the gas system enters through the bottom of the chamber. This concept could potentially save meters of tubing and space. the exhaust system is different as it is sealed and consists of a pipe connected to the chamber on one end and to the outside on the other. It also has regulators and valves to control the flow.

Concept Design 8: The concept design 8, The concept is similar to design 3 but in this case the pipes will not be metallic and will not go subway to the well plates. The gas enters the bioreactor through a series of valves and regulators to control the flow. The outlet system consists of a fan connected to the outside of the bioreactor.

G. Subsystem 6: Liquid Handling

Regardless of the size and significance of the research being carried out, the most current laboratories are embracing automation as a means of conducting increasingly efficient and complex research. Being one of the main activities within the laboratory, the precise and reproducible handling of liquids is a basic task and must be performed routinely by laboratory professionals. Liquid handling equipment include pipettes and micropipettes, digital and electronic, with fixed or disposable tips; microplate or microtiter plate dispensers, stackers, handlers, and washers; and a wide variety of automated robotic systems. Common multichannel pipetting configurations can incorporate 4, 12, 96, 384, or 1536 channels [19]. This equipment is essential to optimize efficiency, achieve more reliable and consistent results, and increase productivity.

To meet the customer needs for this project, disposable tips will be used to avoid cross-contamination. The design used for liquid handling will depend on the best dispense rate, accuracy, and precision. Below are shown the governing equations for this subsystem along with the concepts.

Governing Equations		
Equation	Reason for Application	Design Applications
$Q = V^{*}A$	This equation will be used to determine the volumetric flow rate of the liquid leaving the pipette to determine if it meets need 36.	All Designs
$V = \frac{2^{*}Pi^{*}RPM^{*}r}{60}$	This equation will be used to convert the rpm of the motor used for liquid handling into meters/seconds.	All Designs
$Re = \frac{VD}{v}$	The Reynold's number equation will be used to determine turbulent flow to ensure that aerosols are not caused.	All Designs

Concept Design 1: The built device has a suction motor with a tip on its end that allow the disposable pipette to be attached and the analyzed culture to be absorbed. After absorption, the fluid is placed on the well plate at the desired rate controlled by the motor. Then, the pipette is disposed on the waste container.

Concept Design 2: The difference between the first and second concepts is the number of pipettes on the device. In order to make the liquid handling system more efficient, increasing the number of pipettes to three, which is the least number of rows/columns that each type of well plate has, is an interesting option.

Concept Design 3: The device combines a suction motor, attachable and disposable tips, and plastic tubes. The analyzed culture passes through the tubes to the device and is placed on the well plate at a rate controlled by a valve. The tip is disposed on the waste container and the sanitizer liquid does the same path the culture liquid did. The waste liquid is then placed on the waste container.

Concept Design 4: An electronic multi-channel pipette is attached on a moving arm, and is controlled by the user interface on the prototype. This concept reduces the number of tubes/cables of the system, make it cleaner, but it might cost more.

Concept Design 5: This concept uses a single motor and disposable pipette tips. The process begins by the pipette pressing down onto the tips, causing one to clip on. It will then absorb the liquid from the fluid reservoir and dispense it into the desired locations. In the case of waste management, the pipette will absorb the waste and dispose of it in the waste reservoir. After the process is finished the pipette is lowered into where the used tips are placed, the idea is that the container will have an opening slightly smaller than the top part of the tip which will cause it to get stuck and fall into the container.

Concept Design 6: This concept uses the same idea as concept 5 to clip on and pull off the pipette tip. The pipette is placed in a square frame, this frame is connected to the structure onto which the motor is mounted. A plate is used to connect the lead screw to the pipette plunger to ensure that when the lead screw moves up and down the plunger will as well. The square frame also allows for various pipette sizes to be used as desired for the function being carried out.

Concept Design 7: This design allows for the use of multiple pipettes. Depending on the chosen configuration of well plates or conical tubes, the pipettes can be added or subtracted to accommodate this. A motor is used to press down on all of the plungers of the pipettes at the same time to ensure the same volumetric flow rate for all pipettes. The waste reservoir will be big enough so the largest amount of pipettes would deposit the waste. Lastly, the disposable tips will be removed using a solenoid, a plate would connect the end of the motor to the bottom of the frame so that the plate will be above the tips and will cause them to be pushed down.

Concept Design 8: Similar to concept 7 a motor is used to ensure the same volumetric flow rate. The difference is that this concept does not use individual pipettes, only individual pipette tips to add or subtract the liquid. the liquid is taken out of the reservoir using a pump, this pump then transfers the liquid into the liquid handling compartment, then the motor is used to extract or absorb the liquid through the pipettes. Similar to concept 7, this design can be adjusted depending on the well plates or conical tubes being used and the disposable tips are removed using a solenoid.

H. Subsystem 7: OD/FI Reader

The current process to evaluate cell growth is completely dissociated with the bioreactor itself. To measure cell growth using OP/FI, the microbial material must be removed from the bioreactor by hand and put into a plate reader for evaluation. This process causes risk of contamination when handling the cells by hand to transport in between the bioreactor and plate reader. Another downside of this process is that cell growth cannot be monitored continuously, but rather at the instance it is placed into the plate reader. To measure growth accurately overtime, a lot of readings need to be completed with the plate reader over a time period. With this method, a lot of time is spent transferring the well plates to and from devices.

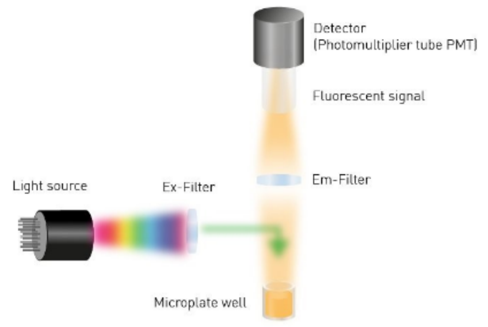


Figure 6: Simple Fluorescence Intensity Detection Setup [6]

The fluorescence intensity reading is an indication of how much light is emitted from the microbial material [6]. As shown in Figure 6, to detect fluorescence, a light source is filtered to produce the excitation light wavelength. This excitation wavelength will trigger the fluorophore within the microbial matter in the well plate. The cell's emission light is filtered for a desired wavelength and a detector will quantify the filtered emitted light. The quantity measured for fluorescence is not an absolute measurement, but rather in reference to another measurement in relative fluorescent units. Typical light sources used in these setups are xenon flash lamps, tungsten halogen lamps, and LED's [6].

Figure 7: Optic Filters[8]

Typical optical filters used in plate readers are shown in Figure 7. These filters are used to filter a desired light wavelength from a light source. The coating on the optic filter is what transmit light of a certain wavelength [8]. The name of the optic filter typically follows the middle transmission wavelength of the range of wavelengths the coating can filter [8].Optical Density is typically measured within a cuvette, in which a solution of a known absorbance placed into the cuvette [5]. To measure absorbance, a light with a known intensity is placed onto the microbial material and a detector is placed on the other side of the sample to measure how much light did not make it through. For typical plate readers, a spectrometer is used as the wavelength detector to measure absorbance. In real application, absorbance is used to find the concentration of proteins, enzyme-linked immunosorbent assay, cell viability, and microbial growth [5]. For commercial use, an example plate reader that can measure optical density and Fluorescence intensity is the BMG LabTech Plate reader models [9]. There does exist a micro-plate reader with climate control. Patent US10180441B2 shows a reader with a control unit for the temperature of the atmosphere while detecting light within the well plates.

Governing Equations		
Equation	Reason for Application	Design Applications
lux = 1333*Vo	This equations governs the luminosity of the diode when paired with a 10k ohm resistor as a function of voltage	Designs 1,2,3,4,6,8
$R = \frac{I(amps)}{L(\text{ watts })}$	This equation governs the diode light sensitivity as a ratio of the current produced by the diode and the amount of light falling on it	All OD/FI Designs
$QE = \frac{R_{\text{Observed}}}{R(100)} \times 100$	This equation governs the efficiency of the diode as a percentage of the number of photons incident on the diode.	All OD/FI Designs

Concept Design 1: It utilizes fiber optics to transfer light. A halogen lamp is filtered using a monochromatic filter wheel to a desired wavelength, where the light directly hits a scanning grate that will precisely filter the exact wavelength. This light will be reflected into a fiber optic and travel to a lens that will shine at a specific well in the well plate and pass through and hit a silicone photodiode or phototransistor. A filter can be added under the well plate to look detect specific wavelengths.

Concept Design 2: It Utilizes the same setup as concept design 1, except instead of a fiber optic directed light source from a lens, a laser is implemented onto the gantry setup. The phototransistors can be replaced with silicone photodiodes and a filter can be added too. The lux equation can be used for the photodiodes to convert the output voltage to light sensitivity.

Concept Design 3: It utilizes slide tray chassis setup. An OLED board can be slid in along with a desired polarizer film. A well plate, with an adjustable slide tray can be added. A breadboard with compartments to measure single or groups of wells at a time with a desired polarizer film can be added. the lux equation can be used for the photodiodes to convert the output voltage to light sensitivity.

Concept Design 4: It shows a slide tray chassis with a small laser gantry setup on top of it. A desired filter can be added, and silicone photodiodes are used as detectors. the lux equation can be used for the photodiodes to convert the output voltage to light sensitivity.

Concept Design 5: It shows a well plate with two x-locked gantry setups. One module has a laser that will shine through a row of wells and the detector will average the row's readings. The lux equation is not needed as the detector can be programmed to give light sensitivity readings.

Concept Design 6: It shows a similar to design to concept design 5 but has a breadboard with silicone photodiodes instead of a PMT Detector. the lux equation can be used for the photodiodes to convert the output voltage to light sensitivity.

Concept Design 7: It has a similar design to concept design 5, but instead of a laser light source there is a fiber optic directed lens as seen in concept design 1. The lux equation is not needed as the detector can be programmed to give light sensitivity readings.

Concept Design 8: It shows a similar design to concept 6, but instead of a laser light source, there is a fiber optic directed lens, as seen from concept design 1. the lux equation can be used for the photodiodes to convert the output voltage to light sensitivity.

I. Subsystem 8: Shaker Subsystem

Shaking of the well plates are required in bioreactors to ensure the growth of cultures, to evenly disperse them in the plate, and to allow for aeration[28]. These shaking patterns are coupled with incubation controls so that the samples in the well plates are adequately mixed and also at an appropriate temperature[7]. The three shaking patterns used are linear, orbital, and double-orbital[28]. These well plates are shaken in these patterns at speeds up to 1100 RPM.

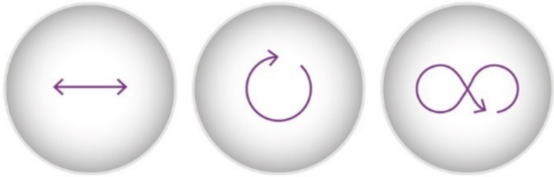


Figure 8: Linear, Orbital, and Double-Orbital Shaking Modes].

Shakers are used in a variety of applications such as chemical expansion and cell extraction[15]. The motion of the shaker can depend on the application in which it is used. Linear shaking tends to be used in many microbiological and chemical applications since the motion acts in a back to forth manner [15]. Orbital shakers rotate in a circular motion, moving the contents in the well plates into a swirl pattern [15]. This shaking pattern is preferred for cultivation of microorganisms and cells since it results in an even distribution of the liquid. Generally, the working principal of an orbital shaker is driven by a combination of rotatory and translation motion. Double-orbital motion is when the shaking pattern occurs in a three-dimensional see-saw motion[15]. This motion typically runs at lower RPMs than linear and orbital patterns. Since it moves at a low rpm, the application is most commonly used for gentle mixing and incubation process.

Governing Equations		
Equation	Reason for Application	Design Applications
$V = RPM^{*}D^{*}\pi$	This equation governs the velocity of the motor to shake well plates in linear, orbital, and double orbital motion, based on the RPM of the motor.	All Robot Motion Designs

Concept Design 1: Concept 1 depicts several adjustable platforms that can hold well plates and tubes of various sizes by clamping them. The appropriate clamp, such as a rounded clamp for the tubes, can be switched out with different plates that can be placed on the base with the motor. Under the platform is this base that contains the motor which will move each individual platform in either a linear, orbital, or double orbital motion. This motion is selected by the user and speed can be adjusted using a knob.

Concept Design 2: Similar to Concept 1, Concept 2 depicts adjustable clamping platforms where well plates and tubes of various sizes can be placed. Although each plate and tube will be able to move independent from one another, they will only be able to move in a linear, orbital, and double-orbital motions depending on which platform they are placed. This motion and speed can be adjusted by the user.

Concept Design 3: Concept 3 depicts a platform that has capabilities to hold each well plate or tube on a flat mat with non-slip capabilities. Each of these platforms have adjustable speeds and motion, and clamping is not necessary to holding the desired well plate or tube. This motion is selected by the user and speed can be adjusted.

Concept Design 4: Concept 4 depicts a platform that holds a magnetic plate can attach to magnetic trays, or platforms for tubes, of adjustable sizes for the given well plate or tube. These trays will need to be separately designed to accommodate for the platform and for each plate and tube. Each of these platforms can move at an independent motion and speed that is user controlled.

Concept Design 5: Concept 5 depicts a simpler design. This design has a platform which is connected to a motor which can operate at a specified speed and shaking motion. This platform will be hollow and be a bit smaller than the tray that will be placed on top of it. This will provide a small insert for the tray to rest on and remain secured during the shaking process. Similar to Concept 4, these trays will need to be manufactured to fit the size of the platform but also account for the size of the plate or tube that will be placed on it.

Concept Design 6: Concept 6 is a design where the well plates and tubes can be placed onto a tray which moves along a railing which moves in the x and y direction. The x and y movement will allow for linear, orbital, and double-orbital motion.

Concept Design 7: Concept 7 springs to achieve the desired shaking motions for the cultures. These springs are horizontally attached to a railing system and also to a platform which will mount the well plates and tubes. This concept is similar to concept 6 since the motion is from the x and y movement of the rails, however, in this concept, the plate that the cultures will be mounted to will not be on the railing, rather to the springs.

Concept Design 8: Concept 8 utilizes bungee cords to secure the well plates and tubes while shaking them in a desired motion. These cords can hook onto the tray at a location to best hold and shake the cultures. It should be noted that the tray that the cultures will be placed on will be slightly elevated from the base and will have holes accommodate for the outer diameter of the tubes. The tubes can be placed in this upright so that it can be secured by the cords. The shaking will be controlled by a motor in the base and the speed and motion can be controlled by the user. This is capable of shaking in a linear, orbital, and double-orbital motion.

J. Faux Design 1

Faux System								
Subsystem	Enclosure	Robot Motion	User Interface	Climate Control	Gas Control	Liquid Handling	OD/FI Reader	Shaker
Concept Number	1	5	1	8	1	6	2	7

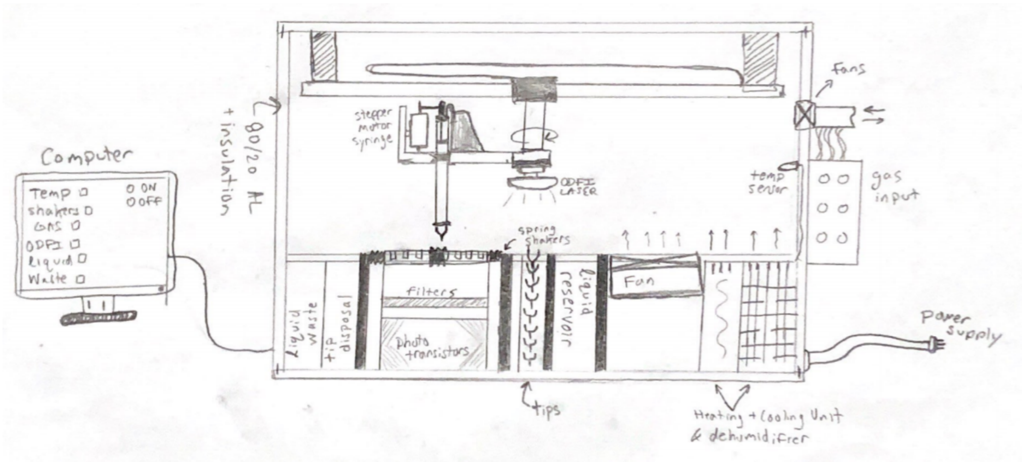


Figure 9: Faux Design 1

In this full assembly design concept, enclosure design 1 was used involving a rectangular 80/20 aluminum insulated enclosure along with an external connected computer device and program user interface. The customized gantry robot arm design 5 was considered, which involved the structure of a Cartesian robot and the SCARA robot arms. Connected to the robot arm at the end of the vertical linear motor is the stepper motor and syringe liquid handling design 6 which was selected to maximize the maneuverability of the liquid handling subsystem as a whole. Due to the ceiling connection of the robot structure, the liquid handling system is able to travel across the entirety of the interior to access liquid disposal and reservoir containers. In addition to that, at the bottom of the robot arm's rotational motor, the OD/FI subsystem's laser was connected so that the gantry robot could position the laser above any well plate location during testing. The remaining components of the OD/FI subsystem design 2 including the filters and photo transistors were placed in slots below the well plate. The spring loaded shaker system design 7 was selected for this full assembly concept connecting springs to each side of the well plate allowing for intense and diverse shaking. Design 1 for the Gas subsystem was used and placed on the right exterior of the full assembly allowing for gas flow in and out of the system. Finally, design 8 of the climate control subsystem was used and positioned at the lower right section of the full assembly including components such as a large fan, heating and cooling unit, and dehumidifier. Overall this faux full assembly concept attempted to create a functional system to maximize subassembly efficiency.

K. Faux Design 2

Faux System								
Subsystem	Enclosure	Robot Motion	User Interface	Climate Control	Gas Control	Liquid Handling	OD/FI Reader	Shaker
Concept Number	2	1	2	1	2	7	4	4

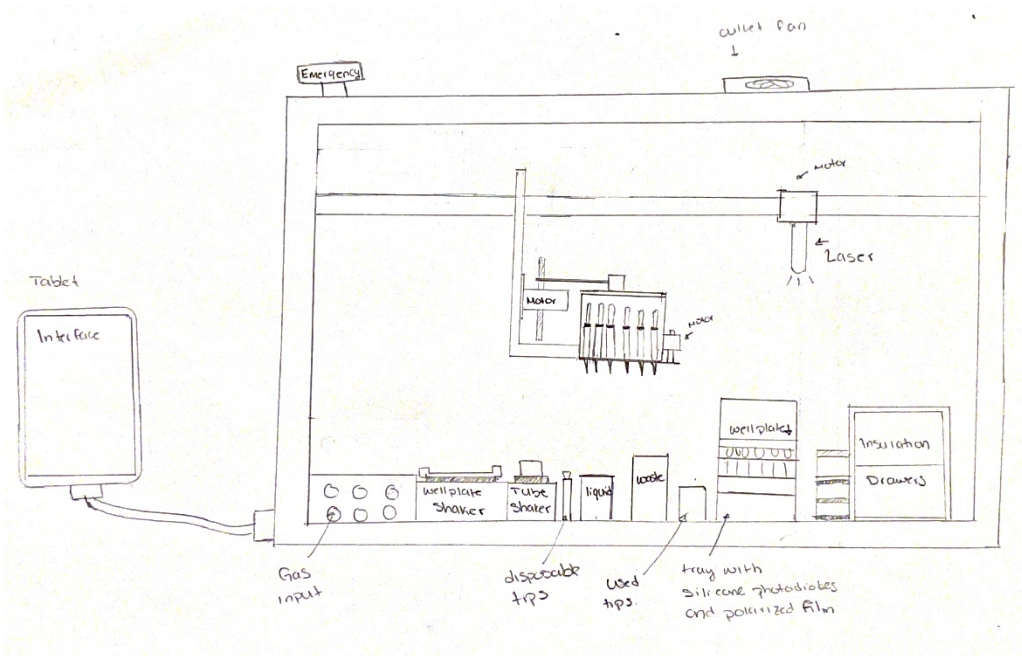


Figure 10: Faux Design 2

This full assembly combines one concept from all the subassemblies to create a fully functional device. The concepts used from each subassembly are stated in the chart above. To create this assembly, the functionality, geometry, and size of each subsystem was taken into account to decide which concepts would work the best together. Enclosure concept 2 was chosen, it uses solid aluminum rods and has a square shape, it was decided that this shape would be best to ensure that the maximum amount of space could be used. For the interface, concept 2 was chosen this concept uses an app on a tablet or phone to control the device, the phone or tablet are connected to the device through a USB. The liquid handling concept chosen was concept 7, this seemed to work the best for this assembly since it utilizes multiple pipettes and the shape of the enclosure allows for more space for this subassembly and pairs well with the robotic movement subsystem chosen which was concept 1. The shaker subsystem chosen was concept 4, this concept does not take up a significant amount of space since it utilizes 1 well plate shaker and 1 tube shaker with magnets. Furthermore, the OD/FI concept chosen is number 4, this concept uses a square structure to hold the well plates and below it a tray with photodiodes and polarized film, along with a laser that is attached from the robot subsystem. The climate design concept chosen was number 1, which utilizes insulation drawers to maintain the well trays and tubes at the desire temperature. Lastly, concept 2 was chosen for the gas subsystem which uses and outlet fan and a square structure with hole for the gas input. All these concepts compliment each other and fit as desired to create a functioning device.

L. Faux Design 3

	Faux System							
Subsystem	Enclosure	Robot Motion	User Interface	Climate Control	Gas Control	Liquid Handling	OD/FI Reader	Shaker
Concept Number	1	1	2	7	3	5	5	1

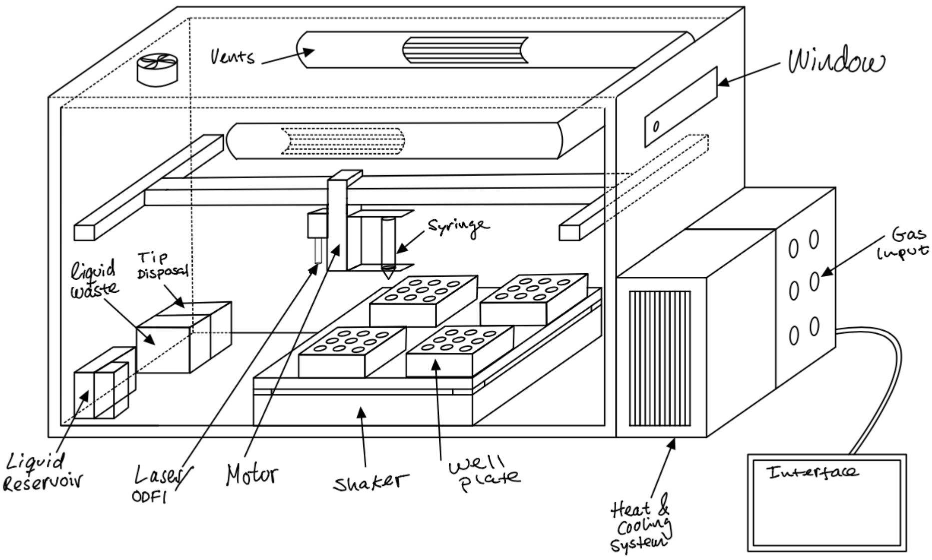


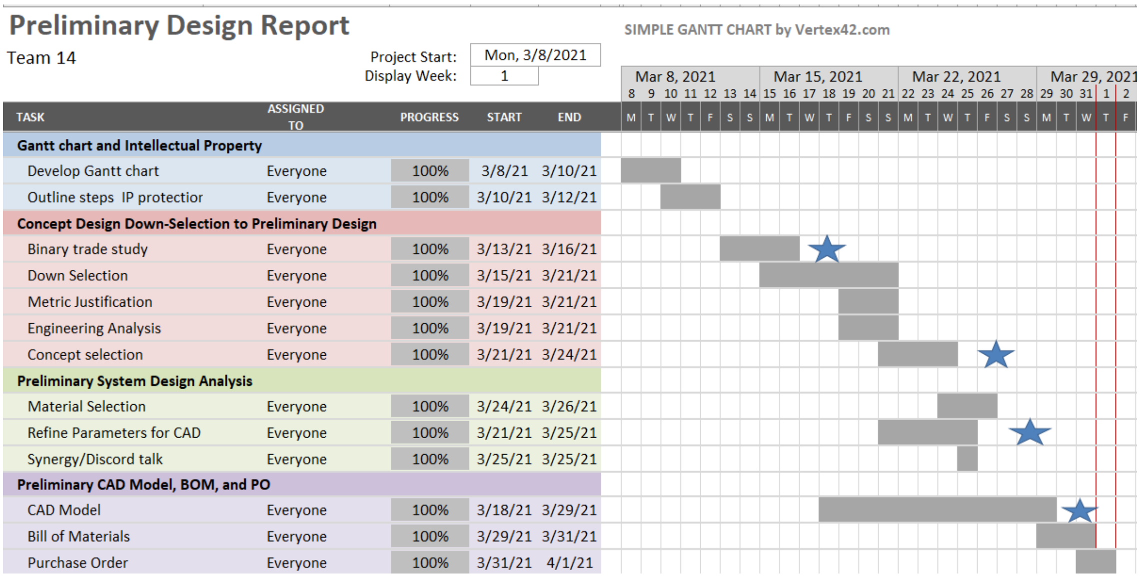
Figure 11: Faux Design 3

The faux design 3 Is a combination of one design from each subsystem. When selecting the designs, the compatibility of the different subsystems has been taken into account to find the best combination to improve efficiency not only in performance terms, but also in terms of manufacturing to save material and space. Enclosure number 1 was chosen because of the size and shape, maximizes the amount of space available. For the robot motion, design 1 was used because of the the mobility it offers (xyz movement) and the fact that it had to be anchored to the wall to leave space for the gas system. For the interface, the design 2 was chosen for the ease of being able to program a simple application that has all the requirements to manage the bioreactor. For the climate control subsystem, the concept design 7 was chosen for being a system that uses fans to distribute heat/cooling, it can be linked to the gas system and use the same vents. Design number 3 was used for the gas handling in order to be able to link both systems, this design distributes the gas homogeneously to all well plates. The concept 5 was chosen because it was the one that best suited to the mechanical arm and the ODFI sensor that will be mounted on the same holder. The ODFI sensor that could be installed in the same holder as the syringe, was design number 5, it is a compact design that offers high precision when measuring. Lastly, concept 1 was chosen for the shaker, this concept has a wide range of motion, is compatible with different types of well plates, and adjusts to the available space.

E. Preliminary Design Report

A. Gantt Chart

The Gantt chart shown below shows how this group allocated time for each part of this project. The blue stars are to show major milestones throughout the completion of each section. The group aimed to have an outline of the IP protection done by 3/12/21, after this the binary trade study was to be completed. This was a milestone because the down selection matrices could not be started without determining the weight factors. Furthermore, the group aimed to finish all the required tasks to complete the down selection matrix and select a concept by 3/24/21. Concept selection was another milestone because it was an important part that needed to be done in order to start CAD. Furthermore, refining parameters for CAD and a group discussion on synergy were to be done by 3/25/21, while completing these two tasks the group was also supposed to work on material selection which had an end date of 3/26/21. Refining parameters was a milestone because it was an important part needed to finish the CAD model. Lastly, the CAD model was set to be done by 3/29/21, allowing us to spend 3 days on the bill of materials and 2 days on the purchase order. We set the end date to 4/1/21 to give ourselves a day to make edits to the report.



Preliminary Design Report

Team 14

Project Start: Mon, 3/8/2021

Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Gantt chart and Intellectual Property				
Develop Gantt chart	Everyone	100%	3/8/21	3/10/21
Outline steps IP protection	Everyone	100%	3/10/21	3/12/21
Concept Design Down-Selection to Preliminary Design				
Binary trade study	Everyone	100%	3/13/21	3/16/21
Down Selection	Everyone	100%	3/15/21	3/21/21
Metric Justification	Everyone	100%	3/19/21	3/21/21
Engineering Analysis	Everyone	100%	3/19/21	3/21/21
Concept selection	Everyone	100%	3/21/21	3/24/21
Preliminary System Design Analysis				
Material Selection	Everyone	100%	3/24/21	3/26/21
Refine Parameters for CAD	Everyone	100%	3/21/21	3/25/21
Synergy/Discord talk	Everyone	100%	3/25/21	3/25/21
Preliminary CAD Model, BOM, and PO				
CAD Model	Everyone	100%	3/18/21	3/29/21
Bill of Materials	Everyone	100%	3/29/21	3/31/21
Purchase Order	Everyone	100%	3/31/21	4/1/21

Figure 12: Gantt Chart

B. Subsystem Visual Map

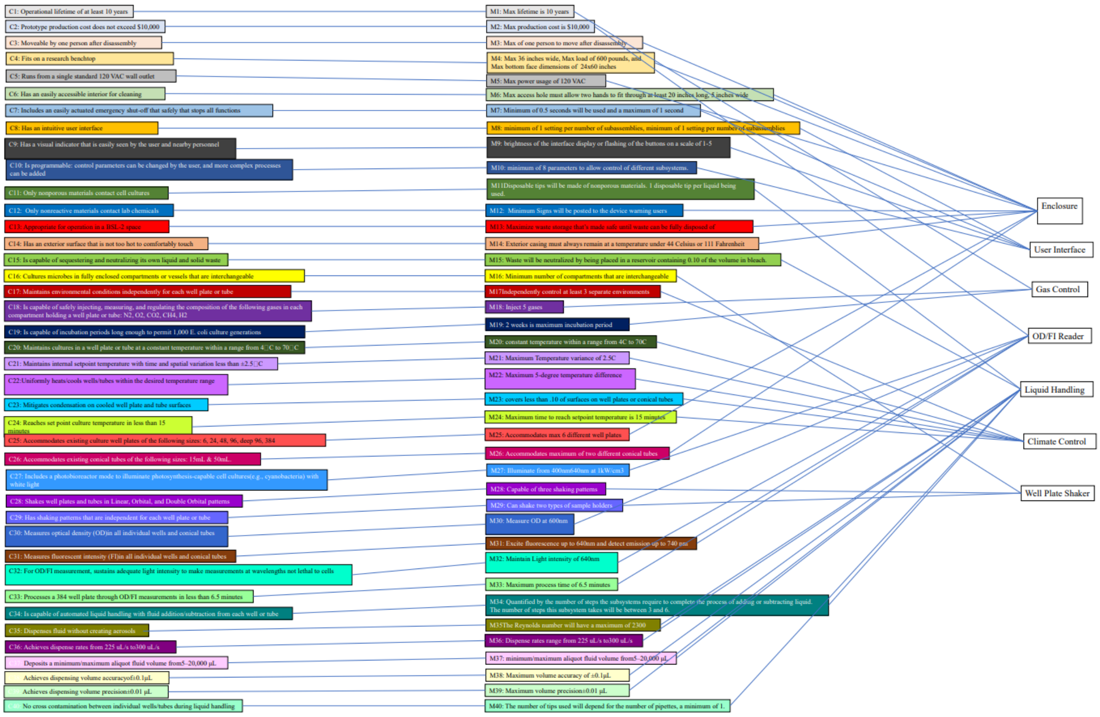


Figure 13: Customer needs mapped to metrics.

C. Finalization of the Hedgehog Concept

The hedgehog concept for this device is to make the most compact autonomous microbioreactor. Our device is designed with space efficiency in mind. The device being compact makes it easier to mobilize and locate in a lab, creating less of an inconvenience for the user. By creating a compact microbioreactor, we are also able to create a more cost effective device. The device being cost effective is an attractive quality for a few reasons. First, the Biofoundry lab could purchase more than one device for the ability to run more experiments at a time. Additionally, with a lower cost the device could be accessible to smaller universities and even high schools. Having this larger customer audience makes the device more profitable. Furthermore, if the device is compact this will also reduce the amount of energy required to use it, making it easier to accommodate in more settings. All in all, making a compact microbioreactor is beneficial not only for efficient use of space, but also for cost and energy efficiency, and being accessible to a wider group of customers.

D. Enclosure Down selection

Trade Study:

A trade study was performed for the Enclosure subsystem among the eight members for group 14 in order to determine the weight factors that will be assigned for each metric that will judge the concept selection for this this subsystem. The metrics are quantified from the customer needs and the weight factors are to determine the importance of each metric according to the subsystem. For this subsystem, 6 metrics were used:

- **Mobility** is chosen as a metric as the entire system needs to be able to be transported by one person. Factors to consider are size, weight, and the maximum carrying force of a single person.
- **Fits on Bench** is chosen as a metric for this subsystem due the need of the entire system to be able to fit on a standard lab bench. The enclosure itself encompasses the dimensions of the entire system.
- **Interior Accessibility** is chosen as a metric for this subsystem due to the need of requiring access to the interior of the entire system. This will determine the ease of access for assembling, cleaning, and functionality.
- **Nonreactive** is chosen as a metric due to the need of requiring the materials of the system to be nonreactive to its surroundings and samples. The nonreactive metric is based off of the volatility of the material.

- **Waste Storage** is chosen as a metric due to the need of being able to sanitize and dispose of the sample cultures after use. This is based off of the ease of storage and the modularity it will have in the enclosure.
- **Exterior Temperature** is chosen as a metric due to the need of requiring the exterior surface temperature to be under 44 degrees Celsius. The temperature of the exterior surface temperature during use will determine the metric.

Figure 14: Enclosure Metric Weight Factors

Metric	Weighting Factor, %
Mobility	0.83%
Fits on Bench	10.00%
Interior Accessibility	25.83%
Nonreactive	27.50%
Waste Storage	15.83%
Exterior Temperature	20.00%

The trade study performed for the Enclosure subsystem shows that nonreactive material and interior accessibility are the two most important factors, followed closely by the exterior surface temperature. Both nonreactive and exterior temperature metrics ultimately ensure safety for the user of the system. The interior accessibility is important due to the large amount of functionality that results with the ease of access. Waste storage and Fits on Bench metrics are under 20% but play an important role in keeping the functionality of the system convenient during operation. Mobility has the smallest weight factor due to the slight advantage it plays for installation convenience.

Metric Justification

Mobility

Mobility is a convenient metric to consider where the customer requires that this system to be able to be moved by one person. In this case, the average male will be considered to move this system [32]. in order to quantify mobility, the average weight that a male can lift with respect to the systems dimensions is to be considered. The following figure shows that max range of lifting by one male with safety as the main consideration.

			Maximal Lifting Weight (lb) Acceptable to 50 Percent Industrial Workers- 1 lift every 8 hours		
Gender	Box width (inch)	Distance (inch)	Floor level to knukle ht	Knukle ht to shoulder ht	Shoulder ht to overhead reach
Male	29.53	29.92	70.4	63.8	48.4
		20.08	74.8	70.4	55
		9.84	83.6	83.6	63.8
	19.29	29.92	83.6	63.8	57.2
		20.08	88	70.4	63.8
		9.84	99	83.6	77
	13.38	29.92	96.8	70.4	66
		20.08	101.2	79.2	74.8
		9.84	114.4	94.6	88

Figure 15: Max lift of Average Male [32]

Due to the conceptual design, each concept is assumed to use the same parts and have the same weight, therefore the size of each concept will decide the mobility rank of each design. The figure shows how the size of the object changes the amount of weight that can be carried. In this case, the larger the object, the harder to carry. The following figure shows how each concepts' volume is compared.

Table 2: **Mobility Values**

Concept	Volume (m^3)
1	0.4
2	0.36
3	0.5024
4	0.4219
5	0.4219
6	0.512
7	0.512

Table 3: **Bench Footprint Values**

Concept	Bottom Face Area (m^2)
1	0.4
2	0.36
3	0.5024
4	0.5625
5	0.5625
6	0.64
7	0.64

Fits on Bench

The customer requires that the entire system to fit on a standard lab bench. The lab bench's standard dimensions are to fit a system that is 24 inches in width and 60 inches in length [22]. To quantify this metric, the surface area of the bottom face is too be compared to the standard lab table by using the following equation:

$$\text{Surface Area} = \text{Length} * \text{Width} \tag{21}$$

The following table show the resulting surface areas for their respective bottom face.

The lowest score will be compared to the max surface area of the lab table of 0.929 m2. The max score will be assigned to the concept with the lowest bottom face area.

Interior accessibility

Interior accessibility is an important metric to consider due to the importance of user convenience when operating the entire system. Everything in the system should be easily accessible in order to properly operate the device while maintaining safe usage. Also, with easy accessibility, if there were an error then this would allow the error to be more accessible to fix. Interior accessibility will be based off of the modularity of the enclosure, which considers the number of screws and how accessible they are, and how easily accessible the enclosure is accessible within a person's reach. The metric scoring will use a ranking system where the ranks are unsatisfactory (0), very poor (2), poor (4), average (5), good (6), very good (8) and excellent (10).

Table 4: **Interior Accessibility Values**

Concept	Ranking	Description
1	Poor	This concept containts zero ability to store any waste
2	Poor	Same justification as concept 1.
3	Very Poor	This concept's circular design makes the enclosure very cluttered and hard to install, while being inaccessible
4	Good	This concept has waste storage that can be easily accessed
5	Excellent	This concept has an easily accessed latch door that provides access to the entire inside of the enclosure
6	Very Good	This concept contains viewing window with a latched hatch on the top of the enclosure.
7	Very Good	Same justification as concept 6.

Table 5: **Nonreactive Ranks**

Concept	Ranking	Description
1	Excellent	This concept informs and cautions the user appropriately and does not contain reactive materials.
2	Excellent	Same justification as concept 1.
3	Excellent	Same justification as concept 1.
4	Excellent	Same justification as concept 1.
5	Excellent	Same justification as concept 1.
6	Excellent	Same justification as concept 1.
7	Excellent	Same justification as concept 1.

Nonreactive

Nonreactive materials are an important feature to consider due to the problematic interference it could bring up during the system's operation. The customer requires that only the nonreactive materials incorporated in the system to contact the lab chemicals. Despite the importance of this requirement, this can easily be avoided and the design for this problem is very system. It is expected for each concept to score the same due to the simplicity of the solution, although a necessary metric to consider. The following table shows scoring for this metric. The scoring will use a ranking system where the ranks are unsatisfactory (0), very poor (2), poor (4), average (5), good (6), very good (8) and excellent (10).

Waste storage

Waste storage is a semi-important feature too consider due to its weight factor. Waste storage allows for easy cleaning and accessible deposits. The customer requires the sanitation of the enclosure after operational use, in which waste storage will be able to export the dead or finished sample. The concepts will be scored based on a ranking system with descriptive reasoning such as: unsatisfactory (0), very poor (2), poor (4), average (5), good (6), very good (8) and excellent (10).

Exterior Temperature

Table 6: **Waste Storage Ranks**

Concept	Ranking	Description
1	Unsatisfactory	This concept contains zero ability to store waste
2	Unsatisfactory	Same justification as concept 1.
3	Unsatisfactory	Same justification as concept 1.
4	Excellent	This concept has waste storage that can be easily accessed
5	Excellent	Same justification as concept 4.
6	Excellent	Same justification as concept 4.
7	Excellent	Same justification as concept 4.

For exterior temperature, a simple one-dimensional heat transfer calculation is applied to test the exterior surface temperature. This design using a composite wall of steel sheet, XPS insulation, and Steel sheet. The thermal conductivity of XPS is 0.031 W/Km [30] and Steel sheet is 2 W/Km [36]. Assuming air convection inside the system at a max temperature of 70 degrees Celsius [22]. and the surrounding environment is at room temperature of 22 degrees Celsius [1]. With 3mm thickness of steel, the minimum insulation thickness needs to be 2.88mm.

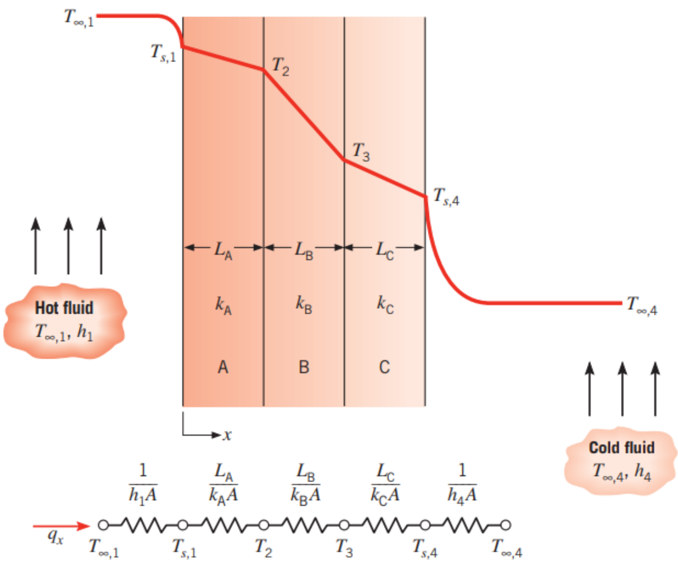


Figure 16: One-Dimensional Composite Wall [37]

$$q'' = \frac{T_{\infty,1} - T_{\infty,2}}{\left[\frac{1}{h_1} + \frac{L_A}{K_A} + \frac{L_B}{K_B} + \frac{L_C}{K_C} + \frac{1}{h_2}\right]}$$
$$q'' = \frac{T_{s,4} - T_{\infty,2}}{\frac{1}{h_2}} \tag{22}$$

By setting both heat flux equations equal to each other with the max desired exterior surface temperature of Ts,4 = 44 degrees Celsius, the minimum insulation length is 2.88. This value will be the minimum value in the rankings.

Concept	Insulation Thickness (mm)
1	3
2	3
3	2
4	5
5	5
6	3
7	3

Figure 17: Exterior Temperature Ranks

Decision Matrix

Concept Selection

Concept 5 was chosen after having the highest total weighted score of 9.649. This shows that this concept is approximately the most effective in every metric identified for the enclosure subsystem. Concept 5 ensure ok mobility and bench footprint due to the bigger size of the concept compared to the other concepts. Concept 5 scored the best in the interior accessibility, nonreactive material, waste storage, and exterior temperature. This ensures that this concept will meet every customer need associated with the metrics assigned. By scoring the best to, it also ensure that it meets its needs most effectively when compared to the other concept.

Table 7: **Down Selection Matrices**

Enclosure Subsystem, Concepts 1-3										
Quantitative	Weight	Concept 1			Concept 2			Concept 3		
Metric	Factor	Value	Normalized	Weighted	Value	Normalized	Weighted	Value	Normalized	Weighted
Mobility	0.008	0.4	7.63	0.063329	0.36	10	0.083	0.5024	1.57	0.013031
Fit on Bench	0.1	0.4	9.37	0.937	0.36	10	1	0.5024	7.75	0.775
Interior Accessibility	0.258	Poor	4	1.0332	Poor	4	1.0332	Very Poor	2	0.5166
Nonreactive	0.275	Excellent	10	2.75	Excellent	10	2.75	Excellent	10	2.75
Waste Storage	0.158	Unsatisfactory	0	0	Unsatisfactory	0	0	Unsatisfactory	0	0
Exterior Temperature	0.2	3	1.51	0.302	3	1.51	0.302	2	0	0
Total				5.085529			5.1682			4.054631

Enclosure Subsystem, Concepts 4-6										
Quantitative	Weight	Concept 4			Concept 5			Concept 6		
Metric	Factor	Value	Normalized	Weighted	Value	Normalized	Weighted	Value	Normalized	Weighted
Mobility	0.008	0.4219	6.33	0.052539	0.4219	6.33	0.052539	0.512	1	0.0083
Fit on Bench	0.1	0.5625	6.8	0.68	0.5625	6.8	0.68	0.64	5.57	0.557
Interior Accessibility	0.258	Good	6	1.5498	Excellent	10	2.583	Very Good	8	2.0664
Nonreactive	0.275	Excellent	10	2.75	Excellent	10	2.75	Excellent	10	2.75
Waste Storage	0.158	Excellent	10	1.583	Excellent	10	1.583	Excellent	10	1.583
Exterior Temperature	0.2	5	10	2	5	10	2	3	1.51	0.302
Total				8.615339			9.648539			7.2667

Enclosure Subsystem, Concepts 7				
Quantitative	Weight	Concept 7		
Metric	Factor	Value	Normalized	Weighted
Mobility	0.008	0.512	1	0.0083
Fit on Bench	0.1	0.64	5.57	0.557
Interior Accessibility	0.258	Very Good	8	2.0664
Nonreactive	0.275	Excellent	10	2.75
Waste Storage	0.158	Excellent	10	1.583
Exterior Temperature	0.2	3	1.51	0.302
Total				7.2667

E. User Interface Down Selection

Trade Study

A trade study was done by each group member individually. The purpose of the trade study was to determine the weight factors of each of the metrics that would be used in the down selection matrix. The trade study is an important part of selecting the correct concept because it ensures that less significant metrics don't outweigh those that are more important for the system. The metrics included in this subsystem are based on the customer needs that the user interface is meant to meet, this subsystem meets four customer needs: 7, 8, 9 and 10. The metrics for this subsystem are as follows:

- **Emergency shut off** this metric is meant to quantify customer need 7. The user interface is the only subsystem that will be constantly interacting with the device as a whole which is the emergency shut off is in this subsystem since its purpose its to stop function of the entire device. This metric will focus on whether each concept includes an emergency shut off and how long it will take to stop all function.
- **Intuitive** is chosen as a metric to meet customer need 8. Its important for the user interface to be intuitive to ensure the user can adjust to it easily and make minimal errors when interacting with it. This metric will be based on how many controls and settings are available to the user.
- **Visual indicator visibility** this metric meets customer need 9. The interface has to have a visual indicator that shows if the system is on or off, the process taking place, elapsed process time and if an error occurs. It is important for this component to be visible to the user from various angles to ensure the user is aware of everything functioning correctly or not.
- **programmable** this metric meets customer need 10. To ensure the user can have the most control over this device, it must be programmable. It is important for the user to be able to adjust all settings in a process and to add more complex processes in the future. How programmable it is will depend on how complex the components that make up the interface are.

Metric Justification

Emergency off

The emergency off button is a crucial part of the user interface since this device will be in a lab

Table 8: **Interface Weight Factors**

Metric	Weighing Factors (%)
Emergency shut off	33.33%
Intuitive	8.33%
Visual indicator visibility	25.00%
programmable	33.33%

Table 9: **Analysis for Emergency shut off**

Concept	Score	Components
1	8	Computer and device connected through USB
2	8	Ipad or smart phone and device connected through USB
3	10	Interface directly on enclosure
4	10	Interface directly on enclosure
5	10	Interface directly on enclosure
6	7	Computer, Arduino and devices all connected
7	7	Display box, controller and device all connected
8	10	Interface directly on device

with other sensitive materials. The emergency off button for all the concepts being considered is located on the enclosure and requires the user to twist it before it can be pressed down. This metric was quantified by estimating how long it would take the system to stop all function. The way the time to shut off was estimated was by taking into account how many components make up the user interface. The concepts with less components would have a faster shut off time because there are less components communicating to make up the interface. For each concept the number of components was determined and then subtracted from 10 to determine the score.

$$10 - components = score \tag{23}$$

Intuitive

How Intuitive the user interface is should be taken into account for a variety of reasons. One of these reasons is that the more intuitive the interface is the easier it will be for a larger number of people to be able to learn to use it in a short amount of time. This is a significant trait since this device will be used by various labs. Additionally, if the user interface is more intuitive it will reduce the risk of the user making errors while changing the settings. Taking this into account, the intuitive score of the user interface was determined by adding together the number of components that make up the user interface and the number of settings that the interface displayed and dividing this by the total number of subsystems for the device. The higher this number was, the better the score would be. Having more components and settings to adjust would reduce the possibility of error and the amount of time the user spends learning how to interact with the interface. Once the ratio of settings and components, to number of subsystems was determined the score was normalized using the maximum and minimum ratios found. The ratio and score for each concept can be seen in the table below. Equation (3) shows the equation used to find the intuitiveness ratio. An example showing how the ratio was calculated for the highest scoring concept will be explained.

Concept 5 was the highest scoring concept. This design consisted of the interface being on the device, meaning one component and there were 12 settings that could be adjusted. Furthermore, the total number of subsystems for the device is 7.

$$\frac{\text{components} + \text{settings}}{\text{total subsystems}} = \text{ratio} \tag{24}$$

$$\frac{1 + 12}{7} = 1.86 \tag{25}$$

Table 10: **Analysis for intuitive ratio**

Concept	Ratio	score
1	1.57	5.5
2	1.29	1
3	1.57	5.5
4	1.57	5.5
5	1.86	10
6	1.57	5.5
7	1.57	5.5
8	1.72	7.8

Visual indicator visibility

The visual indicator is an important part of the user interface for safety purposes. It is important for the user to clearly be able to see if the system is on or off, how much progress its made in the mode it is in, how much time has elapsed, and most importantly, if an error has occurred. This metric was quantified by how well the user could see the visual indicator from different angles, and from different sides of the device. The visual indicator visibility for each concept was rated excellent (10), very good (8), good (6), average (5), unsatisfactory (0). When rating each concept the size of the display was also taken into account, a larger display would be visible from further away and from more angles. The table below shows how each concept was scored based on the qualities defined above.

Table 11: **Visual indicator visibility analysis**

Concept	description	Score
1	Interface is on a computer, a large screen makes for good visibility from further, but the user would have to move the computer to see it from more angles.	8
2	This concept uses an ipad as the interface, while an ipad can be moved, the screen is smaller, and the user would not be able to see it from very far.	8
3	The interface is directly on the enclosure, this makes it big and easier to see from far. Since it is on the enclosure it cannot be moved and the user would not see it from various angles.	8
4	This interface is also on the enclosure, the same reasoning as concept 3 is used.	8
5	This interface is on the enclosure, the same reasoning as concept 3 is used.	8
6	This interface consists of a computer and an Arduino. For the computer portion the same reasoning as concept 1 is used.	8
7	This concept uses a display box and a control box. The display box cannot be moved due to it being connected to the device and the control box which limits its visibility.	8
8	This interface is on the enclosure, the same reasoning as concept 3 is used.	8

Programmable

This metric is one of the highest weight factors, it is an important part of the user interface because it can cause limitations for the device itself or allow it to do more functions than what it starts with. Ideally, the user interface would be programmable enough for the user to be able to add settings in the future. This metric is quantified by how many components the user would have to program for the user interface, a lower number is more desirable because it would mean its easier to program. An example would be the interface that uses the computer is easier to program than the interface that uses the Arduino. If the interface had 1 programmable component it received an excellent (10), if it had 2 or more programmable components it received a score of good (6), and if the number of programmable components exceeded that it would have received a score of unsatisfactory (0). The table below shows how each concept scored and the description of its components.

Table 12: **Programmable metric analysis**

Concept	description	Score
1	The only programmable component is the computer.	Excellent
2	The ipad is the only programmable component.	Excellent
3	There is only one programmable component because the interface is on the enclosure.	Excellent
4	The same description of concept 3 can be used.	Excellent
5	The same description of concept 3 can be used.	Excellent
6	This interface's programmable components are the computer and Arduino.	good
7	This interface's programmable components are the controller and the display.	good
8	This interface is on the enclosure, the same reasoning as concept 3 is used.	Excellent

Decision Matrix

Concept Selection

The concept with the highest score from the down selection matrix is concept 5. This concept has the user interface on the enclosure as a big screen and had a large number of settings for the user to adjust. To ensure better synergy between all subsystems in the device, concept 6 was chosen instead of concept 5. The interface for concept 6 uses a computer and an arduino to interact with the device. It was determined that this concept would work better for our device after taking into account the numerous sensors that have to be implemented such as temperature, gas and pressure. The sensors that are expected to be used are all compatible with the arduino. Additionally, the user will have an easier time controlling the device from a computer since its something they're already familiar with. Using a computer instead of putting the interface directly on the enclosure will also cut back on manufacturing time. Furthermore, the hedgehog concept is a compact microbioreactor, it would not be ideal for the interface to be on the device if it is going to be small because that would affect visibility and make it more difficult to adjust settings. Lastly, an display screen will be added to the user interface. The screen will be placed on the enclosure as an additional visual indicator. On this screen the user will be able to see if the system is functioning, how much time has been spent on the process and if an error occurs. All in all, the user interface will consist of a computer who will be connected to the device through a USB, the arduino that will be connected to numerous sensors, the display on the enclosure, and an emergency shut off.

Table 13: **Down Selection Matrices**

User interface							
Quantitative Metric	Weight Factor	Concept 1			Concept 2		
		Concept 1	C1 Normalized	Weighted Normal C1	Concept 2	C2 Normalized	Weighted Normal C2
Metric 1	0.3330	8	8	2.664	8	8	2.664
Metric 2	0.0830	1.57	5.50123778	0.45660274	1.29	1.00022505	0.08301868
Metric 3	0.2500	very good	8	2	very good	8	2
Metric 4	0.3330	Excellent	10	3.33	Excellent	10	3.33
Total	1.00			8.45060274			8.07701868

User interface							
Quantitative Metric	Weight Factor	Concept 3			Concept 4		
		Concept 3	C3 Normalized	Weighted Normal C3	Concept 4	C4 Normalized	Weighted Normal C4
Metric 1	0.3330	10	10	3.33	10	10	3.33
Metric 2	0.0830	1.57142857	5.50123778	0.45660274	1.5714286	5.501237779	0.46
Metric 3	0.2500	very good	8	2	very good	8	2.00
Metric 4	0.3330	Excellent	10	3.33	Excellent	10	3.33
Total	1.00			9.11660274			9.12

User interface							
Quantitative Metric	Weight Factor	Concept 5			Concept 6		
		Concept 5	C5 Normalized	Weighted Normal C5	Concept 6	C6 Normalized	Weighted Normal C6
Metric 1	0.3330	10	10	3.33	7	7	2.331
Metric 2	0.0830	1.85714286	10.0022505	0.83018679	1.57142857	5.50123778	0.45660274
Metric 3	0.2500	very good	8	2	very good	8	2
Metric 4	0.3330	Excellent	10.00	3.33	good	6	1.998
Total	1.00			9.49018679			6.78560274

User interface							
Quantitative Metric	Weight Factor	Concept 7			Concept 8		
		Concept 7	C7 Normalized	Weighted Normal C7	Concept 8	C8 Normalized	Weighted Normal C8
Metric 1	0.3330	7	7	2.331	10	10	3.33
Metric 2	0.0830	1.57142857	5.50123778	0.45660274	1.71428571	7.75174414	0.64
Metric 3	0.2500	very good	8	2	very good	8	2.00
Metric 4	0.3330	good	6	1.998	excellent	10	3.33
Total	1.00			6.78560274			9.30

F. Climate Control Down selection

Trade Study

A trade study was carried out by the 8 members of this group. The aim of the study was to determine the relevance of each metric in the subsystem (weight factors). Each of the metrics is directly linked to a customer need.

- **Number of Independent Environments** was chosen as an essential metric in this subsystem. It received a weighting factor of 0.26 in a trade study.
- **Temperature Range** was chosen as an essential metric. It received a weighting factor of 0.28 in a trade study.
- **Temperature Stability** was chosen as a metric for this subsystem. It received a weighting factor of 0.23 in a trade study.
- **Time to Reach Setpoint** was chosen as a metric for this subsystem. It received a weighting factor of 0.08 in a trade study
- **Condensation Coverage** was chosen as a metric for this subsystem. It received a weighting factor of 0.09 in a trade study.
- **Power Demand** was chosen as a metric for this subsystem. It received a weighting factor of 0.06 in a trade study.

Metric Justification

Number of Independent Environments

Number of Independent Environments was chosen as an essential metric in this subsystem. One of the ways a concept can distinguish itself over competing designs is by allowing the user to independently control the climate of multiple environments.

Concept 1

Concept 1 includes two separate temperature-controlled environments, Giving a total count of 2 independent environments.

Concept 2

Concept 2 includes a separate environment for each size of culture container needed. Due to the lack of flexibility of conduction-based heating and cooling, this design will only maintain 1 independent environment for each type of culture container.

Concept 3

Concept 3 can support up to four independent environments simultaneously, with two environments capable of supporting conical tubes and 2 supporting well plates. Using the standard set by concept 2, this concept can maintain 2 independent environments.

Concept 4

Concept 4 details the use of a single chamber capable of accommodating any of the requested culture containers. By the standard set previously, this concept can maintain 1 independent environment.

Concept 5

Concept 5 is like concept 3 in all ways except the method of temperature sensing and mitigating condensation. Therefore, this concept also has 2 independent environments.

Concept 6

Concept 6 is similar to concepts 3 and 5. This design can accommodate 2 independent environments.

Concept 7

Concept 7 is a variation of concept 6, and it too can maintain 4 independent environments.

Concept 8

Concept 8 is a variation of concept 6, and it too can maintain 4 independent environments.

Temperature Range

Temperature Range was chosen as a metric. One of the customer needs outlined in the customer needs statement was the ability of the final design to reach setpoints at any temperature in the range between 4 Celsius and 70 Celsius.

Concept 1

Concept 1 uses hot and cold water that is available on demand in the laboratory setting to warm and chill the cultures. Theoretically, this design could accommodate temperatures from just above the freezing point of water to just below the boiling point. Therefore, this concept can achieve the full range of desired temperatures, and receives a score of 1 out of 1.

Concept 2

Concept 2 uses conductive heating to control the temperatures of the cultures. Since this design does not feature a cooling method, the minimum temperature it can achieve is ambient, and maximum temperature exceeds the desired range. Assuming ambient temperatures of 20 C, the concept has a temperature range from 20 C to 70 C. This gives the concept a score of:

$$\frac{70-20}{70-4} = 50/66 = 0.7575 \tag{26}$$

Concept 3

Concept 3 uses a prefabricated heating and refrigeration unit that uses air to warm and cool the cultures. Simple units like this commonly can achieve temperatures from 16 C to 31 C. The score for this concept can be calculated as follows:

$$\frac{31-16}{70-4} = 15/66 = 0.2273 \tag{27}$$

Concept 4

Concept 4 uses a hybrid system that uses microwave radiation for heating, and a refrigeration unit for cooling. This concept can achieve temperatures in excess of 70 C, and, like concept 3, can achieve a minimum temperature of 16 C. The score is calculated as follows:

$$\frac{70-16}{70-4} = 54/66 = 0.8182 \tag{28}$$

Concept 5

Concept 5 uses a prefabricated heating and refrigeration unit that uses air to warm and cool the cultures. Simple units like this commonly can achieve temperatures from 16 C to 31 C. The score for this concept can be calculated as follows:

$$\frac{31-16}{70-4} = 15/66 = 0.2273 \tag{29}$$

Concept 6

Concept 6 uses water to control the temperature of the cultures through forced convection. The concept uses microwave heating to rapidly heat water, and a refrigeration unit attached to a reservoir to provide cold water on demand. Like concept 1, this unit achieves a score of 1.

Concept 7

Concept 7 uses a refrigeration unit to achieve temperatures as low as 4 C, and uses a heating unit to achieve temperatures in excess of 70 C, giving this concept a score of 1.

Concept 8

Concept 8 uses an identical heating and cooling system as concept 7, and therefore also earns a score of 1.

Temperature Stability

Temperature Stability was chosen as a metric for this subsystem. This metric combines two of the customer needs into a single metric - those being needs 21 and 22, which describe the need for uniform heating and cooling and stable setpoints during static operation, respectively.

Concept 1

Concept 1 uses water as the medium for convection, the specific heat of water is 4179 J/kgK, and that value is also the raw score.

Concept 2

Concept 2 uses a conductive heating conductive composed of a highly conductive metal. For the purposes of this evaluation, we will use the specific heat of copper, which is 385 J/kgK.

Concept 3

Concept 3 uses air as the medium. The specific heat of air is 1005 J/kgK.

Concept 4

Concept 4 uses air as the medium for temperature maintenance. The specific heat of air is 1005

J/kgK.

Concept 5

Concept 5 uses air as the medium. The specific heat of air is 1005 J/kgK.

Concept 6

Concept 6 uses water as the medium. The specific heat of water is 4179 J/kgK.

Concept 7

Concept 7 uses air as the medium. The specific heat of air is 1005 J/kgK.

Concept 8

Concept 8 uses air as the medium. The specific heat of air is 1005 J/kgK.

Time to Reach Setpoint

Time to Reach Setpoint was chosen as a metric for this subsystem. In the customer needs statement, the customer outlined their desire for a final design capable of reaching a given setpoint in less than 15 minutes. Metric 4 calculations will be based on the time required to achieve a temperature increase of 66 C in 15 minutes using heat load calculations. Lower heat loads are considered superior as they indicate faster heating if power supply is equal.

Heat Load Sample Calculation

Selecting the optimal temperature control equipment for a given bioreactor application requires knowledge of desired batch size and characterization of the reaction as endothermic, exothermic, or static. For a bioreactor that requires a wide temperature range, Thermo Fisher recommends a bath circulator with refrigeration [1]. Further, they provide a methodology for determining the chiller wattage needed to accomplish a given magnitude of temperature change over a given period of time. The calculation begins by determining the heat load and the desired temperature. The heat load can be calculated as in:

$$Q = MC\Delta T \tag{30}$$

Q is the heat load, M is the mass of the substance that is changing temperature, C is the specific heat of the substance that is changing temperature, and ΔT is the desired temperature change. For our purposes, it is useful to determine the maximum change in temperature desired. Assuming a desired range of 4C to 70C, as given in the customer needs statement, the maximum desired change in temperature is 66C. The mass of the substance can depends on the final design of the bioreactor. For this example calculation, we will use the mass of a single 50 mL conical tube containing a substance that is roughly as dense as water. 50 mL of water, using a density of 1 kg/L, has a mass of 0.05 kg. Further, water has a specific heat of 1 cal/g*K. Therefore, the heat load of the medium can be calculated:

$$Q_1 = 50\,[g] * 1\left[\frac{cal}{g}\right] * 339\,[K] = 16.95[kcal] \tag{31}$$

It is also necessary to calculate the heat load of the conical tube holding the culture, and the water present in the temperature control unit. Thermo Fisher suggests using a 7L chiller with 3L present in the hoses, and a 5L jacket for a 50L bioreactor. Since the desire temperature and specific heat for the all of the water in the system is the same, the heat load may be scaled proportional to mass. The heat load of the conical tube requires a separate calculation due to its unique specific heat. Grainger supplies 50 mL conical tubes, which are made of polypropylene and have a specific heat of 0.4299 cal/g*K [3],[4]. The mass of these tubes is listed as 7.056 kg for a pack of 500, giving an individual mass of 0.014112 kg [3]. Thus the heat loads of the remaining substances in the system can all be calculated:

$$Q_2 = 7\,[g] * 1\left[\frac{cal}{g}\right] * 339\,[K] = 2.373[kcal] \tag{32}$$

$$Q_3 = 3\,[g] * 1\left[\frac{cal}{g}\right] * 339\,[K] = 1.017[kcal] \tag{33}$$

$$Q_4 = 5\,[g] * 1\left[\frac{cal}{g}\right] * 339\,[K] = 1.695[kcal] \tag{34}$$

$$Q_5 = 14.112\,[g] * 0.4299\left[\frac{cal}{g}\right] * 339\,[K] = 2.057[kcal] \tag{35}$$

The total specific internal energy to be added is therefore 24.092 kcal per 50mL conical tube. This calculation assumes that each conical tube has an individual jacket, chiller, and hosing system. However, depending on the final design, multiple conical tubes may be controlled by a single HVAC system, thus changing some of these values. The value above can be converted to 27.95 watts per hour using a constant conversion factor. To accomplish this temperature change in 15 minutes, the required wattage would increase by a factor of 4. Therefore, the required power to accomplish a temperature change of 66 C in 15 minutes for the stated temperature control design is 111.79 watts. The above calculation can be performed

Table 14: **Heat Load Calculations**

	1	2	3	4	5	6	7	8
Q1	16.95	16.95	16.95	16.95	16.95	16.95	16.95	16.95
Q2	0	14.12	0	0	0	0	0	0
Q3	8.475	0	0	0	0	8.475	0	0
Q4	33.90	0	0	0	0	67.18	0	0
Q5	2.057	2.057	2.057	2.057	2.057	2.057	2.057	2.057
Tot (kcal)	**61.382**	**33.127**	**19.007**	**19.007**	**19.007**	**94.662**	**19.007**	**19.007**
Tot (W*0.25hr)	**285.6**	**154.1**	**88.4**	**88.4**	**88.4**	**440.4**	**88.4**	**88.4**

for each of the climate control system design, allowing us to evaluate each design on its ability to efficiently convert electric power into desired temperature change. The table below summarizes the results of these calculations for climate control subsystem concept designs 1 through 8. For each concept, the calculations represent the heat load for a filled 50 mL conical tube.

Condensation Coverage

Condensation Coverage was chosen as a metric for this subsystem. In the customer needs statement, the customer outlined their desire for a device capable of self-mitigating condensation on culture containers. Metric 5 will be scores based on the surface area which can be defogged by the concept. Scoring for this metric will be expressed as a percentage of the total surface area of the container.

Concept 1

Concept 1 uses water for temperature control, therefore condensation is not an issue. Concept 1 receives a score of 1.

Concept 2

Concept 2 uses a gas-permeable membrane to mitigate condensation. Similar membranes have been shown to be reduce condensation by roughly 0.9 in practice. Therefore, concept 2 receives a score of 0.9.

Concept 3

Concept 3 uses a gas-permeable membrane to mitigate condensation. Similar membranes have been shown to be reduce condensation by roughly 0.9 in practice. Therefore, concept 3 receives a score of 0.9.

Concept 4

Concept 4 uses a gas-permeable membrane to mitigate condensation. Similar membranes have been shown to be reduce condensation by roughly 0.9 in practice. Therefore, concept 4 receives a score of 0.9.

Concept 5

Concept 5 uses a dehumidifier in the main chamber to mitigate condensation. Dehumidifiers can typically reduce humidity by 0.65. Therefore, concept 5 receives a score of 0.65.

Concept 6

Concept 6 uses water for temperature control, therefore condensation is not an issue. Concept 1 receives a score of 1.

Concept 7

Concept 7 uses a defogger fan linked to a small heating unit to mitigate condensation. This method allows the entire surface of the container to be defogged. Concept 7 receives a score of 1.

Concept 8

Concept 8 uses a defogger fan linked to a small heating unit to mitigate condensation. This method allows the entire surface of the container to be defogged. Concept 8 receives a score of 1.

Power Demand

Power Demand was chosen as a metric for this subsystem. In the customer needs statement, the customer outlined their desire for a device capable of running on a standard 120V outlet. Since the climate control system is one of the largest power draws, this metric was included as a part of this subsystem. Metric 6 will score the concepts based on the power demands of each concept. Concepts with a lower power demand are considered superior.

Power demands are based on system specifications – assuming each concept will have the same heat load – of existing devices with similar design features to the concepts. However, since some devices have the capability to control several environments, the raw score of the device will be normalized to the power demanded to control the climate of a single environment, e.g.:

$$P_n = P_t/n \tag{36}$$

Where Pn is the normalized power demand, in units of kW/environment, Pt is the overall power demand of the device, in units of kW, and n is the number of environments controlled by the device.

Normalized Power Demand Sample Calculation

The normalized power demand of two devices will be calculated and compared in the following section. Device 1 has an overall power demand of 5 kW and can control 2 environments given that power supply. Device 2 has a power demand of 3 kW and can control 1 environment given that power supply. The normalized power demand of device 1 can be calculated:

$$P_{norm_1} = \frac{P_{tot1}}{n_1} = \frac{5[kW]}{2[env]} = 2.5[kWenv] \tag{37}$$

Similarly, the normalized power demand of device 2 can be calculated as:

$$P_{norm_2} = \frac{P_{tot2}}{n_2} = \frac{3[kW]}{1[env]} = 3[kWenv] \tag{38}$$

In conclusion, the above example shows that, although device 1 demands more power than device 2, it compensates for that deficiency by supporting more environments. This calculation allows us to compare dissimilar systems in a way that does not intrinsically favor concepts which control fewer environments.

Concept 1

Concept 1 uses local water heating that is assumed to be available in-lab. Thomas Scientific offers a laboratory water heater and cooler that is believed to be comparable to what may be available in the UF laboratory. This device has a power demand of 6.6 kW [1]. However, this device is capable of controlling 2 environments, giving it a raw score of 3.3 kW/env.

Concept 2

Concept 2 uses a conduction-based heating system to heat and cool the cultures. Fisher scientific offers a dry bath/block heater device that uses comparable heating strategies. This device requires up to 1.8 kW [2]. This device is limited to supporting only a single environment, giving it a raw score of 1.8 kW/env.

Concept 3

Concept 3 uses a pre-fabricated heating and refrigeration unit with a built-in fan. Rigid HVAC Co. offers a micro-aircon device that requires 450 W of power [3]. Since concept 3 supports 2 independent environments, it receives a raw score of 0.225 kW/env.

Concept 4

Concept 4 uses a small microwave oven to heat the cultures, and a heating and cooling unit for cooling and temperature maintenance. A small microwave oven has a typical power demand of around 600 W. Additionally, this concept will incorporate the same 450 W aircon system described above, giving a total power demand of 1.05 kW. Because concept 4 supports 1 environment, it receives a raw score of 1.05 kW/env.

Concept 5

Concept 5 uses similar heating and cooling unit to the one described in concepts 3 and 4. Additionally, this concept incorporates a dehumidifier unit. A typical small dehumidifier unit uses 280 W [4]. Therefore, because concept 5 uses 730 W total and can support 2 environments, it receives a raw score of 0.365 kW/env.

Concept 6

Concept 6 uses an integrated water cooling unit for temperature reduction, and a microwave oven for heating. The power demand of a typical small microwave oven had been previously given to be 600 W. LabTech US offers a small water chilling unit that requires 500 W [5]. Concept 6 has an overall power demand of 1.1 kW, and supports 4 independent environments, giving it a raw score of 0.225 kW/env.

Concept 7

Concept 7 uses a micro heating and cooling unit, two external fans, and a second heating unit for defogging. The heating and cooling unit has a power demand of 450 W, small fans add a negligible power demand to the overall system, and a small heating unit can be reasonably expected to have a power demand of 300 W [6]. Concept 7 receives a raw score of 0.1875 kW/env.

Concept 8

Concept 8 uses a very similar setup to concept 7. Specifically, it uses a small HVAC unit with a power demand of 450 W and a dehumidifier unit with a power demand of 280 W. Concept 8 receives a raw score of 0.1825 kW/env.

Decision Matrix

The decision matrix for this subsystem is shown below. The winning concept was concept 8, as it received the highest score after normalization and weighting.

Climate Control

Quantitative Metric	Weight Factor	Concept 1: Concept 1	Concept 1: C1 Normalized	Concept 1: Weighted Normal C1	Concept 2: Concept 2	Concept 2: C2 Normalized	Concept 2: Weighted Normal C2	Concept 3: Concept 3	Concept 3: C3 Normalized	Concept 3: Weighted Normal C3	Concept 4: Concept 4	Concept 4: C4 Normalized	Concept 4: Weighted Normal C4
Metric 1	**0.26**	2	4	1.0332	1	1	0.2583	2	4	1.0332	1	1	0.26
Metric 2	**0.28**	1	10	2.833	0.76	7.19	2.03693	0.23	1	0.2833	0.82	7.9	2.23807
Metric 3	**0.23**	4179	10	2.25	385	1	0.225	1005	2.47	0.55575	1005	2.47	0.55575
Metric 4	**0.08**	285.6	4.96	0.41317	154.1	8.32	0.69306	88.4	10	0.833	88.4	10	0.833
Metric 5	**0.09**	1	10	0.917	0.9	7.43	0.68133	0.9	7.43	0.68133	0.9	7.43	0.68133
Metric 6	**0.06**	3.3	1	0.0583	1.8	5.33	0.31074	0.225	9.88	0.576	1.05	7.5	0.43725
Total				7.50467			4.20535			3.96259			5.00

Quantitative Metric	Concept 5: Concept 1	Concept 5: C1 Normalized	Concept 5: Weighted Normal C1	Concept 6: Concept 2	Concept 6: C2 Normalized	Concept 6: Weighted Normal C2	Concept 7: Concept 3	Concept 7: C3 Normalized	Concept 7: Weighted Normal C3	Concept 8: Concept 4	Concept 8: C4 Normalized	Concept 8: Weighted Normal C4
Metric 1	2	4	1.0332	2	4	1.0332	4	10	2.583	4	10	2.58300
Metric 2	0.23	1	0.2833	1	10	2.833	1	10	2.833	1	10	2.83300
Metric 3	1005	2.47	0.55575	4179	10	2.25	1005	2.47	0.55575	1005	2.47	0.55575
Metric 4	88.4	10	0.833	440.4	1	0.0833	88.4	10	0.833	88.4	10	0.83300
Metric 5	0.65	1	0.0917	1	10	0.917	1	10	0.917	1	10	0.91700
Metric 6	0.365	9.47	0.5521	0.225	9.88	0.576	0.1875	9.99	0.58242	0.1825	10	0.58300
Total			3.34905			7.6925			8.30417			8.30475

Concept Selection

From the decision matrix down selection process, concept 8 was selected as the most well-rounded climate control concept. However, this selection must be considered in terms of its synergy and discord with the overall system design as well.

Metric	Weighting Factors (%)
A	0,5
B	0,375
C	0,125

G. Gas Control Down selection

Trade Study

A trade study was carried out by the 8 members of this group. The aim of the study was to determine the relevance of each metric in the subsystem (weight factors). Each of the metrics is directly linked to a customer need.

- **Measure/Regulate Composition of Gases** was chosen as an essential metric in this subsystem. Since one of its tasks is to control the amount of each gas (flow rate) that is introduced into the enclosure.

- **Incubation Periods** was chosen as a metric, since the bioreactor must be able to incubate for at least two weeks in order to grow 1,000 E. coli culture generations. One of the necessary conditions for this to happen is to have the right environment for these cultures to grow therefore, the gas surrounding the culture would be critical and key to achieve the objective.

- **Operational Lifetime** was chosen as a metric for this system as it has pipes and ducts that will require some degree of maintenance to function properly.

Metric Justification

Measure/Regulate Composition of Gases
The calculated flow rate is important in order to correctly size the concepts. The flow rate is given by the laboratory, i.e., the tank with the gases is located outside the reactor and is connected through a pipe to supply it, so it is a constant and fixed flow. Although the bioreactor will be able to regulate it if necessary with valves and regulators. To estimate it, it has been necessary to research tanks of different gases used in laboratories and an arithmetic mean of the flow rate of the six tanks has been calculated.
Each concept has the same flow rate but not every concept has the same capability to distribute and homogenize the gases supplied to the well plates. The precision and accuracy can only by determined with a physical test therefore, a quantification method was used instead.Unsatisfactory (0), very poor (2), poor (4), average (5), good (6), very good (8) and excellent (10).

Incubation Periods

One of the requirements that the bioreactor had to meet is that it must be able to have incubation periods long enough to permit 1,000 E. coli culture generations. The generation time is basically the time it takes for a population of cells/bacteria to duplicate, i.e. to reproduce. In a laboratory this is an estimated 15-20 minutes [29].

Minutes it takes to permit 1000 E.coli culture generations:

$$20 * 1000 = 20000 \text{ minutes} \tag{39}$$

Minutes in a day:

$$24 * 60 = 1440 \text{ minutes} \tag{40}$$

Concept	Capability of Measure/Regulate Composition of Gases	Description
1	Good	This concept by not having closed chambers for each well plate has less gas control over each well plate.
2	Average	This concept does not have any gas homogenization system, so it is dosed inefficiently.
3	Very Good	This concept is capable of regulating and measuring gases but has less precision and accuracy than the previous concept.
4	Good	Same justification as concept 1
5	Excellent	This concept is able to regulate and accurately measure the quantity of each gas supplied to each well plate.
6	Very Good	Same justification as concept 3
7	Excellent	Same justification as concept 5
8	Very Good	Same justification as concept 3

Days it takes to reach 1000 generations:

$$\frac{20000}{1440} = 13.89 \text{ Days} \tag{41}$$

This is roughly equivalent to a two-week incubation period.

Operational Lifetime
The useful life of the system is important to consider, because depending on how durable it is, the customer will incur future expenses. The requirement is that it should last a maximum of 10 years. The life expectancy of each element of each concept is subject to a number of unpredictable variables, for this reason we have opted for a quantification system [2]. Poor (4-8) years, average (8-10) years, Very Good (10-12) years and Overperformance (+12) years.

Decision Matrix

Concept Selection

Concept 3 was the winning concept as it has a total score of 7,6375, which is not the highest but at this stage of the project we also had to take into account how the different subsystems complement each other so all concepts with a score higher than 7 (we considered that a score above 7 would be valid) could be used and comparing this concept with the rest of the subsystems the concept that best fit and would perform better was concept 3. This concept is able to achieve a homogeneity in the composition of the gases, since it has two fans that push the gases throughout the enclosure.

Concept	Operational Lifetime	Description
1	Very Good	This concept relies on electronic devices with a certain life time, however, they are designed to last the established time without failure.
2	Overperformance	The concept will not require a lot of maintenance and parts replacement as there are no significant tube lengths and no moving parts. It will last longer than required.
3	Very Good	Same justification as concept 1
4	Overperformance	Same justification as concept 2
5	Average	This concept has a more complex and longer piping-vents system than the others and electronic devices to dispense the gas.
6	Average	Same justification as concept 5
7	Average	Same justification as concept 5
8	Overperformance	Same justification as concept 2

H. Liquid Handling Down selection

Trade Study

The eight members of the group conducted a trade study for the Liquid Handling system to assess the weight factors for each metric used. The customer needs were used to determine the metrics, and the weight factors will assess the relative value of each need within the subsystem. Regarding this subsystem, 8 metrics were determined:

- **Cross Contamination** was chosen as a metric due to the customer requirement of avoiding cross contamination between individual wells/tubes during liquid handling. This is directly related to the use or not of disposable components and the sterilization process.
- **Neutralizing Waste** was selected as a metric regarding the customer need of being capable of sequestering and neutralizing its own liquid and solid waste. This metric is related to the size of the waste containers that need to be able to hold the liquid and the disposal tips.
- **Fluid Addition/Subtraction** was used as a metric to meet the customer requirement of being capable of automated liquid handling with fluid addition/subtraction from each well or tube. The addition and subtraction of the fluid is related to the steps needed for the fluid to be added in the well/tube, and release in the waste containers.
- **Aerosols Created** was chosen as a metric since the device needs to dispense fluid without creating aerosols. The presence of aerosols is related to the Reynolds number, where it needs to be less than 2300 for the flow not be considered turbulent.
- **Dispense Rate** was selected as a metric due to the need of achieving dispense rates from 225 uL/s to 300 uL/s. This metric is directly related to the flow rate calculated using the smaller tip diameter.
- **Fluid Volume** was used as a metric to meet the customer need of depositing a minimum/maximum aliquot fluid volume from5–20,000 µL. The fluid volume is related to the size of the pipette used in the system.
- **Volume Accuracy** was chosen was a metric due to the customer need of achieving dispensing volume accuracy of ±0.1µL. This is related to the accuracy of the step motor used.

Table 15: **Down Selection Matrices**

Quantitative Metric	Weight Factor	Concept 1			Concept 2			Concept 3		
		Concept 1	C1 Normalized	Weighted Normal C1	Concept 2	C2 Normalized	Weighted Normal C2	Concept 3	C3 Normalized	Weighted Normal C3
Measure/Regulate Composition of Gases	0,5	6	2,8	1,4	5	1	0,5	8	6,4	3,2
Incubation Periods	0,375	2	10	3,75	2	10	3,75	2	10	3,75
Operational Lifetime (10 Years)	0,125	12	5,5	0,6875	14	10	1,25	12	5,5	0,6875
Total	1			5,8375			5,5			7,6375

Gas Control

Concept 4			Concept 5			Concept 6			Concept 7			Concept 8		
Concept 4	C4 Normalized	Weighted Normal C4	Concept 5	C5 Normalized	Weighted Normal C5	Concept 6	C6 Normalized	Weighted Normal C6	Concept 7	C7 Normalized	Weighted Normal C5	Concept 8	C8 Normalized	Weighted Normal C8
6	2,8	1,4	10	10	5	8	6,4	3,2	10	10	5	8	6,4	3,2
2	10	3,75	2	10	3,75	2	10	3,75	2	10	3,75	2	10	3,75
14	10	1,25	10	1	0,125	10	1	0,125	10	1	0,125	13	7,75	0,96875
		6,4			8,875			7,075			8,875			7,91875

Table 16: **Liquid Handling Metric Weight Factors**

Metric	Weighing Factor, %
Cross Contamination	7.58
Neutralizing Waste	12.95
Fluid Addition/Subtraction	14.73
Aerosols Created	15.18
Dispense Rate	9.38
Fluid Volume	6.70
Volume Accuracy	17.41
Volume Precision	16.07

- **Volume Precision** was selected as a metric due to the need of achieving dispensing volume precision of ±0.01µL. The volume precision is related to the precision of the step motor using to fluid addition/subtraction.

The trade study for the Liquid Handling system shows that the Volume Accuracy and Volume Precision are the main metrics analyzed. On the other hand, Cross Contamination and Fluid Volume are the least important factors during the analysis.

Metric Justification

Cross Contamination

Cross contamination should still be considered a significant factor during the process even if its weighting factor is one of the smallest. In the case of the liquids that will be used in this analysis, the contamination of a specific type of liquid with another during the handling process directly affects the acquisition of satisfactory results. The concepts were analyzed based on the presence or not of cleaning liquid and the use or not of disposable pipette tips. Thus, they were approximately classified as unsatisfactory (0), average (5), good (6), very good (8), and excellent (10), and the results can be seen below.

Neutralizing Waste

There exist two containers on the device that are responsible for the disposal of both the liquid and the tip. Therefore, neutralizing waste factor of each concept was analyzed based on the size of the containers. On the Concept Design Report, the size of the containers in each design was not specified, but it was assumed to be the same for all drawings. Since the measurements of the container were not determined, the concepts were categorized as unsatisfactory (0), average (5), good (6), very good (8), and excellent (10). Having the same size, they were all considered excellent, as can be seen in the table below.

Table 17: **Cross-Contamination Values**

Concept	Value
1	Excellent
2	Excellent
3	Good
4	Excellent
5	Excellent
6	Excellent
7	Good
8	Average

Table 18: **Neutralizing Waste Values**

Concept	Value
1	Excellent
2	Excellent
3	Excellent
4	Excellent
5	Excellent
6	Excellent
7	Excellent
8	Excellent

Fluid Addition/Subtraction

One of the main functions of this system is to be capable of adding fluid to the well/tube that will be analyzed, avoiding cross contamination. Thus, the concepts were classified based on the number of steps it would take to perform this function, in which less steps received a higher score. The equation used to find the quantitative score for each concept can be seen below.

$$10 - \text{ number of steps } = \text{ score} \tag{42}$$

The steps include the attachment of the pipette to the disposal tip, the analyzed fluid absorption, the fluid release to the well/tube, the fluid release to the waste container, the absorption of the cleaning solution, the second release to the waste reservoir, and finally the tip disposal. The results can be seen in the table below.

Aerosols Created

Aerosols are microscopic particles that remain suspended in the air and can carry chemical, biological, radioactive, and other elements. All laboratory procedures must be conducted with the utmost care to avoid the formation of aerosols. Therefore, the liquids from the pipettes must always be smoothly disposed. The concepts were scored based on the Reynold's number, which is used to identify the fluid behavior. The numbers calculated were compared to 2300, characterized to be turbulent flow. Thus, the smallest Reynold's number obtained a higher score. The equation and results can be seen below, where is the density of the fluid, u is the flow speed, D is the pipette tip diameter, and µ is the dynamic viscosity of the fluid.

$$Re = \frac{\rho u D}{\mu} \tag{43}$$

For concept 7:

$$Re = \frac{997\frac{\text{kg}}{\text{m}^3} * 1.41\frac{\text{m}}{\text{s}} * 0.00046 \text{ m}}{0.00108\frac{\text{kg}}{\text{m}\cdot\text{s}}} = 600.33 \tag{44}$$

Table 19: **Fluid Addition/Subtraction Values**

Concept	Value
1	6
2	6
3	5
4	6
5	6
6	6
7	5
8	7

Table 20: **Aerosols Values**

Concept	Value
1	654.00
2	640.35
3	882.58
4	660.37
5	656.36
6	850.47
7	600.33
8	800.44

Dispense Rate

The device needs to achieve a dispense rate, or a flow rate, from 225 uL/s to 300 uL/s. First, (4) was used to calculate the velocity from the step motor specifications, where r is the pipette radius, and RPM is the revolutions per minute specified on the motors.

$$V = \frac{2\pi}{60} * r * RPM \tag{45}$$

Then, the flow rate was estimated by (5), where V is the velocity and A is the pipette tip area.

$$Q = VA \tag{46}$$

For concept 6:

$$\begin{gathered} V = \tfrac{2\pi}{60} * 0.009565 \text{ m} * 2250 \tfrac{\text{rev}}{\text{min}} = 2.26 \tfrac{\text{m}}{\text{s}} \\ Q = 2.26 \tfrac{\text{m}}{\text{s}} * 0.000000166 \text{ m}^2 = 0.000000345 \tfrac{\text{m}^3}{\text{s}} = 375 \tfrac{\mu L}{\text{s}} \end{gathered} \tag{47}$$

The concept with the highest flow rate, assuming the maximum RPM, received the highest score. The results can be seen in the table below.

Fluid Volume

The maximum fluid volume the system can deposit depends on the size of the designed pipette. It is called pipette, but it works as a syringe, where it has a cylindrical shape and a seal that is responsible for controlling the pressure inside it. The fluid volume of each concept was calculated by (8), where r is the pipette radius and h is the height, and the concept with the highest volume received the highest score. The results can be seen in the table below.

$$V = \pi r^2 h \tag{48}$$

For concept 6:

$$V = \pi(8.5 \text{ mm})^2 * 85 \text{ mm} = 19,293 \text{ mm}^3 = 19,293\mu L \tag{49}$$

Table 21: **Dispense Rates**

Concept	Value (µL/s)
1	256
2	251
3	345
4	258
5	257
6	375
7	235
8	313

Table 22: **Fluid Volume**

Concept	Value (µL)
1	19,574
2	18,900
3	18,600
4	19,304
5	18,100
6	19,293
7	16,960
8	19,100

Volume Accuracy and Precision

The volume accuracy and precision are the metrics with the highest weighting factors, which is a reasonable fact. The precision and accuracy of the pipetted volumes are extremely important for the result to be reliable. Considering that both accuracy and precision are mainly estimated experimentally, and that experiments were not possible to be made due to external conditions, a NEMA motor was applied to each concept since it is known to have high precision and accuracy. The motors selected have the same step angle, but they differ in size and velocity. The step angle and its accuracy are the same for all concepts, 1.8 and +/- 0.05 degrees, respectively. Therefore, all concepts are considered very good, with a normalized value of 8. The results are shown in the tables below.

Decision Matrix

Concept Selection

Based on the down selection matrices approach, concept 6 was the design selected with a score of 8.4909. Not all the metrics for this concept scored the highest when compared to the other ones, but what made this concept to be chosen was mainly a higher value in dispense rate and fluid volume. This concept is basically composed of a cylindrical pipette, a disposable tip, a plunger, a lead screw M8X8, a bracket, and a NEMA 17 motor. Considering that the system needs to deposit a maximum aliquot fluid volume from 20,000 µL, which is a standard value, and that most parts already exist in the market and are cost effective, the bracket is the only element that is manufactured. Before, on the Concept Design Report, concept 6 did not have a sterilization process, which would be another step to be considered. After some analysis, this extra function was implemented on the design. Regarding the system's functionality, the pipette is first attached to the disposal tip. Then, it absorbs the analyzed fluid and release it to the well/tube. After the release of the desire amount of liquid, it is inserted in the waste container. The pipette is sterilized by absorbing the cleaning solution, which is then released to the waste reservoir again. Finally, the tip is disposed. Therefore, the concept is able to perform correctly its main functions of moving cultures suspended in liquid between compartments, disposing waste, and sterilizing itself.

Table 23: **Accuracy and Precision**

Concept	Value
1	Very good
2	Very good
3	Very good
4	Very good
5	Very good
6	Very good
7	Very good
8	Very good

Table 24: **Down Selection Matrices**

Liquid Handling

Quantitative Metric	Weight Factor	Concept 1			Concept 2			Concept 3		
		Value	Normalized	Weighted	Value	Normalized	Weighted	Value	Normalized	Weighted
Cross Contamination	0.0759	Excellent	10	0.7589	Excellent	10	0.7589	Good	6	0.45534
Neutralizing Waste	0.1295	Excellent	10	1.2946	Excellent	10	1.2946	Excellent	10	1.2946
Fluid addition/subtraction	0.1473	6	6	0.88392	6	6	0.88392	5	5	0.7366
Aerosols created	0.1518	654	9.67790914	1.4690098	640.35	9.75982716	1.481444165	882.58	8.30612735	1.26078707
Dispense rate	0.0938	256	2.86	0.268125	251	2.56	0.24	345	8.2	0.76875
Fluid volume	0.0670	19,574	9.80825206	0.6567606	18,900	9.50487622	0.636446512	18,600	9.36984246	0.62740465
Volume accuracy	0.1740	very good	8	1.392	very good	8	1.392	very good	8	1.392
Volume precision	0.1607	very good	8	1.28568	very good	8	1.28568	very good	8	1.28568
Total	1.00			8.0089954			7.972990677			7.82116172

Liquid Handling

Quantitative Metric	Weight Factor	Concept 4			Concept 5			Concept 6		
		Value	Normalized	Weighted	Value	Normalized	Weighted	Value	Normalized	Weighted
Cross Contamination	0.0759	Excellent	10	0.76	Excellent	10	0.7589	Excellent	10	0.7589
Neutralizing Waste	0.1295	Excellent	10	1.29	Excellent	10	1.2946	Excellent	10	1.2946
Fluid addition/subtraction	0.1473	6	6	0.88	6	6	0.88392	6	6	0.88392
Aerosols created	0.1518	660.37	9.63968073	1.46	656.36	9.66	1.46686	850.47	8.498829743	1.29003737
Dispense rate	0.0938	258	2.98	0.28	257	2.92	0.27375	375	10	0.9375
Fluid volume	0.0670	19,304	9.68672168	0.65	18,100	9.1447862	0.6123349	19,293	9.681770443	0.64829135
Volume accuracy	0.1740	very good	8	1.39	very good	8	1.392	very good	8	1.392
Volume precision	0.1607	very good	8	1.29	very good	8	1.28568	very good	8	1.28568
Total	1.00			8.01			7.9680449			8.49092872

Liquid Handling

Quantitative Metric	Weight Factor	Concept 7			Concept 8		
		Value	Normalized	Weighted	Value	Normalized	Weighted
Cross Contamination	0.0759	Good	6	0.45534	Average	5	0.38
Neutralizing Waste	0.1295	Excellent	10	1.2946	Excellent	10	1.29
Fluid addition/subtraction	0.1473	5	5	0.7366	7	7	1.03
Aerosols created	0.1518	600.33	10	1.5179	800.44	8.7990758	1.34
Dispense rate	0.0938	235	1.6	0.15	313	6.28	0.59
Fluid volume	0.0670	16,960	8.631657914	0.57797581	19,100	9.59489872	0.64
Volume accuracy	0.1740	very good	8	1.392	very good	8	1.39
Volume precision	0.1607	very good	8	1.28568	very good	8	1.29
Total	1.00			7.41009581			7.95

Table 25: **OD/FI Metric Weight Factors**

Metric	Weighting Factor, %
Cost	1.67
Analysis Speed	6.67
OD Measurement Capability	25.83
White Light Illumination	12.5
Non Lethal Wavelengths	27.5
Fi Measurement Capability	25.83

I. OD/FI Reader Down selection

Trade Study

A trade study was performed for the OD/FI system among the eight members of the group to determine the weight factors for each metric used. The metrics are based of the customer needs and the weight factors will determine the importance of each need according to the subsystem. For this subsystem, 6 metrics were chosen:

- **Cost** is chosen as a metric as this subsystem is considered to use the biggest portion of the system budget of $10,000. The cost will depend on the materials used to manufacture and the OTS parts purchased from online stores
- **Analysis Speed** is chosen as a metric for this subsystem due the customer need of requiring the system to analyze OD/FI readings in under 6.5 minutes. The analysis speed depends on the gantry movement and time it takes to read and send the values to the computer.
- **OD Capability** is chosen as a metric due to the customer need of requiring the system to be able to measure optical density. OD is based off the ability to read cell absorbance and depends on the light source and filters used.
- **White Light Illumination** is chosen as a metric due to the customer need of requiring the system to be able to provide white light that allows cells to photosynthesize. This illumination is based off the lighting within the system that depends on the wavelength of the light.
- **Non-Lethal Wavelengths** is chosen as a metric due to the customer need of not having wavelengths present that could potentially damage the cells being tested. This metric is based off whether or not the light sources used have lethal wavelengths.
- **FI Capability** is chosen as a metric due to the customer need of requiring the system to be able to measure fluorescence intensity. FI is based off the ability to read fluorescence and depends on the light source and filters used.

The trade study performed for the OD/FI subsystem shows that the most important factors are the OD and FI measurement capability. Following are non-lethal wavelengths and white light illumination, where these metrics are important to consider but not as essential as OD and FI. The least important metrics are analysis speed and cost, as these are merely conveniences for the system.

Metric Justification

Cost

The cost of the OD/FI system is important to consider due to the potentially high prices of the OTS parts used and the entire budget of the system. With a budget of $10,000, each item used in the subsystem was based around similar products found off online stores. Amount of materials used were approximated to account for material cost. OTS parts found on the web considered parts that are available to purchase in the U.S. and are of the cheapest competitors. The ranking a total cost to produce each concept can be found in table .

Analysis Speed

From an online source which spoke on similar servo and belt gantry style robots, the linear loaded velocities in the horizontal z and x directions as well as the vertical y direction can fall around 2000 mm/s, however at a maximum load of up to 30 kg, it can be assumed that the velocity falls to about 1200 mm/s or 60 percent of the maximum speed [22]. The distance needed to be traveled will consider the standard dimensions of the largest well plate that the system will use, a 384 well plate which has dimensions of approximately 127.76 mm long, 85.48 mm wide, with a well depth of 12.7 mm [22]. Also, considering each well is 4.5mm in diameter, and the OD/FI subsystem must be able to analyze each well in the well plate. The analysis speed will be calculated assuming the OD/FI system starting position is at a well plate. The flash from the light is to be considered in the time analysis, where the time to digitally send the absorbance

Table 26: **Cost for each Concept**

Concept	Cost	Parts
1	$346.43	Filter wheel, Scanning Grating, Fiber optics x1ft, Xenon lamp, Slow Motor, Condenser Lens,Photodiode x24, 80/20 x2ft, and breadboard x4
2	$477.08	Laser, breadboard x4, 600nm filter, 80/20 x2ft, and Photodiode x24
3	$200.18	LEDx24, breadboard x8, 600nm filter, 80/20 x8ft, and Photodiode x24
4	$486.57	Laser, breadboard x4, 600nm filter, 80/20 x4ft, and Photodiode x24
5	$550.49	Laser, Motor x2, PMT, and 80/20 x2ft
6	$786.18	Laser, Motor x2, 600nm filter x4, Photodiode x8, breadboard x2, and 80/20 x2ft
7	$841.33	Laser, Motor x3, Fiber optics x1ft, Filter wheel, Xenon lamp, Scanning Grating, PMT, and 80/20
8	$684.04	Laser, Motor x3, Fiber optics x1ft, Filter wheel, Xenon lamp, Scanning Grating, 80/20 x4ft, Photodiode x8, and breadboard x2
9	$987.33	Xenon lamp, Filter set, PMT, ABS, 600nm LED x24, breadboard x4, Condenser Lens x2, and

and fluorescence intensity to the computer is 0.5 seconds. For a 384-plate using a top-down system, it will take:

$$0.5 * 384 = 192 \text{ seconds} \tag{50}$$

For concepts that utilize a horizontal light source, it will take approximately 16 seconds to digitally send the absorbance and fluorescence intensity to the computer. To find the time it takes to for the gantry to carry the OD/FI reader across the well plate, the following equation is used.

$$\frac{\text{Well plate diameter } (\text{ column } * \text{ rows } + \text{ rows })}{\text{gantry velocity at max load}} \tag{51}$$

For a top/down concept:

$$\frac{4.5(16 * 24 + 24)}{1200} = 1.53 \text{ seconds} \tag{52}$$

For concept 9:

$$\frac{4.5(17 * 25 + 24)}{1200} = 1.68 \text{ seconds} \tag{53}$$

For a horizontal reader concept:

$$\frac{4.5(16)}{1200} = 0.06 \text{ seconds} \tag{54}$$

FI Capability

FI capability will quantify the ability for each concept to measure fluorescence. This metric has a large weight factor due to the importance of FI measurements to the system's functionality. Since FI measurements rely on filters and light sources to function, similar to OD measurements, specific measurements cannot be made. Therefore, a ranking system as such: unsatisfactory (0), very poor (2), poor (4), average (5), good (6), very good (8) and excellent (10), is made to quantify each concept. Results can be seen in

Table 27: **Analysis Time For Each Concept**

Concept	Analysis Time (seconds)
1	193.53
2	193.53
3	96
4	193.53
5	16.06
6	16.06
7	16.06
8	16.06
9	193.68

Table 28: **FI Capability Ranks**

Concept	Ranking	Description
1	Unsatisfactory	This concept cannot measure FI
2	Very Good	This concept measures FI at an accurate level, but requires a filter switch to also do OD measurements
3	Good	This concept measure FI at a semi accurate level and also needs a filter switch to measure OD
4	Very Good	same justification as concept 2
5	Unsatisfactory	same justification as concept 1
6	Good	same justification as concept 3
7	Unsatisfactory	same justification as concept 1
8	Good	This concept measures FI for all well plates and tubes, but with an averaged value decreasing accuracy
9	Excellent	This concept can measure FI at an accurate level for all well plates and tubes

Table 29: **Down Selection Matrices**

OD/FI Subsystem, Concepts 1-3										
Quantitative Metric	Weight Factor	Concept 1			Concept 2			Concept 3		
		Value	Normalized	Weighted	Value	Normalized	Weighted	Value	Normalized	Weighted
Cost	**0.02**	$346.43	8.33	0.139111	$477.08	6.83	0.114061	$200.18	10	0.167
Analysis Speed	**0.07**	193.53 s	1.1	0.07337	193.53 s	1.1	0.07337	96 s	5.9	0.39353
OD Capability	**0.26**	Very Good	8	2.0664	Very Good	8	2.0664	Good	6	1.5498
White Light	**0.13**	Excellent	10	1.25	Excellent	10	1.25	Average	5	0.625
Non-Lethal	**0.28**	Excellent	10	2.75	Excellent	10	2.75	Excellent	10	2.75
FI Capability	**0.26**	Unsatisfactory	0	0	Very Good	8	2.0664	Good	6	1.5498
Total				6.278881			8.320231			7.03513

OD/FI Subsystem, Concepts 4-6										
Quantitative Metric	Weight Factor	Concept 4			Concept 5			Concept 6		
		Value	Normalized	Weighted	Value	Normalized	Weighted	Value	Normalized	Weighted
Cost	**0.02**	$486.57	6.73	0.112391	$550.49	5.99	0.100033	$786.18	3.3	0.05511
Analysis Speed	**0.07**	193.53 s	1.1	0.07337	16.06 s	10	0.667	16.06 s	10	0.667
OD Capability	**0.26**	Good	6	1.5498	Good	6	1.5498	Good	6	1.5498
White Light	**0.13**	Very Good	8	1	Excellent	10	1.25	Excellent	10	1.25
Non-Lethal	**0.28**	Excellent	10	2.75	Excellent	10	2.75	Excellent	10	2.75
FI Capability	**0.26**	Very Good	8	2.0664	Unsatisfactory	0	0	Good	6	1.5498
Total				7.551961			6.316833			7.82171

OD/FI Subsystem, Concepts 7-9										
Quantitative Metric	Weight Factor	Concept 7			Concept 8			Concept 9		
		Value	Normalized	Weighted	Value	Normalized	Weighted	Value	Normalized	Weighted
Cost	**0.02**	$841.33	2.67	0.044589	$684.04	4.47	0.074649	$987.33	1	0.0167
Analysis Speed	**0.07**	16.06 s	10	0.667	16.06 s	10	0.667	193.68 s	1	0.0667
OD Capability	**0.26**	Good	6	1.5498	Good	6	1.5498	Excellent	10	2.583
White Light	**0.13**	Excellent	10	1.25	Excellent	10	1.25	Excellent	10	1.25
Non-Lethal	**0.28**	Excellent	10	2.75	Excellent	10	2.75	Excellent	10	2.75
FI Capability	**0.26**	Unsatisfactory	0	0	Good	6	1.5498	Excellent	10	2.583
Total				6.261389			7.841249			9.2494

table 35.

Decision Matrix

Concept Selection

Concept 9 was chosen as the winning concept with a total score of 9.2494 based off the down selection matrices. This concept scored the highest in the metrics that carries the most weight. This concept was found to be the most effective at OD measurements due to the PMT reader and the filter choice. Similar to OD, this concept was found to be the most effective at FI measurements. Both the FI and OD readers have a synergy that allow them to effectively read at the same time. Unlike the other concepts, this concept has a custom chassis that will house both the OD and FI readers, allowing for such synergy. Like all other concepts, this concept does not utilize lethal wavelengths. This concept also allows for white light illumination like most of the other concepts. Concept 9 did score the lowest in cost and analysis speed, but the concept still meets the customer need. Although not quantified as a metric, this system will be able to synergize with the liquid handling as it the reader will be mounted onto the same gantry system.

	Weighing Factors (%)
A	4.17%
B	20.83%
C	7.14%
D	16.67%
E	10.71%
F	23.21%
G	17.26%

J. Shaker Down selection

Trade Study

A trade study was conducted for the Shakers Subsystem amongst the 8 members of the group to determine the weight factors of each metric. There are 7 metrics for this subsystem, each based off of a customer need. The 7 metrics chosen were:

- **Enclosed and interchangeable vessel** was chosen as a metric to meet customer need 16. This requires for this subsystem to ensure that the cell cultures are in enclosed vessels, but also that they can be changed out if necessary.

- **Shaking motion** was chosen as a metric to meet customer need 28. This depends on the motions that the shaker is capable of making. The customer need requires the shaker to move in linear, orbital, and double-orbital motions.

- **Speed**, although not a specific customer need, was chosen as a metric since research indicates that shakers generally require a motor that functions up to 600 RPM. This metric looks at the different motors used in each design concept.

- **Independent shaking patterns** was chosen as a metric to meet customer need 29. This relies on the shaker system having an independent shaking pattern for each well plate or tube.

- **Nonporous materials** was chosen as a metric to meet customer need 11. Nonporous materials depend on the material of the shaker and tray.

- **Accommodates well plates** was chosen metric to meet customer need 25. This requires the subsystem to accommodate for cell cultures in well plates of size 6, 24, 48 96, deep 96, and 384.

- **Accommodates well tubes** was chosen as a metric to meet customer need 26. This requires the subsystem to accommodate for cell cultures in well tubes of size 15 mL and 50 mL.

The Trade Study was performed, and it resulted in accommodating various well plates and shaking patterns to be most important for this subsystem. Following this is the accommodating various well tubes and having all required shaking motions. These 4 are very important to the shaker subsystem since they are outlined in the customer needs. The metric ranked as least important is for the subsystem to be fully enclosed and have interchangeable vessels. Although this is important since it is a customer need, this must be met to allow for the cell cultures to be in a changeable yet controlled enclosure.

Metric Justification

Enclosed and Interchangeable Vessels

It is important to ensure that the cell cultures are in vessels which are fully enclosed and interchangeable so that they are in a controlled environment and shaking pattern, while also having the capability to be switched out when necessary. This is a metric that all designs will end up meeting due to the nature of the bioreactor. Thus, the rankings for each system are as follows:

Table 30: **Enclosed and Interchangeable Vessels**

Concept	Ranking	Description
1	Excellent	Concept ensures cell cultures are in a fully enclosed vessel that can be changed out
2	Excellent	Same justification as concept 1
3	Excellent	Same justification as concept 1
4	Excellent	Same justification as concept 1
5	Excellent	Same justification as concept 1
6	Excellent	Same justification as concept 1
7	Excellent	Same justification as concept 1
8	Excellent	Same justification as concept 1

Table 31: **Shaking Motions**

Concept	Number of Shaking Motions	Description
1	3	Can move in 3 motions
2	3	Same justification as concept 1
3	3	Same justification as concept 1
4	3	Same justification as concept 1
5	3	Same justification as concept 1
6	3	Same justification as concept 1
7	3	Same justification as concept 1
8	3	Same justification as concept 1

Shaking Motions

The customer needs require that the shakers must allow for the well plates and tubes to move in 3 shaking motions: linear, orbital, and double orbital. This metric will check how many shaking motions is capable for each shaker.

Speed

This metric looks at the speed of the device based on the motor used. This calculation assumes that the shakers undergo a rotation of radius 1.5 inches, or 0.0321 meters. To determine the speed of each system with its motor, the following equations are used.

The speed of the concepts will be found by the maximum RPM of their respective motor. This is determined by first finding angular velocity.

$$\omega = \frac{(\text{ RPM } * 2 * \pi)}{60} \tag{55}$$

Then this angular velocity must be converted into a linear velocity using:

$$\text{v} = \omega * \text{r} \tag{56}$$

It will be assumed that the radius of the circular path of the motor is 1.5 inches, or 0.0381 meters.

For concepts 1, 3, 5, 6, and 7, a motor with a maximum RPM of 500 is used, yielding:

Table 32: **Speed**

Concept	Speed (m/s)
1	1.99
2	1.59
3	1.99
4	11.97
5	1.99
6	1.99
7	1.99
8	1.59

$$\omega = \frac{(500 \text{ RPM } * 2 * \pi)}{60} = 52.36 \frac{\text{rads}}{\text{s}} \tag{57}$$

Thus, the velocity is:

$$\text{v} = 52.36 * 0.0381 = 1.99 \frac{\text{m}}{\text{s}} \tag{58}$$

For concepts 2 and 8, a motor with a maximum RPM of 400 is used, yielding:

$$\omega = \frac{(400 \text{ RPM } * 2 * \pi)}{60} = 41.89 \frac{\text{rads}}{\text{s}} \tag{59}$$

Thus, the velocity is:

$$\text{v} = 41.89 * 0.0381 = 1.59 \frac{\text{m}}{\text{s}} \tag{60}$$

Concept 4 uses a motor with a maximum RPM of 3000.Thus,

$$\omega = \frac{(3000 \text{ RPM } * 2 * \pi)}{60} = 314.16 \frac{\text{rads}}{\text{s}} \tag{61}$$

Thus, the velocity is:

$$\text{v} = 314.16 * 0.0381 = 11.97 \frac{\text{m}}{\text{s}} \tag{62}$$

Independent Shaking Patterns

This metric is similar to the second metric of the shaking motions; however, the core difference is that shaking motions requires for there to be 3 different motions while independent shaking patterns observes if there are independent shaking patterns for each well plate or tube. This will be given a ranking of unsatisfactory to excellent, where unsatisfactory means that there are not independent shaking patterns for each well plate and tub while excellent means that the subsystem allows for there to be independent shaking patterns for the variety of plates and tubes.

Nonporous Materials

This metrics checks to ensure that the cell cultures do not make contact with materials that are not nonporous. The materials of the trays that will be holding the plates and tubes will be the focus of this metric, in the case that the cell cultures are over shaken and over spill onto the tray.

Accommodates well tubes

This metric looks at how many well plates can be accommodated by the concept design. There are 6 plates that need to be accounted for. These are size 6, 24, 48 96, deep 96, and 384 respectively.

Accommodates well plates

This metric looks at how many well plates can be accommodated by the concept design. There are 6 plates that need to be accounted for. These are size 6, 24, 48 96, deep 96, and 384 respectively.

Table 33: **Independent Shaking Patterns**

Concept	Number of Independent Shaking Patterns	Description
1	3	Can move in 3 motions
2	1	Each shaker is only capable of one of the motions
3	3	Same justification as concept 1
4	3	Same justification as concept 1
5	3	Same justification as concept 1
6	3	Same justification as concept 1
7	3	Same justification as concept 1
8	3	Same justification as concept 1

Table 34: **Nonporous Materials**

Concept	Ranking	Description
1	Excellent	Concept ensures cell cultures are in a fully enclosed vessel that can be changed out
2	Excellent	Same justification as concept 1
3	Excellent	Same justification as concept 1
4	Excellent	Same justification as concept 1
5	Excellent	Same justification as concept 1
6	Excellent	Same justification as concept 1
7	Excellent	Same justification as concept 1
8	Unsatisfactory	Tubes and Plates secured by bungee cords, a porous material

Table 35: **Accommodates Well Plates**

Concept	Number of Plates Supported	Description
1	6	Can hold size 6, 24, 48 96, deep 96, and 384 well plates
2	6	Same justification as concept 1
3	6	Same justification as concept 1
4	6	Same justification as concept 1
5	6	Same justification as concept 1
6	6	Same justification as concept 1
7	6	Same justification as concept 1
8	6	Same justification as concept 1

Table 36: **Accommodates Well Tubes**

Concept	Number of Tubes Supported	Description
1	2	Can hold size 15 mL and 50 mL well tubes
2	2	Same justification as concept 1
3	2	Same justification as concept 1
4	2	Same justification as concept 1
5	2	Same justification as concept 1
6	2	Same justification as concept 1
7	2	Same justification as concept 1
8	2	Same justification as concept 1

Table 37: **Decision Matrix**

Shakers													
Quantitative	Weight	Concept 1			Concept 2			Concept 3			Concept 4		
Metric	Factor	Concept	C1	Weighted	Concept	C2	Weighted	Concept	C3	Weighted	Concept	C4	Weighted
		1	Normalized	Normal C1	2	Normalized	Normal C2	3	Normalized	Normal C3	4	Normalized	Normal C4
Enclosed and Interchangeable	0.0417	Excellent	10	0.417	Excellent	10	0.417	Excellent	10	0.417	Excellent	10	0.417
Shaking Motions	0.2083	3	10	2.083	3	10	2.083	3	10	2.083	3	10	2.083
Speed	0.0714	1.994911	1.90	0.1356600	1.595929	1.90	0.1356600	1.9949113	1.90	0.13566	11.969468	6.4	0.45696
Independent Shaking Pattern	0.1667	3	10	1.667	1	0	0	3	10	1.667	3	10	1.667
Nonporous Material	0.1071	Excellent	10	1.071	Excellent	10	1.071	Excellent	10	1.071	Excellent	10	1.071
Accomodes well plates	0.2321	6	10	2.321	6	10	2.321	6	10	2.321	6	10	2.321
Accomodes well tubes	0.1726	2	10	1.726	2	10	1.726	2	10	1.726	2	10	1.726
Total	1.00			9.42066			7.75366			9.42066			9.74196

Quantitative	Weight		Concept 5			Concept 6			Concept 7			Concept 8	
Metric	Factor	Concept	C5	Weighted	Concept	C6	Weighted	Concept	C7	Weighted	Concept	C8	Weighted
		1	Normalized	Normal C5	2	Normalized	Normal C6	3	Normalized	Normal C7	4	Normalized	Normal C8
Enclosed and Interchangeable	0.0417	Excellent	10	0.417	Excellent	10	0.417	Excellent	10	0.417	Excellent	10	0.417
Shaking Motions	0.2083	3	10	2.083	3	10	2.083	3	10	2.083	3	10	2.083
Speed	0.0714	1.99491134	1.90	0.13566	1.9949113	1.90	0.13566	1.9949113	1.90	0.13566	1.595929	1.90	0.13566
Independent Shaking Pattern	0.1667	7069	10	1.667	3	10	1.667	3	10	1.667	3	10	1.667
Nonporous Material	0.1071	Excellent	10	1.071	Excellent	10	1.071	Excellent	10	1.071	Jnsatisfactor	1	0.1071
Accomodes well plates	0.2321	6	10	2.321	6	10	2.321	6	10	2.321	6	10	2.321
Accomodes well tubes	0.1726	2	10	1.726	2	10	1.726	2	10	1.726	2	10	1.726
Total	1.00			9.42066			9.42066			9.42066			8.45676

Decision Matrix

Concept Selection

Concept 4 was chosen as the winning concept with a total score of 9.74196 based on the down selection matrices. This concept scored high in concepts that carry the most weight as well as concept which carry less weight. It should be noted that many of the designs scored the same in several of the metrics. This is since these designs are non-negotiable and must be included for the shaker subsystem within the bioreactor. The metrics that scored the same all throughout were metrics 1,2, 6, and 7. Concept 4 has capabilities to accommodate for all well plate and sizes. Additionally, Concept 4 meets the requirement of moving in all 3 motion patterns while also allowing there to be independent motions for each plate or tube. A notable quality of this design is that the user will be able to switch between different sized tubes and plates using a magnetic tray. This is a simple way to have the trays sit on the shakers and also for the user to switch between the desired plate or tube. This allows for metric 1, the fully enclosed and interchangeable vessel, to be met. Additionally, this concept will use a NEMA8 Stepper Motor which can operate up to 3000 RPM. This has the highest RPM amongst all designs and allows for a motion of up to 11.97 m/s.

K. Material Selection

Enclosure

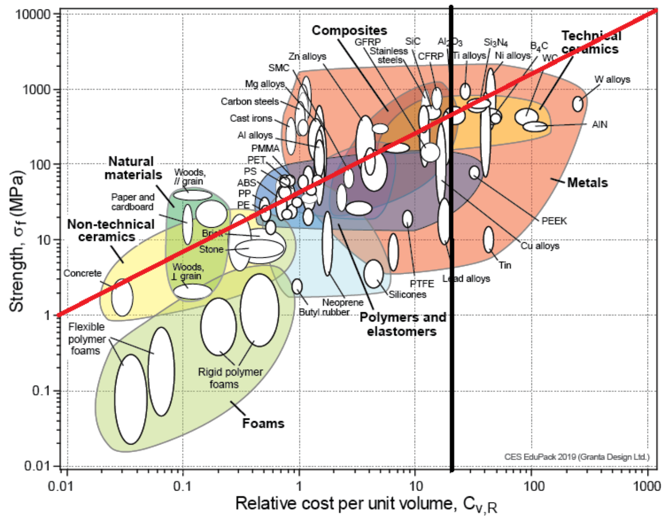


Figure 18: Relative Cost vs. Strength (Enclosure)

To select the ideal material for the enclosure that encapsulates each of the subsystems, the cost and strength are the two most important factors to consider. Relative cost is important due to the sheer amount of material required to construct the functioning enclosure. The black line in the figure above shows the desired relative cost. This upper bound was chosen in order to keep a lower budget that will maintain the integrity of the hedgehog concept of conserving cost, space, and increasing efficiency. Based off of prior experience, most enclosures are typically built with steel or aluminum variants due to their rigidity and reliability. Therefore, the possible candidates for the enclosure's material will be aluminum and steel. Considering the requirements of the enclosure, it must hold together, be easy to transport, machine, install, and cost efficient. The most effective material for the frame will be aluminum due it being able to meet these requirements. For the inside and outside covering, steel sheet is chosen to be the material due to its ability to be machined easily, cost effective, and thin. These are desired to keep this design well with the hedgehog concept of being as small as possible while conserving materials consumed. Both these materials are to be considered in the heat transfer analysis to determine the insulation in the enclosure engineering analysis section. By using the heat flux equation, it was determined that steel, which generally has a lower k value, would be more suited insulating.

Heat Flux Equation
q”= k*dt/dx
Aluminum k value: 205.0 W/m*K
Steel k value: 50.2 W/m K

User Interface

Most of the user interface subsystem are parts that will bought and no material can be selected, such as the Arduino and the sensors. The only part for which the material can be chosen is the emergency shut off button. The only time a force will be acting on the button is when the user hits it to shut it off, for this reason the maximum, average, and minimum stress due to the slap of a human hand were calculated. These calculations can be seen in the analysis portion of this report. On the Ashby plot the 3 sloped lines were drawn from the maximum, average and minimum stresses which were found to be 0.76 MPa, 0.58 Mpa, and 0.4 MPa. The vertical line was made from the maximum temperature the component is expected to be exposed to. The maximum outside temperature of the device cannot exceed 44 degrees Celsius, this was the temperature used for the Ashby plot. Looking at the area where the lines meet, it was concluded that ABS would be used for the emergency shut off button. This material is a good fit for our purposes because ABS is known to have a low cost and be a durable material.

Climate Control

ASHBY PLOT FOR MATERIAL SELECTION – JACKET SURFACES

The goal of this analysis is to determine what materials would be ideal for the inner and outer

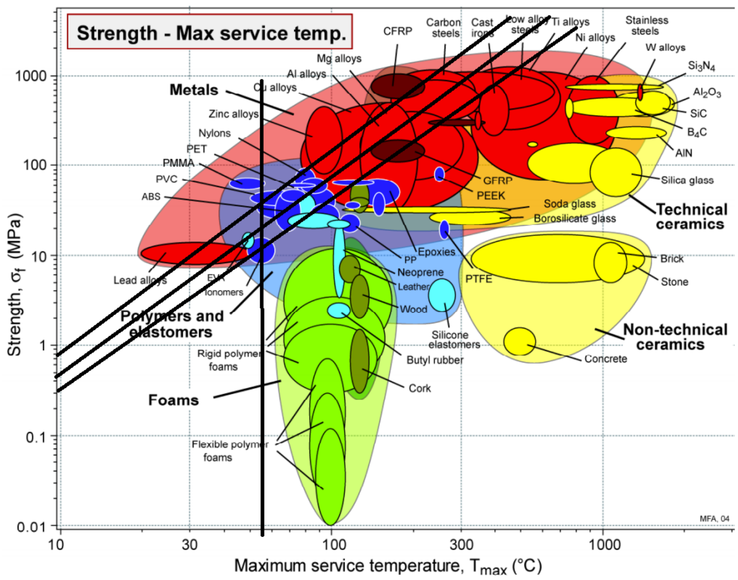
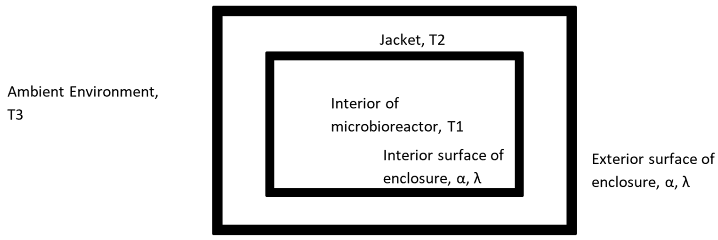


Figure 19: Temperature vs. Strength (User Interface) [16]

surfaces of the jacket. Since the microbioreactor uses a heating/cooling jacket, the outer surface of the jacket should be an insulating material with minimal thermal expansion to minimize heat transfer between the interior of the microbioreactor and the ambient environment. Further, the inner surface of the jacket should be a conductive material to maximize heat transfer between the jacket and the interior of the microbioreactor.

In order to select the optimal materials for these interrelated applications, we will be utilizing the Ashby plot relating coefficients of thermal expansion, , and thermal conductivity, .

A section of the jacket wall has a thermal expansion coefficient and a thermal conductivity coefficient for both the interior and exterior surface.



Variables we cannot change: T1, T2, T3

Variables we can change: α, λ

$$\frac{Heat\ Flux}{Thermal\ Expansion} = \frac{q}{\alpha} = -\frac{\lambda \Delta T}{\alpha} = -\left(\frac{\lambda}{\alpha}\right)\Delta T \longleftarrow \quad \text{Minimize}$$

Value Index

Figure 20: Derivation of value index

In order to avoid compromising the structural strength of the jacket, the interior surface material should have a minimum strength of 1 MPa, and the exterior surface a minimum strength of 100 MPa. In the figure below, the Ashby plot is divided into three sections, with the upper section including materials that may be used for either surface, the middle section including materials that can be used only for the interior surface, and the bottom section including materials that cannot be used for either the interior or exterior surface.

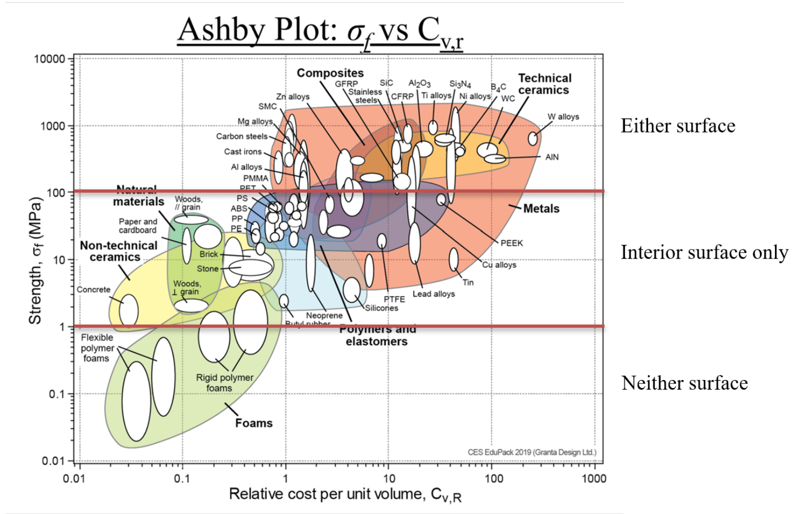


Figure 21: Ashby plot showing strength vs. cost

$$\frac{Heat\ Flux}{Thermal\ Expansion} = \frac{q}{\alpha} = -\frac{\lambda \Delta T}{\alpha} = -\left(\frac{\lambda}{\alpha}\right)\Delta T$$

$$C_i = \frac{\lambda}{\alpha}$$

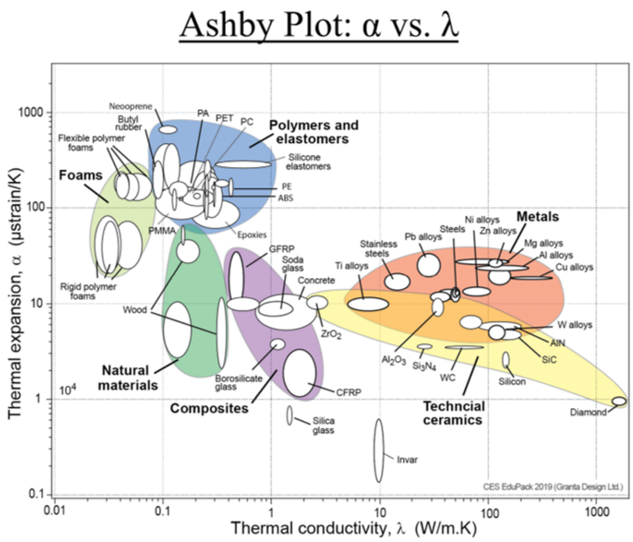


Figure 22: Ashby plot showing thermal expansion vs. thermal conductivity

Candidate Materials, Exterior:
Rigid Polymer Foams: C = 0.001 W/m*μstrain
Flexible Polymer Foams: C = 0.0002 W/m*μstrain
Wood: C = 0.05 W/m*μstrain
Butyl Rubber: C = 0.00045 W/m*μstrain

Candidate Materials, Interior:
Diamond: C = 1000 W/m*μstrain
Silicon: C = 75 W/m*μstrain
Copper Alloys: C = 10 W/m*μstrain
Aluminum Alloys: C = 5 W/m*μstrain
Silicon Carbides: C = 40 W/m*μstrain
Stainless Steels: C = 1 W/m*μstrain

Exterior

For typical insulation applications, polymer foams are the most common. Specifically, most freezers and refrigerators use polyurethane rigid foam. This material is cheap, readily available, easy to manipulate, safe, and has been used successfully in similar applications many times. For these reasons, polyurethane foam is the most promising of the candidate materials for the exterior surface of the jacket. Furthermore, rigid foams meet the strength criteria given in step 2.

Interior

The interior surface of the material requires more thoughtful selection. While diamond is the best performing candidate material in terms of properties, there are other factors that make it highly impractical. Chief among these is cost, the cost of using diamond to construct a large structure like the interior surface of the jacket would likely be prohibitively expensive, in addition to being unnecessary.

Silicon is another of the top performers in terms of thermal properties. However, silicon does not meet the strength criteria given in step 2, and therefore is not a viable option. Silicon carbide, another candidate material, does meet the strength needs of the device, and offers enticing thermal properties. However, it too has shortcomings. For one, silicon carbide is relatively dense compared to some of the options. Further, it is very hard, and thus difficult to shape. Additionally, silicon carbide can be quite brittle.

The most promising candidate materials for the interior surface of the jacket are aluminum alloys and copper alloys, and stainless steels. Of these materials, we believe that stainless steel is the best option. Stainless steel has high strength, low cost, and performance that is sufficient for this application. Copper is disadvantaged by its relatively low cost and its softness. Aluminum alloys, while having high strength and low weight, are somewhat more expensive than steel. It is expected that stainless steel provides benefits like low cost and high strength while also meeting the needs of this device in terms of thermal performance. For these reasons, stainless steel is the material of choice for the interior surface of the jacket.

Gas Control

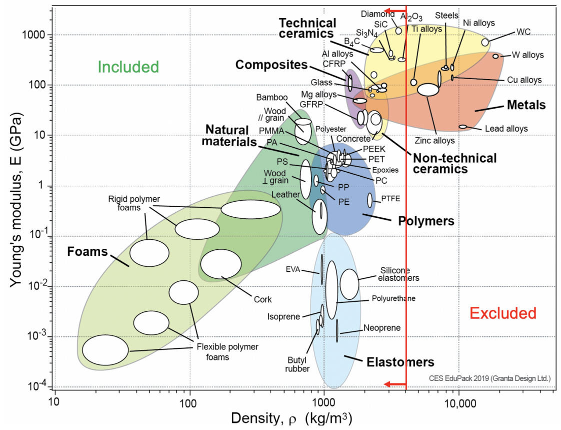


Figure 23: Young´s modulus vs. Density (Gas Control)

When choosing the material for the ventilation ducts, we had to consider it was going to be hung from the wall so the piping system should not weigh too much. To calculate a density to exclude very heavy materials we have estimated an approximate weight of 200g-400g and calculated a volume of a pipe with diameters of 3.5in and 3in and 5.9in in length. The average density calculated was around 2 Mg/m3 . For safety issues a density of 3 Mg/m3 was chosen. Using the Ashby plot comparing the young modulus and density we were able to discard a large number of materials.

$$\rho \leq 3.0 Mg/m^3 \tag{63}$$

Another factor we had to take into consideration was that this tube would be full of gas, therefore it should be nonporous, so there is no gas leakage.

Polymers - C=1500 Kg/m3
Al.alloys - C=1700 Kg/m3

Having eliminated all the materials that did not meet the specifications required for the design, we were left with two groups of materials: metals and polymers. As our function was to minimize the weight of the pipes we opted for pvc which is a polymer widely used in the industry to handle fluids.

Liquid Handling

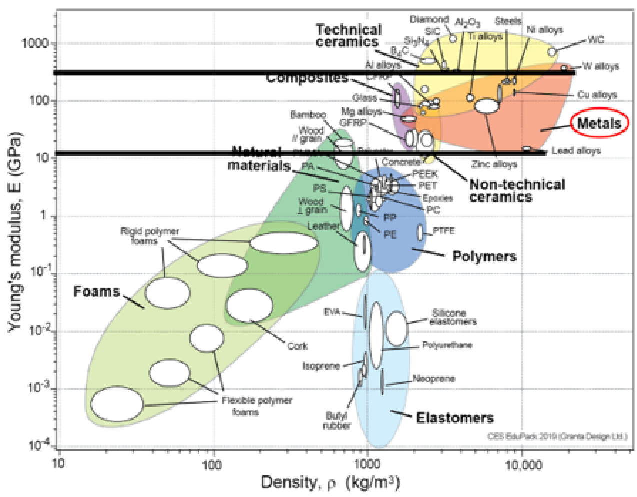


Figure 24: Density vs. Young's Modulus (Liquid Handling) [16]

This system is basically composed of six parts, where five of them are OTS parts and one is a designed one, which is the bracket that is attached to the plunger. Regarding the OTS parts, the disposable tips are made of Polypropylene, which has a significant impact resistant, resistant to friction, flexion and notch fatigue, low cost, and highly light. The pipette and plunger are made of Polypropylene and Natural Rubber. Natural rubber is one of the most used rubbers. It is just not suitable for resisting heat (temperatures above 80 ºC) or for resisting oils, which is not the case for this device. The lead screw M8x8 is made of Carbon steel due to its good machinability and corrosion resistance. The motor enclosure materials are Aluminum and Steel. The bracket, the only manufactured part, is made of aluminum. Aluminum is a non-ferrous metal used in the most diverse industries due to its advantages such as lightness, high resistance, resistance to corrosion and because it is infinitely recyclable. Figure 11 shows two horizontal lines where the top one represents the stiffest metallic alloy, and the bottom one the least stiff metallic alloy. Regarding the device being designed, there is no need for selecting a material in one of the extremes, it can be an intermediate one due to its weight and cost. Therefore, aluminum alloys would be the best option.

OD/FI Reader

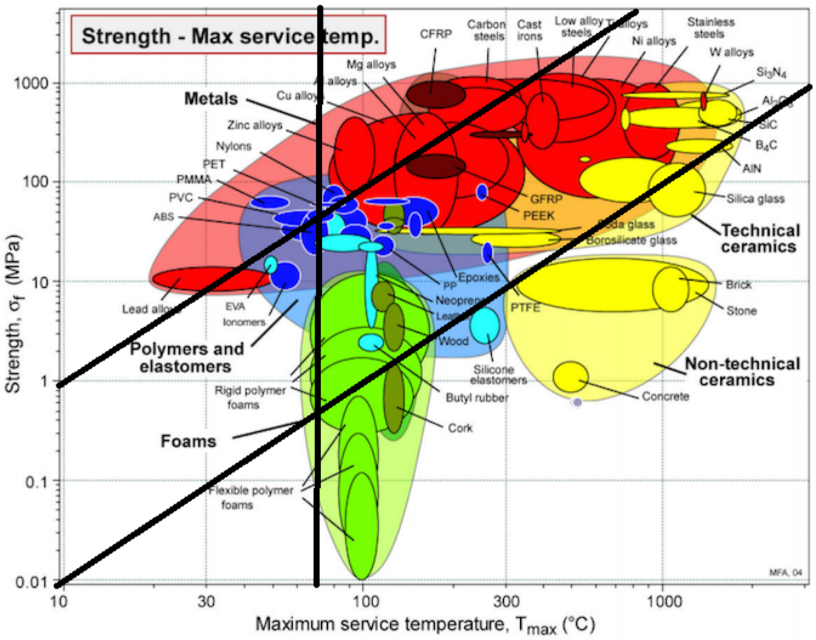


Figure 25: Temperature vs. Strength (OD/FI) [16]

To choose the best material for the OD/FI reader, a couple of factors need to be considered. The cost, machinability, strength, and service temperature are of the most important factors to be considered. Of the two, the service temperature and strength requirements can be calculated whereas the other factors are to be analyzed. Based off the customer needs, the material must be able to withstand 0-70 degrees Celsius. Therefore, in figure 26, the vertical black line represents the max temperature range. The sloped line represents the range of desired strengths. A couple of the notable stresses were solved in the engineering analysis section of the report. The stresses to be considered were calculated as:

$$n = \frac{S_y}{\sigma} = \frac{215}{0.290} = 741.4 \tag{64}$$

$$\sigma = \frac{F}{A} = \frac{0.389N}{38.93} = 0.001MPa \tag{65}$$

$$\sigma_x = \frac{My}{I} = \frac{11.68 * 7.5}{965.38} = 0.902\text{MPa} \tag{66}$$

By looking at the graph and the set ranges, the possible material candidates are PVC, EVA, Lead Alloys, and ABS. Of all these candidates, ABS plastic is the best candidate. Compared to the other materials ABS is the most cost effective with a price of $0.04/cm3 [39]. EVA is not a good candidate as the plastic is rubber-like and will not be able to hold a structure when in use. Lead alloy is too heavy and too expensive to consider as the material choice. PVC is a good candidate that meets all the needs except the temperature range. Otherwise, ABS plastic is very easy to machine, especially with 3D printing and has a strong enough tensile stress to meet the small stresses applied to it.

Shaker

To choose the best material for the shaker tray, several factors need to be considered. The material must be non-porous to meet the customer need. This considers the scenario in which the cell cultures may spill over onto the tray if over shaken. Additionally, this material needs to have magnetic properties in order to be compatible with the interchangeable nature of the winning design concept. Cost will also play an important role since the team aims to mitigate costs wherever possible. An Ashby plot detailing the relationship between material strength vs. cost, where we want to minimize cost and maximize material strength, will be used.

From article 'Interferometric Volume Measurement in Microplates', the upper limit of the mass of a filled well plate is 80 g[18]. Gravitational constant is 9.81 m/s. Area of well plates, from a top-down view is 127.76 mm x 85.48 mm = 10920.9248 mm^2 = 0.0109209248m^2.

Thus, the minimum stress required is

$$\sigma = \frac{\mathrm{F}}{\mathrm{A}} = \frac{0.08\mathrm{kg} * 9.81\frac{\mathrm{m}}{\mathrm{s}^2}}{10920.9248\mathrm{m}^2} = 71.86\mathrm{MPa} \tag{67}$$

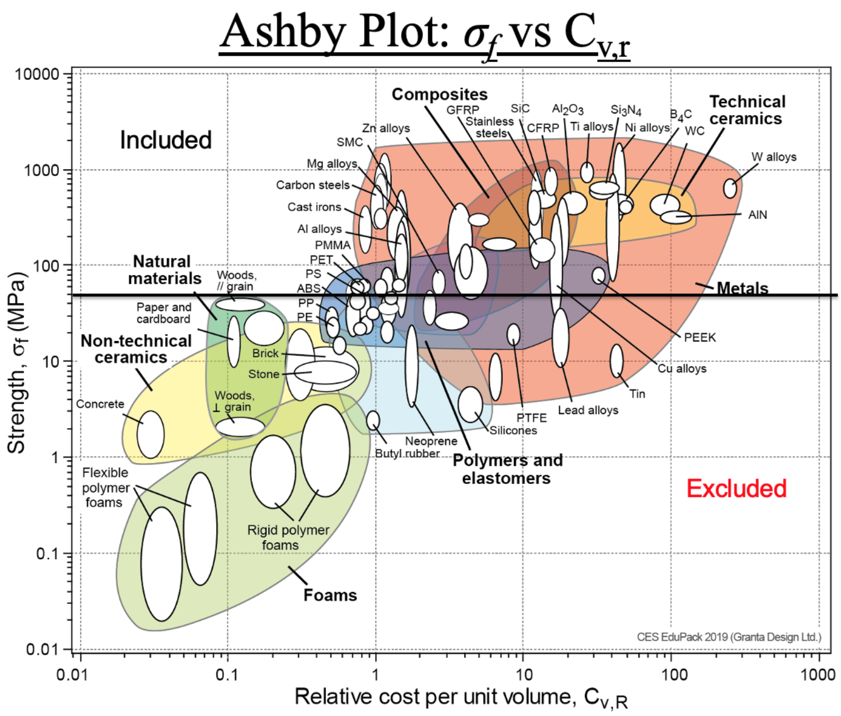


Figure 26: Cost vs. Strength (Shaker Tray) [16]

This means that the material of the tray can fall under the category of metals, composites, technical ceramics, and polymers and elastomers. These all successfully fall under the customer requirement for a non-porous material. However, the scope can be narrowed down since the material needs to be magnetic. This limits the choice to metals. The two strong contenders are aluminum and steel. However, steel is chosen as the material for the trays due to it having good magnetic properties and is also easily machinable. This is an important criterion to also consider since trays need to be manufactured for the various well plate and tube sizes.

System CAD Model

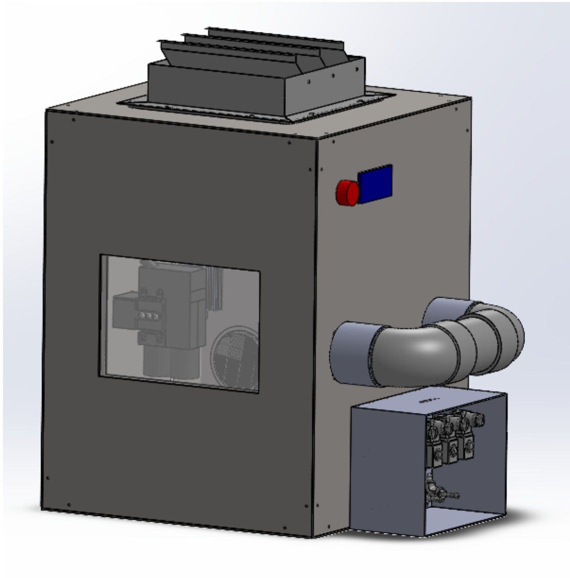


Figure 27: Front View of CAD Assembly

F. Final Design Report

A. Executive Summary with Hedgehog Concept

Biological researchers commonly grow cells to perform experiments on – a process known as cell culturing. Cell culturing enables researchers to perform a myriad of experiments in the pursuit of better understanding and more effective manipulation of cells. Cellular experimentation has a wide range of practical applications in some of the most impactful fields of human research – cell culturing experiments are important in medical research, the generation of vaccines, biomedical engineering, plant sciences, and many other areas.

The process of cell culturing has many steps and typically requires a great deal of human attention. The CAMbox seeks to improve the efficiency of biological research and eliminate human error in cell culturing by automating many of the tasks required to successfully culture cells.

The CAMbox is a multi-functional, highly-automated bioreactor designed for use in laboratory, commercial, educational, and personal applications. The CAMbox offers a unique value proposition in that it offers state of the art performance and experimental control in a very compact package and at an affordable price. At every junction, the designers of CAMbox went to great lengths to ensure that each component of the CAMbox was as compact and user-friendly as possible, without ever compromising on performance or quality.

The goals of the CAMbox design team centered around packing as much capability into as small and affordable a package as possible. We endeavored to design a device capable of automating much of the work typically associated with cell culturing. The CAMbox can provide cell nourishment, remove cell waste, and monitor cell cultures without any human intervention. Additionally, the CAMbox can generate a wide range of culturing conditions by controlling the temperature and atmospheric composition of the growth environment.

During the design process, the CAMbox was broken down into several subsystems to promote a greater attention to detail. The key subsystems of the CAMbox are the enclosure, the gas control subsystem, the liquid handling subsystem, the user interface, the climate control subsystem, the OD/FI reader, and the shaker subsystem. The enclosure is made from steel and isolates the culturing environment from the outside world. The enclosure is thermally insulated and corrosion-resistant to allow for worry-free cleaning and to promote longevity. The gas control subsystem uses solenoid valves to regulate gas input and ultimately provides the end user with the ability to culture cells in an environment with unlimited options concerning atmospheric composition.

The liquid handling subsystem uses a prefabricated gantry that moves in three dimensions to deposit nutrients and remove waste from the cull cultures – without any need for human intervention, minimizing the risk of contamination. Additionally, the liquid handling system is capable of adding and removing fluid from cell cultures with an extremely high degree of accuracy - extra steps were taken to ensure that no aerosols are create during liquid addition or removal. The user interface gives the end user control over the

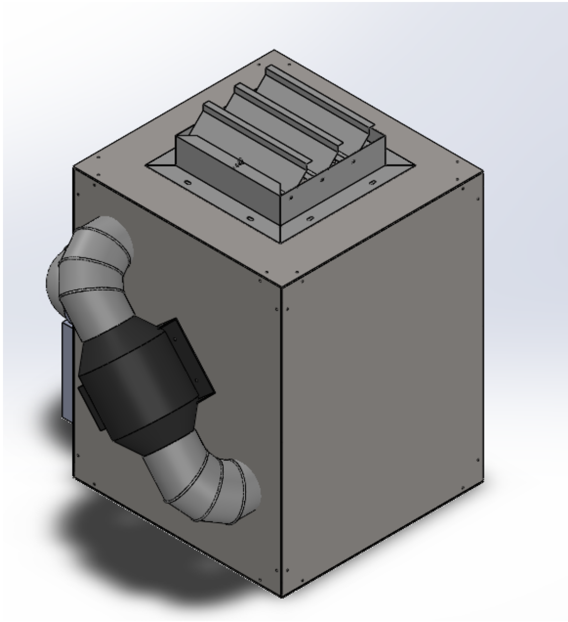


Figure 28: Back View of CAD Assembly

temperature, atmospheric composition, shaking pattern, while providing feedback from the inbuilt OD/FI monitoring system.

The climate control subsystem allows the end user to control the temperature at which the cells are cultured and mitigates condensation on the surface of culture containers, offering a remarkable temperature range of 4 Celsius to 70 Celsius, and the ability to achieve these temperatures in under 15 minutes by using forced convection to heat and cool cell cultures. Finally, the well plate shaker provides the end user with the ability to automatically shake the cell cultures in linear, orbital, and double orbital patterns using small, efficient, high-speed motors and long-lasting springs. The CAMbox also uses a custom cell monitoring system capable of both optical density and fluorescence intensity measurements. The designers behind the CAMbox to care to ensure that OD/FI reading is fast, efficient, and not harmful to cell cultures.

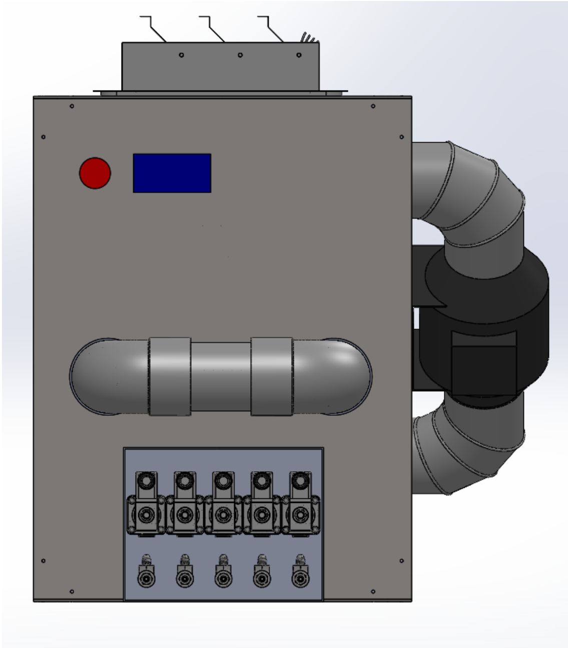


Figure 29: Right View of CAD Assembly

B. Design Revisions

There were several recommended changes brought forward during design review 2. This section lists those recommendations and explains the changes that were made to the design for this final version.

1. The first recommendation was to add a feature in the CAD model designed to prevent light entering the enclosure and affecting OD/FI measurements. The final CAD model features a shutter that can be opened and closed to prevent light from entering the enclosure during OD/FI reading, while also allowing the end user to view the inside of the enclosure when OD/FI readings are not taking place.
2. The second recommendation was to consider making the enclosure panels from fewer sheet metal parts to simplify manufacturing. To meet this recommendation, the number of separate sheets of metal was reduced to the lowest number possible without compromising on the functionality of the enclosure.
3. The third recommendation was to perform heat transfer calculations to determine the amount of time required to reach the setpoint, and to confirm that this time was less than the customer requirement of 15 minutes. To meet this recommendation, a detailed heat transfer calculation was performed to determine the amount of time required to reach the setpoint for both conical tubes and well plates. The result of these calculations confirmed that, in either case, the climate control system is capable of reaching any setpoint within the customer's desired range in under 15 minutes.
4. The fourth recommendation was to consider the impact of heat dissipation in the heat transfer calculations. Initially, the heat transfer calculations performed neglected potential effects of heat dissipation. It was determined that the cooling system selected initially was not powerful enough to cool the cultures when the effect of heat dissipation was accounted for. The manufacturer that produced the initial cooling system offered a similar, more powerful model which was ultimately used as a replacement.
5. The fifth recommendation was to show the proper mounting of the heating and cooling units in the CAD model. The initial CAD model did not have the heating element correctly placed, and the cooling element was not properly installed on the CAD model. To remedy these problems, the heating element has been added to the latest CAD model, and the cooling unit has been installed in the manner consistent with the manufacturer's instruction.
6. The sixth recommendation was to relocate the heating element. The heating element had to be moved from the exterior of the enclosure to the interior of the enclosure. In the latest CAD model, this change has been made.
7. The seventh recommendation was to perform calculations to ensure that spilling will not occur during shaking. Since design review 2, our team has performed fluid dynamic analysis to determine whether the liquid inside the well plates will spill over the side of the container during maximum acceleration. The result of these calculations indicate that even at maximum acceleration, and assuming that the wells are overfilled, spilling will not occur.
8. The eighth recommendation was to conduct a cyclic fatigue analysis on the shaker and components that will be affected by cyclic loading. Since design review 2, our team has performed cyclic loading analysis on all parts affected by cyclic loading – including the shaker, the shaker mount, and the springs used within the shaker.

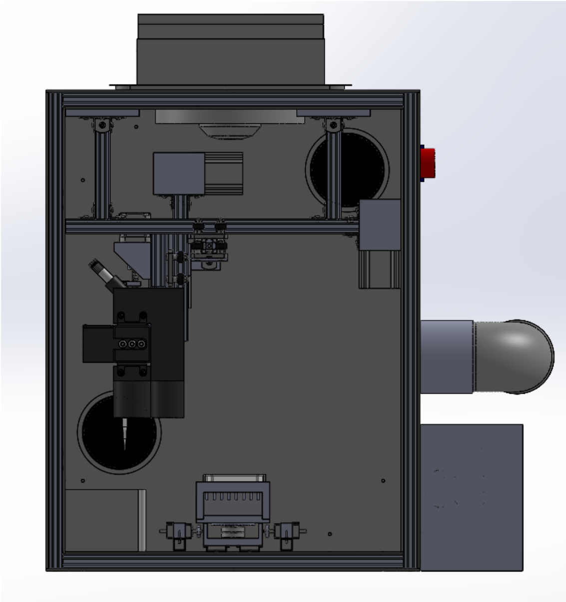


Figure 30: Inside View of CAD Assembly

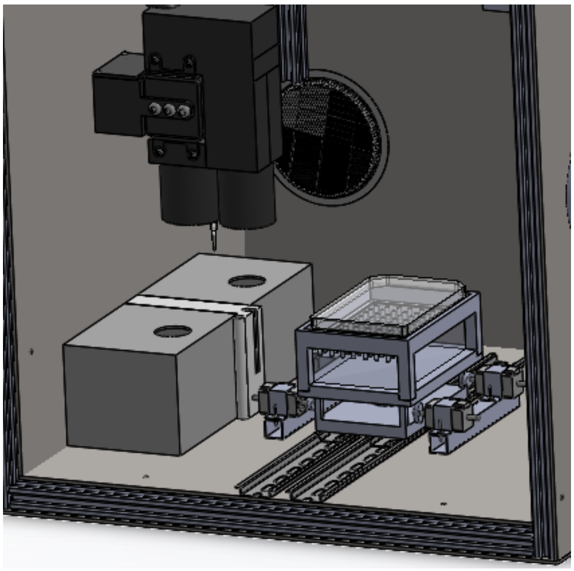


Figure 31: Close View of Inside

9. The ninth recommendation was to make the enclosure opening large enough to allow for easier access to the interior of the CAMbox. Since design review 2, the opening has been enlarged to allow for a user to fit both hands through the opening, and is now 20 inches long and 5 inches wide.

C. Gantt Chart

The figure seen below shows the Gantt chart that was used by group 14 throughout the process of working on the FDR. This Gantt chart was used to ensure no parts of the FDR were skipped, and to ensure everything was finished in a timely manner. It should be noted that the last portion of the report (CAD drawings) were set to be finished on April 25th, instead of 26th, this was to give us enough time to compile and edit the report for any mistakes. Additionally, the stars shown on the chart are meant to show when we achieved a milestone. Finishing the design review 2 revisions was a milestone because it meant no more design changes would be made to the device and it allowed us to start and finish the remainder of the parts. Next, Finishing the bill of materials was a milestone because then the purchase order could be completed and cross-checked to make sure all parts were accounted for. A major milestone was the engineering analysis being finishes, this is a big part of the report because it includes critical and noncritical components. Finishing the analysis meant that the math done for our device was accounted for and explanations for why we chose different parts were also done. The last milestone was the full CAD

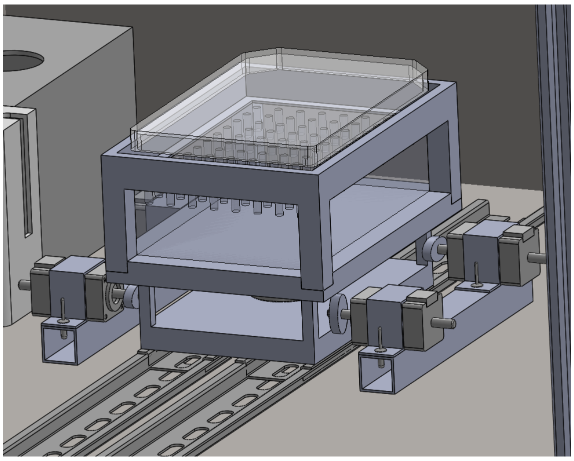


Figure 32: Shaker and OD/FI System

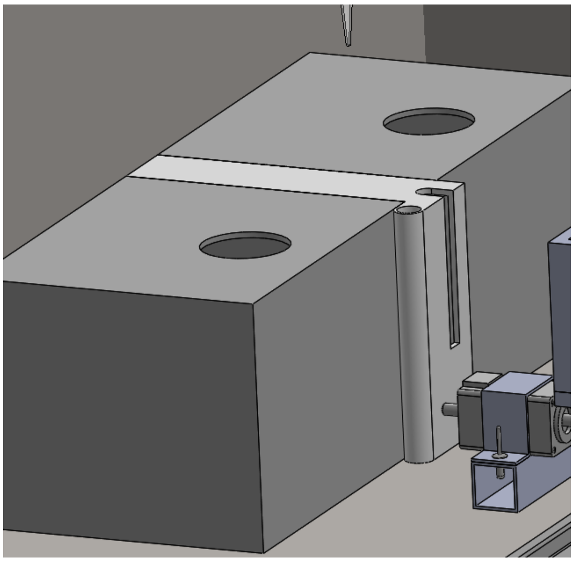
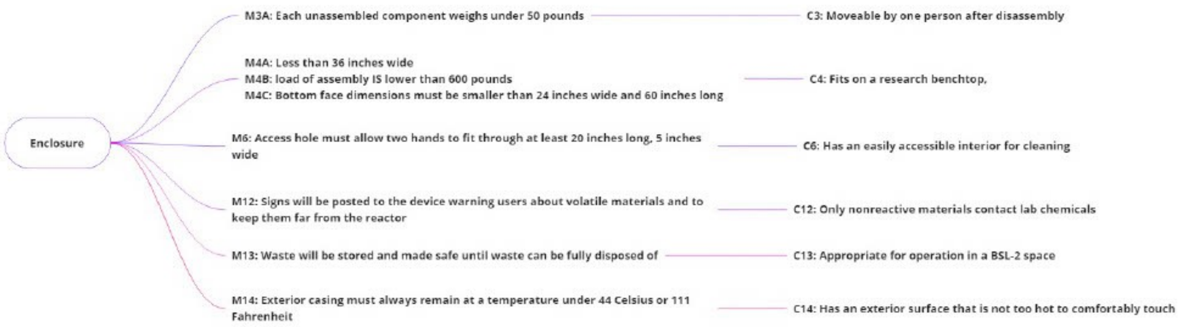


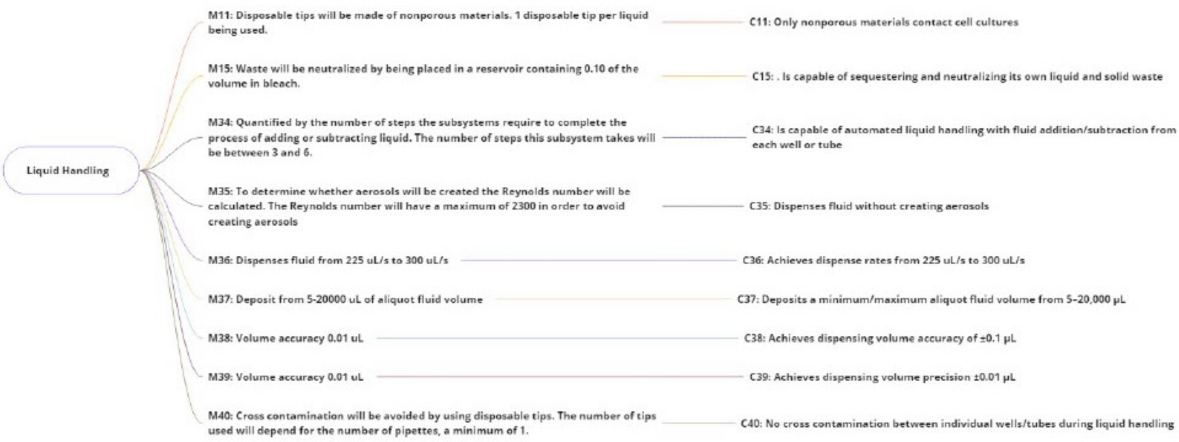
Figure 33: Pipette Tips and Waste Storage

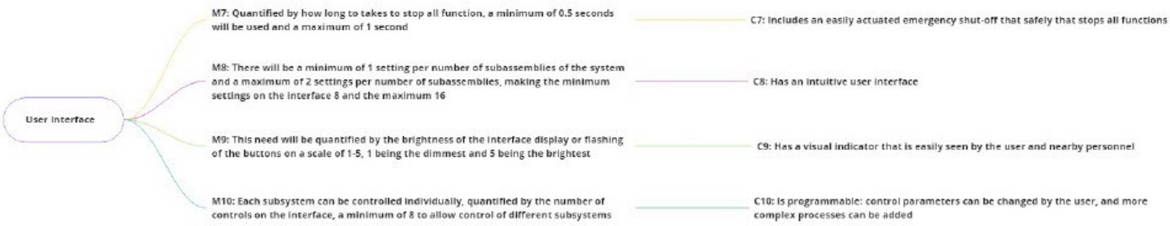
model. This part was allotted the most time because there were parts to be fixed and design changes to be made, but it was important that this was done because without it we could not start on the assembly plan, or drawings.

D. Customer Needs Map

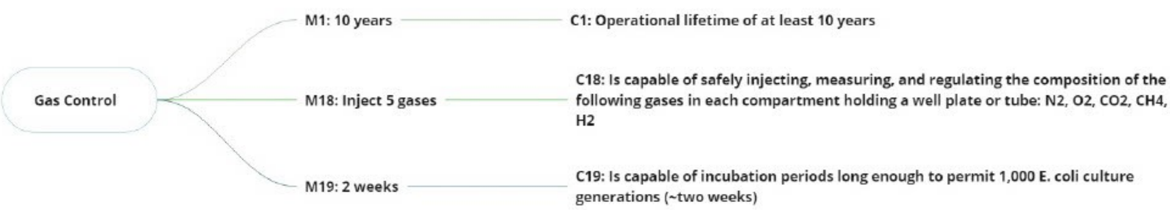
Customer Need	Metric	Subsystem	Feature	Kano Category	Likert Score
1: Operational Lifetime of at least 10 years	10 years	Gas Control	Solenoid valves	Performance	5
2. Prototype production cost does not exceed $10,000	10000 dollars	OD/FI	Prefabricated light unit	Attractive	5
3. Moveable by one person after disassembly	Each individual component weighs less than 50 pounds	Enclosure	Stainless steel case with insulation	Attractive	5
4. Fits on a research benchtop, taking into consideration:					
a. Clearance through doors (when assembled)	Less than 36 in wide				
b. Benchtop loadbearing capacity	Load of assembly is lower than 600 pounds				
c. Benchtop footprint	Bottom face dimensions smaller than 24 in wide and 60 in long	Enclosure	Stainless steel case with insulation	Basic	0
5. Runs from a single standard 120 VAC wall outlet	Runs from a single standard 120 VAC wall outlet	Climate Control	200W heater and cooler	Basic	0
6. Has an easily accessible interior for cleaning	Access hole must allow two hands to fit through at least 20 inches long 5 inches wide	Enclosure	Large access hole on front of enclosure	Attractive	5
7. Includes an easily actuated emergency shut-off that safely that stops all functions	Quantified by how long to stop all function, a minimum of 0.5s and a maximum of 1s	User Interface	Stop button with rapid shutdown capability	Basic	0
8. Has an intuitive user interface	There will be a minimum of 1 setting per number of subassemblies and a maximum of 2 settings per number of subassemblies.	User Interface	User interface enables control over all of the subsystems	Basic	0
9. Has a visual indicator that is easily seen by the user and nearby personnel, and that shows:					
a. System on/off					
b. Process mode, elapsed process time, and remaining process time					
c. If an error occurred	This need will be quantified by the brightnes of the interface display or flashing of the buttons.	User Interface	LED-Illuminated user interface	Attractive	0
10. Is programmable: control parameters can be changed by the user, and more complex processes can be added	Each subsystem can be controlled individually, quantified by the number of controls on the interface	User Interface	User interface enables control over each subsystem independently	Attractive	0
11. Only nonporous materials contact cell cultures	Disposable tups will be made of nonporous materials, 1 disposable tip per liquid being used	Liquid Handling	Disposable tip dispenser and waste bin	Basic	0
12. Only nonreactive materials contact lab chemicals	Signs will be posted to the device warning users about volatile materials and to keep them far from the reactor	Enclosure	Large sign on enclosure exterior warning users	Basic	0
13. Appropriate for operation in a BSL-2 space	Waste will be stored and made safe until waste can be fully disposed of	Enclosure	Internal waste storage	Performance	0
14. Has an exterior surface that is not too hot to comfortably touch	Exterior casing must always remain at a temperature below 44 C	Enclosure	Insulation ensures minimal heat transfer from interior to exterior of enclosure	Basic	0
15. Is capable of sequestering and neutralizing its own liquid and solid waste	Waste will be neutralized by being placed in a reservoir containing 0.1 of the volume in bleach	Liquid Handling	Waste bin is filled with bleach to neutralize waste	Performance	0
16. Cultures microbes in fully enclosed compartments or vessels that are interchangeable	Every componenent is interchangeable	Shakers	Each component	Performance	0
17. Maintains environmental conditions independently for each well plate or tube	Independently controls a single environment for each well plate or tube	Climate Control	Enclosure allows climate control system to isolate cultures from outside environment	Attractive	5
18. Is capable of safely injecting, measuring, and regulating the composition of the following gases in each compartment holding a well plate or tube: N2, O2, CO2, CH4, H2	Injects 5 gases	Gas Control	5 solenoid valves, 1 for each desired gas	Performance	5
19. Is capable of incubation periods long enough to permit 1,000 E. coli culture generations (~two weeks)	2 weeks	Gas Control	Gas control runs on cycles of up to 2 weeks	Performance	5
20. Maintains cultures in a well plate or tube at a constant temperature within a range from 4□C to 70□C	4-70 degrees C	Climate Control	PTC heating unit and thermoelectric cooling unit	Performance	0
21. Maintains internal setpoint temperature with time and spatial variation less than ±2.5□C	2.5 degree variation	Climate Control	Several fans throughout environment ensure uniform heat distribution	Performance	0
22. Uniformly heats/cools wells/tubes within the desired temperature range	5 degree variation	Climate Control	Heating cultures via forced convection encourages uniform heating	Performance	0
23. Mitigates condensation on cooled well plate and tube surfaces	Covers less than 10% of surfaces on well plates or conical tubes	Climate Control	Fan built in to heater can be used to defog culture containers during cooling	Attractive	0
24. Reaches setpoint culture temperature in less than 15 minutes	15 minutes	Climate Control	High-speed fan for forced convection maximizes rate of heat transfer	Performance	5
25. Accommodates existing culture well plates of the following sizes: 6, 24, 48, 96, deep 96, 384	Hold well plates of 6, 24, 48, 96, deep 96, 384	Shakers	Shaker has interchangeable mounts for each well plate	Basic	5
26. Accommodates existing conical tubes of the following sizes: 15mL & 50mL	Hold conical tubes of 15mL and 50mL	Shakers	Shaker has interchangeable mounts for each conical tube	Basic	5
27. Includes a photobioreactor mode to illuminate photosynthesis-capable cell cultures (e.g., cyanobacteria) with white light	Illuminate from 400nm to 640nm at 1kW/cm3	OD/FI	Uses light with the specified power output and wavelength range	Performance	5
28. Shakes well plates and tubes in Linear, Orbital, and Double Orbital patterns	Capable of 3 shaking patterns	Shakers	Springs and motors allow for linear, orbital, and double orbital shaking	Performance	5
29. Has shaking patterns that are independent for each well plate or tube	Adaptable to shake well plates and tubes	Shakers	Interchangable mounts allow for use with either conical tubes or well plates	Performance	5
30. Measures optical density (OD) in all individual wells and conical tubes 2	Measure OD at 600nm	OD/FI	OD reader uses light with 600nm wavelength	Performance	0
31. Measures fluorescent intensity (FI) in all individual wells and conical tubes	Excite fluorescence up to 640nm and detect emission up to 740nm	OD/FI	Exciting light at 640nm and detection up to 740nm	Performance	0
32. For OD/FI measurement, sustains adequate light intensity to make measurements at wavelengths not lethal to cells3	Maintain light intensity of 640nm	OD/FI	Light intensity is stable at 640nm	Basic	0
33. Processes a 384 well plate through OD/FI measurements in less than 6.5 minutes	6.5 minutes	OD/FI	OD/FI system mounted on gantry capable of moving over all wells in 384 well plate in 6	Performance	5
34. Is capable of automated liquid handling with fluid addition/subtraction from each well or tube	Quantified by the number of steps the subsystems require to complete the process of adding or subtracting liquid	Liquid Handling	Disposable tips eliminate the need for human input	Attractive	5
35. Dispenses fluid without creating aerosols	To determine whether aerosols will be created the Reynolds number will be calculated	Liquid Handling	Flow rate/Reynolds number low enough that aerosols will not form	Basic	-5
36. Achieves dispense rates from 225 uL/s to 300 uL/s	Dispenses fluid from 225uL/s to 30uL/s	Liquid Handling	Fluid pump capable of moving fluid at desired rates	Performance	0
37. Deposits a minimum/maximum aliquot fluid volume from 5–20,000 μL	Deposit from 5-20000uL of aliquot fluid volume	Liquid Handling	Fluid reservoir capable of holding from 5-20000 uL	Performance	0
38. Achieves dispensing volume accuracy of ±0.1 μL	Volume of accuracy of 0.01uL	Liquid Handling	OTS pipette with high accuracy	Performance	5
39. Achieves dispensing volume precision ±0.01 μL	Volume precision of 0.01uL	Liquid Handling	OTS pipette with high precision	Performance	5
40. No cross contamination between individual wells/tubes during liquid handling	Cross contamination avoided by using disposable tips	Liquid Handling	Use of disposable pipette tips	Basic	5

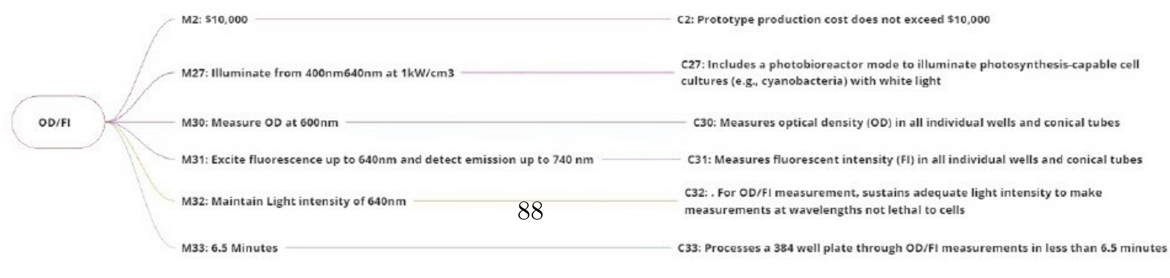

Enclosure
M3A: Each unassembled component weighs under 50 pounds
C3: Moveable by one person after disassembly
M4A: Less than 36 inches wide
M4B: load of assembly IS lower than 600 pounds
M4C: Bottom face dimensions must be smaller than 24 inches wide and 60 inches long
C4: Fits on a research benchtop.
M6: Access hole must allow two hands to fit through at least 20 inches long, 5 inches wide
C6: Has an easily accessible interior for cleaning
M12: Signs will be posted to the device warning users about volatile materials and to keep them far from the reactor
C12: Only nonreactive materials contact lab chemicals
M13: Waste will be stored and made safe until waste can be fully disposed of
C13: Appropriate for operation in a BSL-2 space
M14: Exterior casing must always remain at a temperature under 44 Celsius or 111 Fahrenheit
C14: Has an exterior surface that is not too hot to comfortably touch


Liquid Handling
M11: Disposable tips will be made of nonporous materials. 1 disposable tip per liquid being used.
C11: Only nonporous materials contact cell cultures
M15: Waste will be neutralized by being placed in a reservoir containing 0.10 of the volume in bleach.
C15: . Is capable of sequestering and neutralizing its own liquid and solid waste
M34: Quantified by the number of steps the subsystems require to complete the process of adding or subtracting liquid. The number of steps this subsystem takes will be between 3 and 6.
C34: Is capable of automated liquid handling with fluid addition/subtraction from each well or tube
M35: To determine whether aerosols will be created the Reynolds number will be calculated. The Reynolds number will have a maximum of 2300 in order to avoid creating aerosols
C35: Dispenses fluid without creating aerosols
M36: Dispenses fluid from 225 uL/s to 300 uL/s
C36: Achieves dispense rates from 225 uL/s to 300 uL/s
M37: Deposit from 5-20000 uL of aliquot fluid volume
C37: Deposits a minimum/maximum aliquot fluid volume from 5-20,000 μL
M38: Volume accuracy 0.01 uL
C38: Achieves dispensing volume accuracy of ±0.1 μL
M39: Volume accuracy 0.01 uL
C39: Achieves dispensing volume precision ±0.01 μL
M40: Cross contamination will be avoided by using disposable tips. The number of tips used will depend for the number of pipettes, a minimum of 1.
C40: No cross contamination between individual wells/tubes during liquid handling


User Interface
M7: Quantified by how long to takes to stop all function, a minimum of 0.5 seconds will be used and a maximum of 1 second
C7: Includes an easily actuated emergency shut-off that safely that stops all functions
M8: There will be a minimum of 1 setting per number of subassemblies of the system and a maximum of 2 settings per number of subassemblies, making the minimum settings on the interface 8 and the maximum 16
C8: Has an intuitive user interface
M9: This need will be quantified by the brightness of the interface display or flashing of the buttons on a scale of 1-5, 1 being the dimmest and 5 being the brightest
C9: Has a visual indicator that is easily seen by the user and nearby personnel
M10: Each subsystem can be controlled individually, quantified by the number of controls on the interface, a minimum of 8 to allow control of different subsystems
C10: Is programmable: control parameters can be changed by the user, and more complex processes can be added


Climate Control
M5: Operate with a 120V AC
C5: Runs from a single standard 120 VAC wall outlet
M17: Independently control at least 3 separate environments
C17: Maintains environmental conditions independently for each well plate or tube
M20: 4-70 degrees Celsius
C20: Maintains cultures in a well plate or tube at a constant temperature within a range from 4C to 70C
M21: 2.5 degree difference
C21: Maintains internal setpoint temperature with time and spatial variation less than ±2.5C
M22: 5 degree difference
C22: Uniformly heats/cools wells/tubes within the desired temperature range
M23: Covers less than .10 of surfaces on well plates or conical tubes
C23: Mitigates condensation on cooled well plate and tube surfaces
M24: 15 minutes
C24: Reaches setpoint culture temperature in less than 15 minutes


Gas Control
M1: 10 years
C1: Operational lifetime of at least 10 years
M18: Inject 5 gases
C18: Is capable of safely injecting, measuring, and regulating the composition of the following gases in each compartment holding a well plate or tube: N2, O2, CO2, CH4, H2
M19: 2 weeks
C19: Is capable of incubation periods long enough to permit 1,000 E. coli culture generations (~two weeks)


OD/FI
M2: $10,000
C2: Prototype production cost does not exceed $10,000
M27: Illuminate from 400nm640nm at 1kW/cm3
C27: Includes a photobioreactor mode to illuminate photosynthesis-capable cell cultures (e.g., cyanobacteria) with white light
M30: Measure OD at 600nm
C30: Measures optical density (OD) in all individual wells and conical tubes
M31: Excite fluorescence up to 640nm and detect emission up to 740 nm
C31: Measures fluorescent intensity (FI) in all individual wells and conical tubes
M32: Maintain Light intensity of 640nm
C32: . For OD/FI measurement, sustains adequate light intensity to make measurements at wavelengths not lethal to cells
M33: 6.5 Minutes
C33: Processes a 384 well plate through OD/FI measurements in less than 6.5 minutes

E. System Cost

F. Bill of Materials

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	EML4501-A-001	Full Assembly	N/a	1
2	EML4501-A-002	Full Assembly Exploded	N/a	1
3	EML4501-A-003	Interior Assembly	N/a	1
4	EML4501-A-004	Exterior Front Panel	3MM A36 STEEL	1
5	EML4501-A-005	Exterior Back Panel	3MM A36 STEEL	1
6	EML4501-A-006	Door Assembly	N/a	1
7	EML4501-A-007	Exterior Door Panel	3MM A36 STEEL	1
8	EML4501-A-008	Door Insulation	POLYURETHANE FOAM RIGID	1
9	EML4501-009	Interior Door Panel	3MM A36 STEEL	1
10	EML4501-010	Exterior Bottom Panel	3MM A36 STEEL	1
11	EML4501-011	Exterior Top Panel	3MM A36 STEEL	1
12	EML4501-012	Front Interior Panel	3MM A36 STEEL	1
13	EML4501-013	Back Interior Panel	3MM A36 STEEL	1
14	EML4501-014	Bottom Interior Panel	3MM A36 STEEL	1
15	EML4501-015	Top Interior Panel	3MM A36 STEEL	1

16	EML4501-016	Right Interior Panel	3MM A36 STEEL	1
17	EML4501-017	Left Interior Panel	3MM A36 STEEL	1
18	EML4501-018	Top and Bottom Insulation	POLYURETHANE FOAM RIGID	2
19	EML4501-019	Front Wall Insulation	POLYURETHANE FOAM RIGID	1
20	EML4501-020	Back Insulation	POLYURETHANE FOAM RIGID	1
21	EML4501-021	Left and Right Insulation	POLYURETHANE FOAM RIGID	2
22	EML4501-022	Interior Corners	2 MM A36 STEEL	4
23	EML4501-023	Window Frame	2 MM A36 STEEL	1
24	EML4501-024	Acrylic Sheet	Acrylic	1
25	EML4501-025	Window Screen Case	ABS	1
26	EML4501-026	Blackout Screen	PLASTIC	1
27	EML4501-027	Electrical Box	2 MM A36 STEEL	1
28	EML4501-028	Electrical Box Door	2 MM A36 STEEL	1
29	EML4501-029	, Liquid Hadeling, ODFI As	N/a	1
30	EML4501-030	NEMA 17 MOTOR HOLDER	A36 STEEL	2
31	EML4501-031	Lead Screw Mount	A36 STEEL	1

32	EML4501-032	Pipette Gantry Mount	A36 STEEL	1
33	EML4501-033	Pipette Mount	A36 STEEL	1
34	EML4501-034	Piston	A36 STEEL	1
35	EML4501-035	Container Holder	A36 STEEL	1
36	EML4501-036	Liquid Resivour	A36 STEEL	3
37	EML4501-037	Tip Disoposal	2 MM A36 STEEL	1
38	EML4501-038	Tip Refill	2 MM A36 STEEL	1
39	EML4501-039	ODFI READER ASSEMBLY	N/a	1
40	EML4501-040	ODFI READER ASSEMBLY	N/a	1
41	EML4501-041	ODFI READER ASSEMBLY	N/a	1
42	EML4501-042	ODFI Top Cover	ABS PLASTIC	1
43	EML4501-043	ODFI Light Bracket	ABS PLASTIC	1
44	EML4501-044	ODFI Chassis	ABS PLASTIC	1
45	EML4501-045	Gas Control Assembly	2 MM A36 STEEL	1
46	EML4501-046	Gas Control Box	2 MM A36 STEEL	1
47	EML4501-047	Gas Box Door	2 MM A36 STEEL	1

48	EML4501-048	Exhaust Cover	2 MM A36 STEEL	1
49	EML4501-049	Shaker Assembly	N/a	1
50	EML4501-050	Shaker Assembly Exploded	N/a	1
51	EML4501-051	Shaker Base Plate	A36 STEEL	1
52	EML4501-052	Shaker Middle Plate	A36 STEEL	1
53	EML4501-053	Shaker Holder Base Plate	A36 STEEL	1
54	EML4501-054	Large Motor Mount	A36 STEEL	1
55	EML4501-055	Bottom Layer Spring Plate	A36 STEEL	3
56	EML4501-056	Top Layer Spring Plate	A36 STEEL	2
57	EML4501-057	Well Plate Holder	A36 STEEL	1
58	EML4501-058	Sealant Washer	RUBBER	10
59	EML4501-059	Hose Fitting	Zinc	5
60	EML4501-060	SOLENOID VALVE	BRASS	5
61	EML4501-061	37 Degree Tube Fitting	ZINC	5
62	EML4501-062	Push To Connect Fitting	ZINC	5
63	EML4501-063	PVC Tubing	PVC	5

64	EML4501-064	outer cooler	STEEL	1
65	EML4501-065	inner cooler	STEEL	1
66	EML4501-066	40 mm fan	STEEL	1
67	EML4501-067	OTS LCD SCREEN	N/a	1
68	EML4501-068	gantry to enclosure attachment	ALUMINUM	1
69	EML4501-069	Bottom Shaker Motor	N/a	1
70	EML4501-070	Flexible Coupling 0.25in x 8mm	6061-TS	1
71	EML4501-071	Alignement ring pipette	STEEL	1
72	EML4501-072	Pipette	Plastic	1
73	EML4501-073	Seal	Rubber	1
74	EML4501-074	Lead Screw Mount	STEEL	1
75	EML4501-075	pipette tip	PLASTIC	1
76	EML4501-076	NEMA Motor Mount	STEEL	2
77	EML4501-077	DFM1 ODFI	N/a	1
78	EML4501-078	Mirror - ODFI	N/a	1
79	EML4501-079	ODFI Lense	GLASS	1

80	EML4501-080	ODFI Lense 630	GLASS	1
81	EML4501-081	ODFI Component	ABS PLASTIC	1
82	EML4501-082	18-8 Hex Screws	STEEL	10
83	EML4501-083	ODFI Scope	ABS PLASTIC	1
84	EML4501-084	ODFI Scope Glass	GLASS	1
85	EML4501-085	ODFI Bracket Sleeve	STEEL	1
86	EML4501-086	ODFI Lightbracket	STEEL	1
87	EML4501-087	ODFI Breadboard	N/a	1
88	EML4501-088	White LED ODFI	N/a	1
89	EML4501-089	topcover for ODFI	ABS PLASTIC	1
90	EML4501-090	18-8 HEX fastener	STEEL	3
91	EML4501-091	8020 odfi attachment	STEEL	1
92	EML4501-092	attachment bracket odfi	STEEL	1
93	EML4501-093	Macron Dynamics-80/20 horizontal	6105-T5 aluminum	2
94	EML4501-094	Macron Dynamics-80/20 short	6105-T5 aluminum	2
95	EML4501-095	Macron Dynamics-Gantry Motor	6105-T5 aluminum	3

96	EML4501-096	Macron Dynamics-	6105-T5 aluminum	3
97	EML4501-097	Macron Dynamics- Nut	6105-T5 aluminum	3
98	EML4501-098	Macron Dynamics- Rod	6105-T5 aluminum	2
99	EML4501-099	Macron Dynamics- 80/20 Z axis	6105-T5 aluminum	1
100	EML4501-100	Macron Dynamics- Rod	6105-T5 aluminum	1
101	EML4501-101	Macron Dynamics- Gantry Motor horizontal	6105-T5 aluminum	1
102	EML4501-102	Macron Dynamics- 80/20 90 degree bracket	6105-T5 aluminum	4
103	EML4501-103	Macron Dynamics- Gantry Receiver motor	6105-T5 aluminum	2
104	EML4501-104	Macron Dynamics- prop shaft	6105-T5 aluminum	1
105	EML4501-105	Macron Dynamics- 80/20 mid	6105-T5 aluminum	2
106	EML4501-106	Macron Dynamics- connecting angle	6105-T5 aluminum	1
107	EML4501-107	Macron Dynamics- z axis fastener	6105-T5 aluminum	4
108	EML4501-108	Macron Dynamics- Screw Axis	6105-T5 aluminum	1
109	EML4501-109	Black Oxide 18-8 Fasteners	Black Oxide Steel	44
110	EML4501-110	Enclosure mount	STEEL	2
111	EML4501-111	Emergency Stop Button	Plastic	1

112	EML4501-112	Radiator	STEEL	1
113	EML4501-113	Wall mount for radiator	STEEL	1
114	EML4501-114	Rubber Feet	Rubber	4
115	EML4501-115	Top Exhaust fan	ALUMINUM	1
116	EML4501-116	exhaust cover	ALUMINUM	1
117	EML4501-117	Rubber Lining on Door	Rubber	4
118	EML4501-118	CLAMP end for latch	ALUMINUM	2
119	EML4501-119	Latch Clamp	ALUMINUM	2
120	EML4501-120	Door Handle	ALUMINUM	1
121	EML4501-121	Door Hinges	ALUMINUM	2
122	EML4501-122	Rivet Assembly	STEEL	116
123	EML4501-123	Male Rivet	STEEL	42
124	EML4501-124	Female Rivet	STEEL	42
125	EML4501-125	18mm hex	STEEL	4
126	EML4501-126	M5x.8 nut	STEEL	4
127	EML4501-127	M4 x40mm Hex	STEEL	19

128	EML4501-128	surface mount hinge	ALUMINUM	4
129	EML4501-129	LED Panel	N/a	1
130	EML4501-130	6 Wellplate Base	Plastic	1
131	EML4501-131	Sliding Base For Shaker	STEEL	3
132	EML4501-132	MOUNTED LINEAR BALL BRNG	STEEL	3
133	EML4501-133	Spring	STEEL	6
134	EML4501-134	cam	STEEL	3
135	EML4501-135	cambig	STEEL	1

G. Purchase Order

REQUEST FOR ITEMS TO BE PURCHASED **Date Requested:** 4/26/2021

1. Purc 1
2. Grou 14
3. Acco MAE Mechanical Design 3
4. Grou Brenden Modi

Description of item to be purchased	Part Number	Qty.	Unit	Price	Shipping	Sub Total	Vendor Name	Vendor Address	Vendor City/State/Zip	Vendor Phone Number
1/4" - 20 Stainless Steel Button Head	92949A832	1	Pack	$ 7.25	$ -	$ 7.25	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
Hex Drive Screws	Web Site:	https://www.mcmaster.com/92949A106/								
R1463 Photmultiplier Tube	R1463	1	Sinlge	$ 250.00	$ -	$ 250.00	Hamamatsu Photonics	360 Foothill Road	Bridgewater, NJ 08807-0910	(908) 231-0960
	Web Site:	https://www.hamamatsu.com/us/en/product/type/R1463/index.html								
1/4" 4-40 Stainless Steel Button Head	92949A106	1	Pack	$ 3.02	$ -	$ 3.02	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
Hex Drive Screws	Web Site:	https://www.mcmaster.com/92949A832/								
Miniature Xenon Lamp	189-1	1	Single	$ 21.57	$ -	$ 21.57	InternationalLight	10 Technology Drive	Peabody, MA 01960	(978) 818-6180
	Web Site:	https://www.intl-lighttech.com/node/1656?gclid=CjwKCAjwu5CDBhB9EiwA0w6sLWZVus1YhlvXBUY_N2qsluLCwY_-7HvpSEZ-Mdv4QY8555qN9vZUwBoCJKkQAvD_BwE								
25mm Dia, Mirror	43-844	1	Single	$ 25.00	$ -	$ 25.00	Edmund Optics	101 East Gloucester Pike	Barrington, NJ 08007-1380	1-800-363-1992
	Web Site:	https://www.edmundoptics.com/p/0deg-aoi-25mm-dia-cold-mirror/5335?gclid=Cj0KCQjwmIuDBhDXARIsAFITC_5C4EjBHT4tvr75FXMcplfeKPhTusMHMf37g9-aMzknSssvfis1sGQaAgNQE								
Cage Cube Connector	C4W-CC	2	Sinlge	$ 54.65	$ -	$ 109.30	Thorlabs	56 Sparta Ave	Newton, NJ 07860	1-973-300-3000
	Web Site:	https://www.thorlabs.com/thorproduct.cfm?partnumber=C4W-CC#ad-image-0								
Kinematic Fluorescence Filter Cube	DFM1	1	Sinlge	$ 386.17	$ -	$ 386.17	Thorlabs	56 Sparta Ave	Newton, NJ 07860	1-973-300-3000
	Web Site:	https://www.thorlabs.com/thorproduct.cfm?partnumber=DFM1								
TXRED Excitation Filter	MF559-34	1	Sinlge	$ 257.54	$ -	$ 257.54	Thorlabs	56 Sparta Ave	Newton, NJ 07860	1-973-300-3000
	Web Site:	https://www.thorlabs.com/thorproduct.cfm?partnumber=MF559-34								
CY3.5/TXRED Dichroic Filter	MD588	1	Sinlge	$ 236.98	$ -	$ 236.98	Thorlabs	56 Sparta Ave	Newton, NJ 07860	1-973-300-3000
	Web Site:	https://www.thorlabs.com/thorproduct.cfm?partnumber=MD588								
TXRED Emission Filter	MF630-69	1	Sinlge	$ 257.54	$ -	$ 257.54	Thorlabs	56 Sparta Ave	Newton, NJ 07860	1-973-300-3000
	Web Site:	https://www.thorlabs.com/thorproduct.cfm?partnumber=MF630-69								
3D Printed ABS Custom Part	ABS	970,000	mm^3	$ 0.00004	$ -	$ 38.80	ToyBuilder Labs	1848 E Walnut St	Pasadena, CA 91107	(626) 808-4010
	Web Site:	https://www.toybuilderlabs.com/blogs/news/13055597-material-cost-for-printing								
Tiny breadboard	65	1	Single	$ 4.00	$ -	$ 4.00	Adafruit	150 Varick St	New York, NY 10013	(646) 248-7822
	Web Site:	https://www.adafruit.com/product/65?gclid=CjwKCAjwu5CDBhB9EiwA0w6sLdNjw71oVMFV-q3KRfdin-hy7bbL5hJEkx6pWs_BhYR1mHxDmnov1RoCt4UQAvD_BwE								
3/4 Solenoid Valve Asco Red Hat	2660K21	5	Single	$ 130.43	$ -	$ 652.15	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
8210G Series	Web Site:	https://www.mcmaster.com/solenoid-valves/premium-solenoid-on-off-valves/								
90 degree elbow for 1/4 tube OD	50715K192	5	Single	$ 35.93	$ -	$ 179.65	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:	https://www.mcmaster.com/50715K192/								
Air and Water, Adapter for 1/4" Hose	5350K32	5	Single	$ 2.01	$ -	$ 10.05	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
ID	Web Site:	https://www.mcmaster.com/5350K32/								
3 Pipe Size, 5 Feet Long	48925K97	1	Single	$ 32.16	$ -	$ 32.16	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:	https://www.mcmaster.com/48925K97/								
Size 4 Galvanized Steel 90 Degree	1766K32	2	Single	$ 10.09	$ -	$ 20.18	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
Elbow	Web Site:	https://www.mcmaster.com/1766K32/								
Arduino Uno Rev3	A000066	1	single	$ 23.00	$ -	$ 23.00	Arduino	33 1/2 union square	Somerville, MA 02143	(917)-470-9721
	Web Site:	https://store.arduino.cc/usa/								
Analog gas sensor for arduino	SEN0127	1	single	$ 6.90	$ -	$ 6.90	DFROBOT	Room 603, 2 Boyun Road, Pudong	Shanghai, China	86-21-61620183
	Web Site:	https://www.dfrobot.com/product-681.html								
Analog CO2 gas sensor	TPX00029	1	single	$ 56.00	$ -	$ 56.00	Arduino	33 1/2 union square	Somerville, MA 02143	(917)-470-9721
	Web Site:	https://store.arduino.cc/usa/								
Temperature and humidity sensor	3251	1	single	$ 8.95	$ -	$ 8.95	adafruit	150 Varick Street	New York, NY 10013	1-646-248-7822
	Web Site:	https://www.adafruit.com/product/3251								
Pressure sensor	3965	1	single	$ 14.95	$ -	$ 14.95	adafruit	150 Varick Street	New York, NY 10013	1-646-248-7822
	Web Site:	https://www.adafruit.com/product/3965?gclid=CjwKCAjwu5CDBhB9EiwA0w6sLdCbe6b4cwnBDLBR34Vw9zjeaoee47CMUuG0wuJHWFudm8epJpxaThoCO4EQAvD_BwE								
Interface display	2232	1	single	$ 59.95	$ -	$ 59.95	adafruit	150 Varick Street	New York, NY 10013	1-646-248-7822
	Web Site:	https://www.adafruit.com/product/2232								
disposable pipette tips	141053	1	pack	$ 98.25	$ -	$ 98.25	RPI	410 E Business Center Dr	Mount Prospect, Illinois, 60056	(847) 635-1177
	Web Site:	https://www.rpicorp.com/products/molecular-biology/filter-pipet-tips/filter-pipet-tips-20ul-960-cs.html								
pipette	8DYZ6	50	pack	$ 41.56	$ -	$ 41.56	Grainger	904 Lee Rd	Orlando, FL 32810	(800) 472-4643
	Web Site:	https://www.grainger.com/product/COVIDIEN-Micropipettor-8DYZ6								
M4 Button Head Hex Drive Screw	92095A476	340	pack	$ 32.16	$ -	$ 32.16	Mcmaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:									
MCS-PSC XYZ Gantry	MCSPSC	1	unit	$ 1,250.00	$ -	$ 1,250.00	Macron Dynamics	100 Phyllis Dr	Croydon, PA 19021	(215) 443-8888
	Web Site:	https://www.macrondynamics.com/linear-robot/mcs-psc								
XPS Insulation		1.55	m^2	$ 1.73	$ -	$ 2.68	Berties Flooring	Wakefield, Flockton	West Yorkshire, UK	(113) 426-5778
	Web Site:	https://www.ebay.com/itm/XPS-Underlay-5mm-Thick-Wood-or-Laminate-Flooring-Insulation-Like-Fibreboard-/254242308347								
3mm Steel Sheet Metal	3DRT9	4.75	m^2	$ 3.94	$ -	$ 18.72	Grainger	6685 Whitfield Industrial Ave	Sarasota, FL 34243	(800) 472-4643
	Web Site:	https://www.grainger.com/product/3DRT9?ef_id=Cj0KCQjwpdqDBhCSARIsAEUJ0hMLHvSaDj3VoTmpcThH1Moc-Ps6v1C3Hht8yCrfENeY2YGGKqgizTMaAi6qEALw_wcB:G:s&s_kwcid=A								
Lead Screw	7549K55	2	single	$ 23.68	$ -	$ 47.36	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:	https://www.mcmaster.com/7549K55/								
Extended-Life Swivel Joint, 3/4" ID, 1-	2699K110	2	single	$ 74.44	-	$ 148.88	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
1/4" OD	Web Site:	https://www.mcmaster.com/2699K11/								
1/4" coupler	2505K122	2	single	$ 74.49	$ -	$ 148.98				
	Web Site:	https://www.mcmaster.com/2505K122/								
Distriman Black Adjustment Ring	GI F1864037	4	single	$ 13.00	$ -	$ 52.00	Pipette Supplies	P.O. Box 132	Mansfield, TX 76063	(817) 483-9883
	Web Site:	https://www.pipettesupplies.com/product/distriman-black-adjustment-ring-gilson/								
25 mm length M5 screw	94209A329	16	pack	$ 8.50	$ -	$ 136.00	mcMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:	https://www.mcmaster.com/94209A329/								
90 Corner Bracket	1556A26	120	single	$ 0.53	$ -	$ 63.60	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:	https://www.mcmaster.com/1556A26/								
Din rail	8961K11	1 meter	single	$ 9.30	$ -	$ 9.30	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:	https://www.mcmaster.com/8961K11/								
NEMA 8 motor	6627T54	1	single	$ 22.69	$ -	$ 22.69	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:									
135 Corner Bracket	1556A26	48	single	$ 0.53	$ -	$ 25.44	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:	https://www.mcmaster.com/1556A26/								
Acrylic Plate	8560K178	1	single	$ 2.92	$ -	$ 2.92	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
	Web Site:	https://www.mcmaster.com/8560K178/								
DIN Rail Enclosure Fan	FGC3	1	single	$ 159.00	$ -	$ 159.00	Enclosure Climate Control	3046 Home Road	Powell, Ohio 43065	(740) 917-5781
	Web Site:	https://www.enclosureclimatecontrol.com/fgc3000-series-din-rail-enclosure-fan-heater-200-300-400w/?gclid=Cj0KCQjwgtWDBhDZARIsADEKwgNCdPi3hd96FbjtSLdQ74e_loWttu8-dV4gh								
Thermoelectric Cooler	3200303	1	single	$ 1,416.00	$ -	$ 1,416.00	AutomationDirect	3505 Hutchinson Road	Cumming, GA 30040	(770) 844-4200
	Web Site:	https://www.automationdirect.com/adc/shopping/catalog/enclosures_-z-_subpanels_-z-_thermal_management_-z-_lighting/enclosure_thermal_management/thermoelectric_coolers/32003(								
Alumnum Sheet Stock 0.032"	15V222	ea.	unit	$ 4.08	$ -	$ 48.62	Grainger	6685 Whitfield Industrial Ave	Sarasota, FL 34243	(800) 472-4643
Thickness	Web Site:	https://www.grainger.com/product/15V222?ef_id=Cj0KCQjwyZmEBhCpARIsALIzmnLI2nYqliLSVFqFjC2U9P0FayF14WK-mjDxRSxJ0FkH7NcxbOGZAfMaAkLHEALw_wcB:G:s&s_kwcid=								
Total										**$ 6,385.27**

H. Manufacturing Tooling and Labor Cost

The table above shows the cost to manufacture the different parts within the system. The cost are calculated from Dr. Traum cost estimations [33].Since a lot of the parts are OTS, this system features a low amount of manufacturing. Most of the manufacturing is directly related to the sheet metal of the enclosure. As calculated from the table, the total manufacturing labor cost is $74.94.

Through an in-depth analysis and computation of the required labor costs to manufacture the various components of the complete Microbioreactor system it was found that to manufacture the final design, $328.44 would be required in labor costs. This value includes all of the skilled manufacturing processes of sheet metal cutting, bending, welding, drilling, milling, etc.

I. Energy Cost

The table above shows the cost to keep the entire system running for a two week period. The cost for Kilowatts per hours is based of the Gainesville Energy cost rate [17]. The entire system will cost $262.50 to run for for 336 hours.

J. Assembly Cost

The tables in the Appendices show the total assembly time that each subsystem will require, the time shown is in seconds. The handling and insertion times were calculated from the Boothroyd Dewhurst Insertion and Handling charts. Each table takes into consideration both handling and insertion time for its components, it also shows the coordinates that were used on the chart to obtain the time. It should be noted that our hedgehog concept is a compact, non-complex device, additionally we also used many OTS parts that do not require assembly which is why our overall assembly time came out to be low. Some of the most complex systems to assemble would be the gantry and the climate control, which are both OTS, and saves a lot of time. None of the subsystems require complex tools to assemble and the assembly can be done by one person since the device is small. The total assembly time came out to 14.2 minutes. Assembly labor rates are estimated to be $56.74/hr, therefore the total cost to assemble is $13.43

K. Total Cost

The total cost of the system includes the purchase order, assembly cost, manufacturing labor cost, and manufacturing tooling cost. The total calculated cost is $7064.58.

L. Material Selection

Subsystem	Part	Description
Enclosure	Exterior Front	ASTM A36 Steel
Enclosure	Exterior Back	ASTM A36 Steel
Enclosure	Exterior Bottom	ASTM A36 Steel
Enclosure	Exterior Top	ASTM A36 Steel
Enclosure	Back Insulation	Polyurethane Foam Rigid
Enclosure	Left Insulation	Polyurethane Foam Rigid
Enclosure	Right Insulation	Polyurethane Foam Rigid
Enclosure	4880K199_STANDARD-WALL WHITE PVC PIPE FITTING	Steel
Enclosure	8020 OD/FI Attachment	Aluminum
Enclosure	Attachment Bracket	ASTM A36 STEEL
Enclosure	ENCLOSURE MOUNT	ASTM A36 STEEL
Enclosure	EMERGENCY STOP PUSH BUTTON SWITCH	PLASTIC
Enclosure	MOUNTING ADAPTERS FOR DIN RAIL	STEEL
Enclosure	POLYURETHANE RUBBER ADHESIVE BACK BUMPER	RUBBER
Enclosure	CLAMP END LATCH	ASTM A36 STEEL
Enclosure	LATCH TOGLE CLAMP	STEEL
Enclosure	FRONT INTERIOR PANEL	ASTM A 36 STEEL
Enclosure	FRONT WALL INSULATION	PLOYURETHANE FOAM RIGID
Enclosure	DOOR ASSEMBLY	ASTM A36 STEEL
Enclosure	RIVET ASSEMBLY	BRASS
Enclosure	BLACK OUT SHIELD	CUSTOM PLASTIC
Enclosure	WINDOWS BLINDS CASE	CUSTOM PLASTIC
Enclosure	M5 BUTTON HEAD SCREW	STEEL
Enclosure	97763A816 BLACK OXIDE 18-8 BUTTON HEAD CAP SCREW	STAINLESS STEEL
Liquid Handling	PIPPETE GANTRY MOUNT	ASTM A36 Steel
Liquid Handling	20 x 20mm V-SLOT 150mm enclosure attachment	Aluminum
Liquid Handling	NEMA 17 MOTOR HOLDER	Steel
Liquid Handling	NEMA 17 Control DC Motor	Steel
Liquid Handling	Flexible Coupling 0.25in x 8mm	6061-T6
Liquid Handling	Piston	AISI316 Stainless Steel
Liquid Handling	Alignment Ring	Plastic
Liquid Handling	Pipette	Acrylic
Liquid Handling	Seal	ABS
Liquid Handling	Pipette Mount	ASTM A36 Steel
Liquid Handling	Lead Screw Mount	ASTM A36 Steel
Liquid Handling	7549K550_RIGHT HAND PRECISION ACME SCREW	Steel

Liquid Handling	Pipette Tip	Acrylic
Liquid Handling	MACRON DYNAMICS-MGS-PSC-12	6061 ALUMINUM ALLOY
Liquid Handling	97763A816_BLACK-OXIDE 18-8 SS BUTTON HEAD CAP SCREW	ALUMINUM
Liquid Handling	LIQUID RESEVOIR	ALUMINUM BRONZE
Liquid Handling	TIP REFILL	ALUMINUM
User Interface	ARDUINO	VARIOUS PLASTIC
User Interface	LCD SCREEN	PLASTIC FILM
User Interface		
Climate Control	02A109-00	STEEL
Climate Control	DIRECT DRIVE LOW PROFILE WALL EXHAUST FAN	ALUMINUM
Climate Control	316mm EXHAUSTER SEAL	RUBBER
Climate Control	OUTER COOLER	STEEL
Climate Control	M6 BUTTON HEAD HEX DRIVE SCREW	ZINC
Gas Control	5350K320_ZINC-PLATED STEEL BARBED HOSE FITTING	Steel
Gas Control	4711K513_BRASS SOLENIOD VALVE	Brass
Gas Control	50715K192_TYPE 316 SS DEGREE FLARED TUBE FITTING	Steel
Gas Control	530K230_ZINC PLATED STEEL BARBED HOSE FITTING	Steel
Gas Control	Gas Control Box	ASTM A36 Steel
Gas Control	93303A107_ARAMID-BUNA-N SEALING WASHER	Rubber
Gas Control	5233K560_MASTERKLEER PVC TUBING	PVC .007 Plasticized
Gas Control	SURFACE MOUNT HINGE	1023 CARBON STEEL SHEET
Gas Control	GAS BOX DOOR	ASTM A36 STEEL
Gas Control	LABEL	PLASTIC, ADHESIVE
Gas Control	40mm FAN	ALUMINUM
OD/FI	OD/FI Filter Cube	Plastic
OD/FI	92949A106_18-8 SS BUTTON HEAD HEX DRIVE SCREW	Steel
OD/FI	Bracket	ABS
OD/FI	LIGHT BRACKET	ABS
OD/FI	RED BOARD	ABS PC
OD/FI	WHITE LED	GLASS
OD/FI	TOP COVER	ABS
OD/FI	9249A537_18-SS BUTTON HEAD HEX DRIVE SCREW	STEEL

Shaker	SHAKER TABLE	ASTM A36 STEEL
Shaker	SHAKER BASE	ASTM A36 STEEL
Shaker	WELL PLATE HOLDER	ASTM A36 STEEL
Shaker	LED BOX	CUSTOM PLASTIC
Shaker	CERAMIX COATED ALUMINUM SHAFT SUPPORT BALLS	ALUMINUM
Shaker	MOUNTED LINEAR BALL BEARING	ALUMINUM
Shaker	MIDDLE PLATE	ASTM A36 STEEL
Shaker	COMPRESSION SPRING	ALUMINUM
Shaker	TOP LAYER PLATE	ASTM A36 STEEL
Shaker	6627T330 POSITION CONTROL DC MOTOR	ALUMINUM
Shaker	6331K860 COMPACT ROUND FACE DC MOTOR	ALUMINUM
Shaker	CAM SHAFT	ALUMINUM
Shaker	SOLID BAR	ASTM A36 STEEL
Shaker	MOTOR SLEEVES	ASTM A36 STEEL

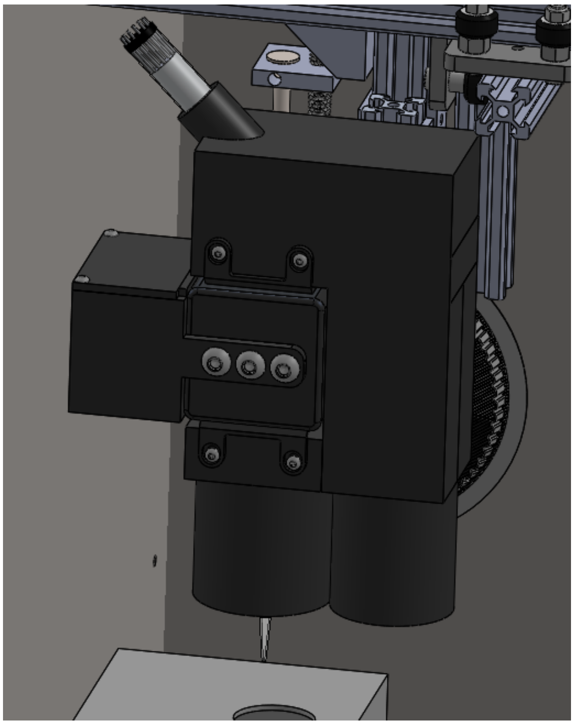


Figure 34: OD/FI Reader

M. Changes Made

N. Critical Parts Engineering Analysis

Enclosure: Minimum Insulation Thickness
The heat flux within the enclosure is important to find the temperature of the surfaces of the material during operation.. This design uses a composite wall of steel sheet, XPS insulation, and Steel sheet sandwiched together. The thermal conductivity of XPS is 0.031 W/Km and Steel sheet is 2 W/Km. Assuming air convection inside the system at a max temperature of 70 degrees Celsius. and the surrounding environment is at room temperature of 22 degrees Celsius. The steel sheets have a thickness of 3mm[23].
This figure shows the general setup for this composite wall, where the following equations can be used to find the heat flux.

$$\begin{gathered} q'' = \frac{T_{\infty,1} - T_{\infty,2}}{R''_{tot}} = \frac{T_{\infty,1} - T_{\infty,2}}{\left[\frac{1}{h_1} + \frac{L_A}{K_A} + \frac{L_B}{K_B} + \frac{L_C}{K_C} + \frac{1}{h_4}\right]} \\ q'' = \frac{T_{s,4} - T_{\infty,2}}{\frac{1}{h_4}} = \frac{44-22}{0.5} = 44 \text{ W/m\^{}2} \end{gathered} \tag{68}$$

To find the heat flux, the thermal resistivity must be considered for each mode of heat transfer. The thermal resistivity must be considered for the fluid environment, steel sheet, and XPS.

$$\begin{gathered} R_1 = R_4 = \frac{1}{h} = \frac{1}{2} = 0.5 \text{ W/K} \\ R_A = R_c = \frac{L}{K} = \frac{0.003}{45} = 6.67e - 5 \text{ W/K} \\ R_B = \frac{L_B}{K_B} = 32.26 \text{ L} \end{gathered} \tag{69}$$

By relating each of the equations with each other, the minimum thickness can be calculated as:

$$\begin{gathered} \frac{44-22}{0.5} = \frac{70-22}{1.000133 + 32.6L} \\ L = 2.88 \text{ mm} \end{gathered} \tag{70}$$

Liquid Handling: Aerosols confirmed with Reynold's number
Aerosols are microscopic particles in the air and can carry chemical, biological, radioactive, and other elements. All laboratory procedures must be conducted with the utmost care to avoid the formation of aerosols. Therefore, the liquids from the pipettes must always be smoothly disposed. This concept's Reynold's number needed to be determined to identify the fluid behavior. The Reynold's number was compared to 2300, characterized to be turbulent flow. The calculations and results can be seen below, where is the density of the fluid, u is the flow speed, D is the pipette tip diameter, and µ is the dynamic viscosity of the fluid.

$$Re = \frac{\rho u D}{\mu} \tag{71}$$

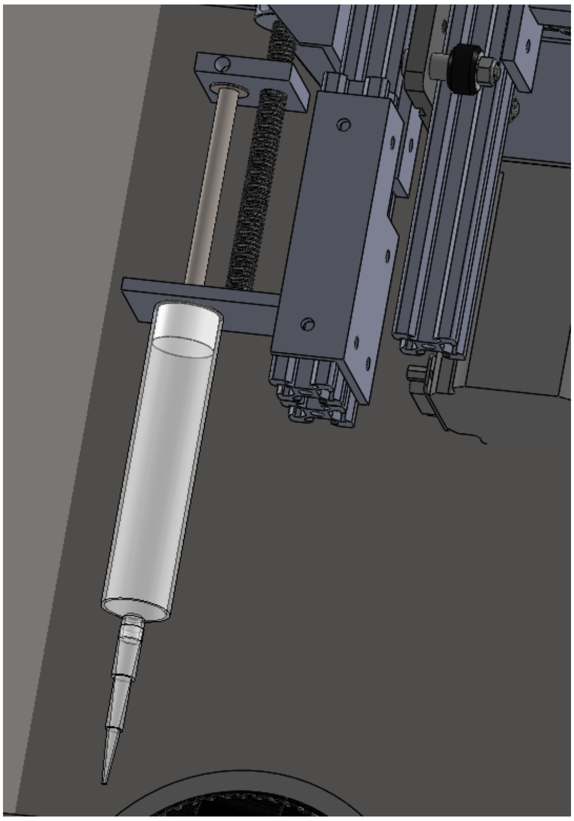


Figure 35: Liquid Handling System

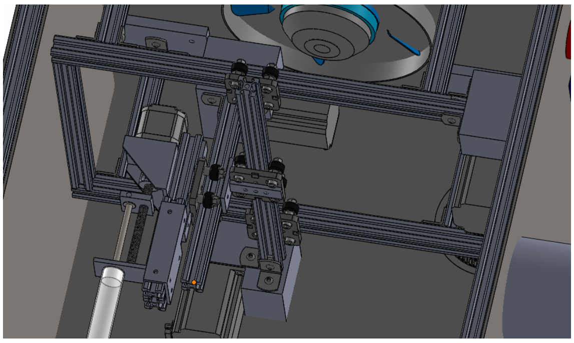


Figure 36: Gantry System

For our design:

$$Re = \frac{997\frac{\text{kg}}{\text{m}^3} * 1.87\frac{\text{m}}{\text{s}} * 0.00046 \text{ m}}{0.00108\frac{\text{kg}}{\text{m}\cdot\text{s}}} = 794 \tag{72}$$

Liquid Handling: Flow Rate
The subsystem needs to achieve a dispense rate, or a flow rate, from 225 uL/s to 300 uL/s. First, velocity was calculated from the step motor specifications, where r is the pipette radius, and RPM is the revolutions per minute specified on the motors.

$$V = \frac{2\pi}{60} * r * RPM \tag{73}$$

Then, the flow rate was estimated by the following equation, where V is the velocity and A is the pipette tip area.

$$Q = VA \tag{74}$$

For our design:

$$\begin{gathered} V = \tfrac{2\pi}{60} * .00794 \text{ m} * 2250\tfrac{\text{rev}}{\text{min}} = 1.87\tfrac{\text{m}}{\text{s}} \\ Q = 1.87\tfrac{\text{m}}{\text{s}} * 0.000000166 \text{ m}^2 = 03.11\tfrac{\text{m}^3}{\text{s}} = 311\tfrac{\mu L}{\text{s}} \end{gathered} \tag{75}$$

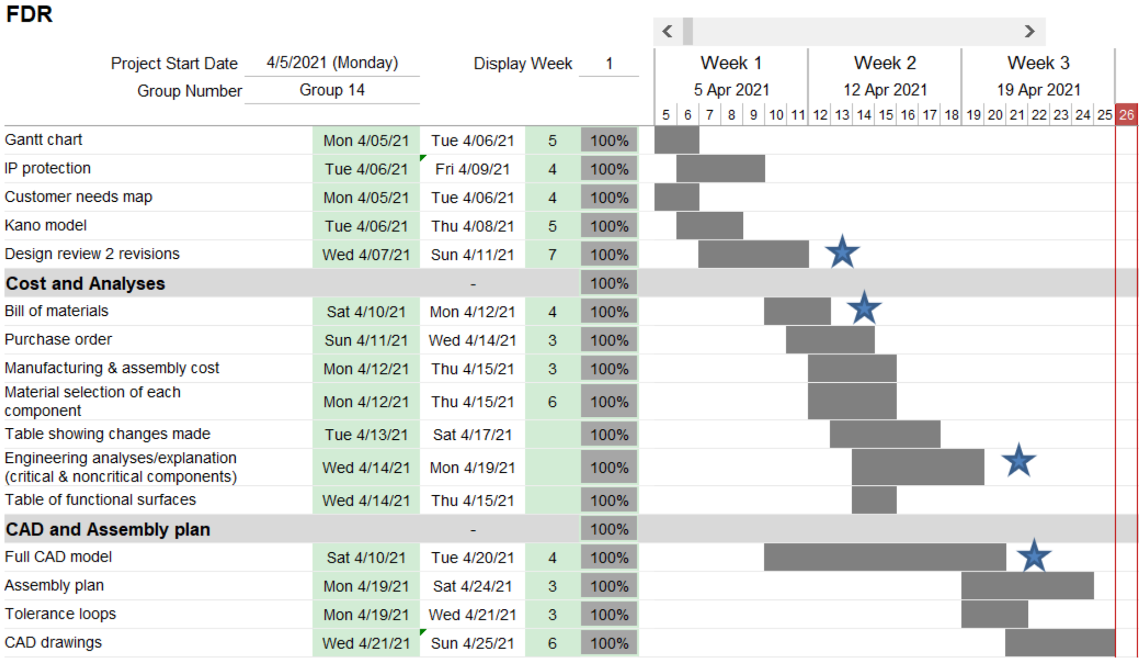


Figure 37: Gantt chart

Process	Unit Cost	Unit	QTY	Total Price
Machining Setup, Change	$ 0.65	unit	6	$ 3.90
Drilled holes < 25.4 mm dia.	$ 0.35	hole	40	$ 14.00
Hand Finish - Material Removal	$ 0.20	cm^3	2	$ 0.40
Hand Finish - Surface Preperation	$ 0.02	cm^2	3	$ 0.06
Knurling	$ 0.10	cm	6	$ 0.60
Threading, Internal (machining)	$ 0.10	cm	2	$ 0.20
Sheet metal bends	$ 0.25	bend	6	$ 1.50
Tube cut	$ 0.15	cm	4	$ 0.60
3D Printing	$ 0.40	cm	134.2	$ 53.68
			Total:	**$ 74.94**

]

Figure 38: Manufacturing Tooling Cost Table

Liquid Handling: Dispense Accuracy

In order to determine the dispense accuracy, first the steps per revolution must be found. The motor step angle is $\pm 0.5°$. Thus, there are 7200 steps per revolution. The lead is 3.175 mm meaning that,

$$\frac{3.175}{7200} = 0.000411 mm/steps \tag{76}$$

This means that the cross sectional area is 0.00014m^2.

Thus, the dispense accuracy was calculated as follows:

$$0.000411 * 10^{-3} * 0.00014 = 6.17 * 10^{-11}\text{m}^3 = \pm 0.06\mu L \tag{77}$$

User Interface: Stress on Emergency Shut Off Button

The engineering analysis done for this subsystem was to calculate the stress on the emergency shut off button. The emergency shut off button will be hit by the user in order to stop the system. To calculate the stress that the force of the user causes on the emergency shut off the average force of a human slap from the side was used [26]. Three different stresses were calculated using the maximum, average, and minimum forces of a human slap from the side. The calculations are detailed below.

Process	Labor time	Total cost
Machining setup	15 minutes	$14.19
Drilled holes< 25.4 mm dia.	25 minutes	$22.70
Hard finish- Material removal	1.5 hours	$85.11
Hard finish- Surface preparation	1 hour	$56.74
Threading, Internal (machining)	1 hour	$56.74
Sheet metal bends	8.3 minutes	$7.85
Waterjet cut	1.5 hours	85.11
	Total	**$328.44**

]

Figure 39: Manufacturing Labor Cost Table

Part	Time (2 weeks)	Energy(KJ/H)	Cost ($/KwH)	Full Cost
LED Panel	336	0.063	0.1142	$2.42
Gantry	336	1.44	0.1142	$55.25
Liquid Handling Motor	336	0.56	0.1142	$21.49
Shaker Motors	336	0.78	0.1142	$29.93
PMT Detector	336	0.11	0.1142	$4.22
Xenon Lamp	336	0.045	0.1142	$1.73
LED Screen	336	0.073	0.1142	$2.80
Heating Unit	336	2.12	0.1142	$81.35
Cooling Unit	336	1.65	0.1142	$63.31
			Total:	**$262.50**

]

Figure 40: Energy Cost Table

$$\sigma = \frac{F}{A} = \frac{6000.8N}{0.0079m} = 0.76MPa \tag{78}$$

$$\sigma = \frac{F}{A} = \frac{4582.3N}{0.0079m} = 0.58MPa \tag{79}$$

$$\sigma = \frac{F}{A} = \frac{3163.8N}{0.0079m} = 0.40MPa \tag{80}$$

From the material selection section, the material for this component was determined to be ABS. The yield stress of ABS was found to be 48.3 MPa [13]. This value will be used to find the factor of safety using all three stresses.

$$n = \frac{Sy}{\sigma} = \frac{48.3}{0.76} = 63.55 \tag{81}$$

$$n = \frac{Sy}{\sigma} = \frac{48.3}{0.58} = 83.27 \tag{82}$$

$$n = \frac{Sy}{\sigma} = \frac{48.3}{0.40} = 120.75 \tag{83}$$

Doing these calculations it was proven that the emergency shut off button will not fail even with a high force being applied by the user.

Climate Control: Time Required to Heat and Cool Cultures

The goal of this analysis is to determine if the current climate control system is capable of meeting the heating and cooling requirements set by the customer. Chief among these is the request that the climate control system be capable of reaching a given setpoint – in the range 4 Celsius to 70 Celsius – in under 15

Subsystem	Part/Smaller Subsystem	Description of Change
Enclosure	Frame	Removed 80/20 from frame
Enclosure	Gantry	Implemented OTS gantry
Gas Control	Tubing	Changed from PVC to vinyl tubes to connect the system to the enclosure
Shaker	Cam Shafts and Motors	Rotated orientation of the cam shafts and motors so that the shaker is no longer shaking three dimensionally

Figure 41: Changes After Design Review 1

Subsystem	Part/Smaller Subsystem	Description of Change
Enclosure	Window	Added a shutter to block light from getting in when taking OD/FI measurements
Enclosure	Door	Increased size of hatch door to allow more user accessibility
Climate Control	Heating and Cooling	Found OTS parts so system would have separate heating and cooling
Shakers	DIN Rails	Removed DIN rails since shaker is easily accessible through doors. Opted to bolt down subsystem to enclosure

Figure 42: Changes After Design Review 2

minutes.

This analysis is broken down into three parts. The first considers the heating and cooling of conical tubes. Since the 50 mL conical tube is likely to be the most demanding on the heating system, it alone will be analyzed – with the assumption that, if the climate control system is capable of meeting the heating and cooling needs of the 50 mL conical tube, it could meet those needs for smaller conical tubes with even greater ease.

The second part of this analysis considers the heating and cooling needs of the skirted well plate. The skirted well plate will be analyzed as a flat plate in parallel flow. Further, in both the skirted and unskirted configuration, we will be analyzing the 6-well configuration, as it is likely the most demanding configuration in terms of heating and cooling requirements.

Part 1: Conical Tubes

The heat transfer analysis for conical tubes will be approximated as a cylinder in cross flow with different internal and external fluids. In our case, the external fluid is the gas which composes the atmosphere within the enclosure, and the internal fluid is the cell culture.

For this computation, the external fluid will be assumed to have the composition typical of air. However, since this device allows atmospheric composition to be manipulated by the end user, the controller for this device should consider the difference in heat transfer properties between air and other potential gaseous compositions – in order to accurately and precisely control the power supplied to the climate control system in a given situation.
Additionally, this computation will assume that the thermodynamic properties of cultures are equivalent to those of water. Since the chemical composition of cell cultures is largely water, this assumption should sustain, and should not introduce meaningful error into these computations.
Conduction
For a hollow cylinder, conduction occurs between the inner and outer surfaces. The conductive heat transfer rate between these surfaces can be determined using the following equation:

$$q_r = \frac{2\pi Lk\left(T_{s,1} - T_{s,2}\right)}{\ln\left(\frac{r_2}{r_1}\right)} \tag{84}$$

From this equation, it is also clear that the thermal resistance is of the form:

$$R_{t,cond} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi Lk} \tag{85}$$

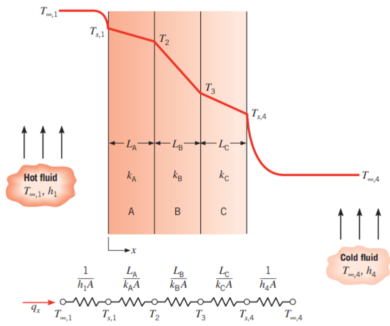


Figure 43: One-Dimensional Composite Wall

The next step in determining the heat transfer rate is to determine the conductive heat transfer coefficient between the inner surface of the cylinder and the internal fluid. We will be assuming the heat transfer coefficient between the interior surface of the tube and the culture within is unchanged by the mixing operations which occur, thus the heat transfer coefficient of relevance here is the conductive heat transfer coefficient. In reality, this will likely give us an underestimation of the true heat transfer rate. For water, the conductive heat transfer rate at an ambient temperature of 293K and atmospheric pressure is 0.5918 W/m/K [5]. Further, the length of heat transfer will be half of the diameter of the conical tube, as that is the length over which heat must be transferred to completely heat the culture within.
Convection Convection occurs when air flows over the outside of the conical tube between the air and the outer surface of the tube. For typical convection, the heat transfer rate can be found using:

$$q = hA\left(T_{\infty} - T_s\right) \tag{86}$$

However, for the case of external cross flow over a cylinder, special considerations need to be made to determine the convective heat transfer coefficient. The convective heat transfer coefficient can be determined using the Nusselt number and the Zukauskas relation:

$$\bar{h} = \frac{Nu_d k}{D} \tag{87}$$

The Nusselt number can be determined using the following equation:

$$\overline{Nu_d} = CRe_D^m Pr^n \left(Pr \backslash Pr_s\right)^{\frac{1}{4}} \tag{88}$$

To determine the Reynolds number used in the equation above we use the formula below, where all properties are evaluated at an ambient temperature of 70 Celsius, or approximately 350 K:

$$Re_D = \frac{VD}{v} \tag{89}$$

Using the specifications of the fan heater selected previously, we can determine the air velocity using the volumetric flow rate and the area of flow. From the spec. sheet of the heater, the flow rate is 31 cubic meters per hour, and the flow area is 0.082 m by 0.110 m, or 0.00902 square meters. Solving for air flow rate in meters per second:

$$V = 31\left[\frac{m^3}{hr}\right] * \frac{1}{0.00902}\left[\frac{1}{m^2}\right] * \frac{1}{3600}\left[\frac{hr}{sec}\right] = 0.955\left[\frac{m}{s}\right] \tag{90}$$

Additionally, the diameter of the tube is known to be 0.03 m, and the viscosity of air at ambient temperature is 20.92*$10^(- 6) m^2/s$[5].

Therefore, the Reynolds number can be calculated:

$$Re_D = \frac{0.955\left[\frac{m}{s}\right] * 0.03[m]}{20.92 * 10^{-6}\left[\frac{m^2}{s}\right]} = 1369.503 \tag{91}$$

From Bergman et. al, the constants 'c' and 'm' in the Nusselt number equation for Reynolds numbers between 1000 and 200,000 are 0.26 and 0.6, respectively. Also, since 'Pr' is under 10, 'n' is 0.37. 'Pr' is 0.700 at the ambient temperature of 350 K, and 'Pr' for the surface is 0.707, at a surface temperature of 25 Celsius, or roughly 300 K [5]. The Nusselt number can then be calculated:

$$\overline{Nu_d} = 0.26(1369.503)^{0.6}(0.700)^{0.37}(0.700\backslash 0.707)^{\frac{1}{4}} = 17.319 \tag{92}$$

Finally, we can determine the convective heat transfer coefficient using the Zukauskas relation:

$$\bar{h} = 17.319 * 30 * \frac{10^{-3}\left[\frac{W}{m*K}\right]}{0.03[m]} = 17.319\left[\frac{W}{m^2 * K}\right] \tag{93}$$

Typical convective heat transfer coefficients for air under forced convection range of 10 to 1,000 W/(m^2K).

Therefore our estimation is on the low side of this range. Possible improvements to this value will be explored later in this paper. With this information, it is possible to setup a thermal circuit to determine the heat transfer rate between the ambient environment and the cultures.
A graphic representation of the thermal circuit is presented in the figure below.

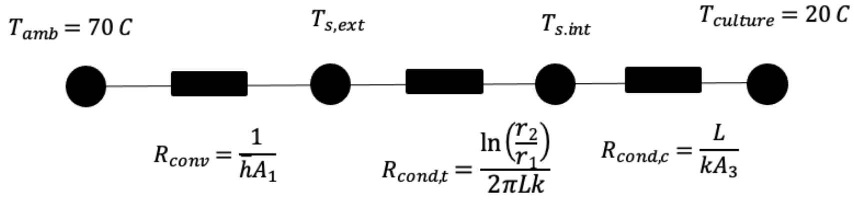


Figure 44: Thermal Circuit Between Ambient Environment and Cultures

A few other prerequisite calculations are required to solve for the heat transfer rate. First, we must know the inner and outer surface areas of the conical tube. For a 50 mL conical tube with dimensions 30 mm by 115 mm and thickness of 2 mm, we can solve for the inner, outer, and mean surface heat transfer areas. Setting up the equations and solving:

$$A_1 = \pi d_o h = \pi * 30[mm] * 115[mm] = 10,838.49\left[mm^2\right] \tag{94}$$

$$A_3 = \pi d_i h = \pi * 26[mm] * 115[mm] = 9393.36\left[mm^2\right] \tag{95}$$

Further, the inner and outer radii of the tube, the length of the tube, and the length of conduction for conduction within the container are required. The inner and outer radii of the tube are 15 mm and 13 mm, respectively. The length of the tube is 115 mm, and the length for internal conduction is 13 mm [3]. Finally, we need the thermal conductivities of the conical tube and the cell culture. For the conical tube, we will be assuming it is made of polypropylene (PP). PP has a reported range of thermal conductivities from 0.11 to 0.22 W/m/K [1]. We will be using the average of this range, 0.165 W/m/K. The thermal conductivity of the culture is assumed to be equal to that of water at 1 bar of pressure and 293 K, which is 598.03 W/m/K. Plugging in these values, we solve for the heat transfer rate:

$$q = \frac{T_{amb} - T_{culture}}{R_{tot}} \tag{96}$$

$$R_{tot} = R_{conv} + R_{cond,t} + R_{cond,c} \tag{97}$$

$$R_{conv} = \frac{1}{\bar{h}A_1} = \frac{1}{17.319\left[\frac{W}{m^2*K}\right] * 1.084 * 10^{-2}\left[m^2\right]} = 5.327\left[\frac{K}{W}\right] \tag{98}$$

$$R_{\text{cond },t} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi Lk} = \frac{\ln\left(\frac{15}{13}\right)}{2\pi * 0.115[m] * 0.165\left[\frac{W}{m*K}\right]} = 1.200\left[\frac{K}{W}\right] \tag{99}$$

$$R_{\text{cond },c} = \frac{L}{kA_3} = \frac{0.013[m]}{598.03\left[\frac{W}{m*K}\right] * 9.393 * 10^{-3}\left[m^2\right]} = 2.313 * 10^{-3}\left[\frac{K}{W}\right] \tag{100}$$

$$R_{tot} = 5.327\left[\frac{K}{W}\right] + 1.200\left[\frac{K}{W}\right] + 2.313 * 10^{-3}\left[\frac{K}{W}\right] = 6.529\left[\frac{K}{W}\right] \tag{101}$$

$$q = \frac{343[K] - 293[K]}{6.529\left[\frac{K}{W}\right]} = 7.658[W] \tag{102}$$

Using this data, we can complete the computation of time required to heat the cultures by utilizing the heat load equation.

$$Q = mc\Delta T \tag{103}$$

For this calculation, we require the heat load of the culture and the container. Therefore, we must know the temperature differential, the specific heats, and the masses of both the culture and the 50 mL conical tube. In each case, we are assuming a temperature differential of 50 K. Polypropylene has a specific heat of

1920 J/kg/K, and a 50 mL conical tube has a mass of 47.91 g. Water has a specific heat of 4150 J/kg/K, and 50 mL of water has a mass of 50 g [2] [4]. Therefore, we can calculate the heat load of the filled conical tube by calculating the two heat loads independently and adding them:

$$Q_w = 0.05[kg] * 4150 \left[\frac{J}{kg * K}\right] * 50[K] = 10,375[J] \\ Q = mc\Delta T = mc \int_{\Delta T=50}^{\Delta T=0} d\Delta T \tag{104}$$

$$Q_t = 0.04791[kg] * 1920 \left[\frac{J}{kg * K}\right] * 50[K] = 4599.36[J] \tag{105}$$

$$Q = 10,375[J] + 4599.36[J] = 14.974[kJ] \tag{106}$$

Up to this point, we have made the working assumption of steady status. That is, the temperature differential is unchanging during the heating process. However, this is obviously not the case. The temperature differential is constantly decreasing during the heating process, approaching zero as equilibrium is reached. This concept can be represented by converting the heat transfer rate from a discrete value to a continuously changing value that varies with the temperature differential, as in:

$$q = \frac{\Delta T}{R_{tot}} = \frac{1}{R_{tot}} * \int_{\Delta T=50}^{\Delta T=0} d\Delta T \tag{107}$$

Further, the heat load calculations also change with respect to a changing temperature differential. This can be represented as in:

$$Q = mc\Delta T = mc \int_{\Delta T=50}^{\Delta T=0} d\Delta T \tag{108}$$

When solving for the time required to heat, we can see that these two continuously variable components cancel one another out. In plain terms: although the heat transfer rate is steadily decreasing as the temperature differential decreases, the heat load decreases at the same rate, leaving the time required to reach the desired temperature as a solvable constant. Finally, we can determine the time required to heat by dividing the heat transfer rate by the heat load:

$$t = \frac{14.974 * 10^3[]}{7.658\left[\frac{J}{s}\right]} = 1955.34[s] \tag{109}$$

This time exceeds the allotted time to heat the cultures. The time above is roughly 33 minutes, and the requested time is 15 or fewer minutes. Therefore, we must determine a way to improve the heat transfer rate. Referring to the calculations, the process with the greatest thermal resistance is the convection process. It is possible to improve the heat transfer rate of the convection process by increasing the air flow rate over the conical tube. This can be achieved by adding a high-powered fan blowing air directly over the conical tube.
The following graph illustrates the relationship between air flow rate and time required to reach the setpoint.

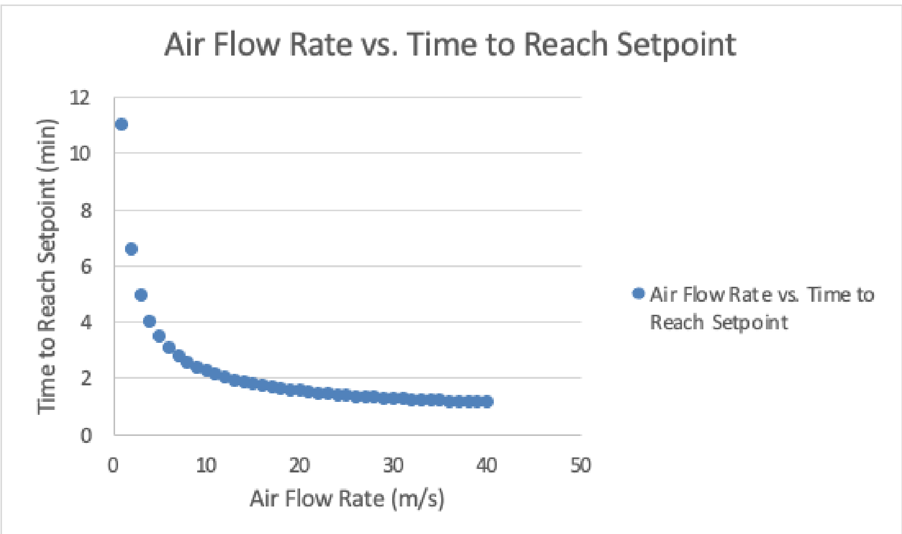


Figure 45: Time Required to meet Setpoint

From this graph, it is evident that a fan of around 5 m/s or so should reach the setpoint in under 15 minutes. However, since the calculations above rely on the assumption that the ambient temperature within the enclosure has already reached the setpoint, we should aim to select a fan that can heat the

cultures in less than 15 minutes.
Before selecting a fan, it is wise to determine the amount of time required for the ambient temperature within the enclosure to reach the setpoint. This can be done with a simple heat load calculation considering the air within the enclosure. The enclosure has dimensions of 0.5 m by 0.5 m by 0.65 m, giving an enclosure volume of 0.1625 cubic meters. The specific heat of air is 1.005 kJ/kg/K, and the mass of 0.1625 cubic meters of air is 0.1957 kg [5]. Further, the temperature differential is 50, solving:

$$Q = mc\Delta T = 0.1957[\text{ kg}] * 1.005\left[\frac{\text{kJ}}{\text{kg}*\text{ K}}\right] * 50[\text{ K}] = 9.83[\text{ kJ}] \tag{110}$$

For our 200 W heater, we can solve for the time to reach the setpoint as:

$$t = \frac{Q}{q} = \frac{9.83 * 10^3[\text{ J}]}{200\left[\frac{J}{\text{J}}\right]} = 49.16[s] = 0.8194[\text{ min}] \tag{111}$$

As an aside, numerous components within the enclosure generate heat. In practice, the process of achieving an ambient enclosure temperature equal to the setpoint is likely to take even less time than this. Therefore, we must select a fan that can achieve the setpoint in about 14 minutes. From the data in the graph above, a fan with a flow rate of 7 m/s can reach the ambient temperature in 14.05 minutes.

Part 2: Skirted Well Plates
One final, additional consideration must be made for the case of skirted well plates. skirted well plates behave more like flat planes during the heating and cooling process, as opposed to the unskirted well plates. It is expected that skirted well plates will have lower heat transfer rates.
Some of the calculations from Part 2 are still relevant. Namely, those concerning the heat load are unchanged in this section. However, a new approach to determining the heat transfer rate is required. This approach will be based on the flat plate in parallel flow outlined in Bergman et. al.
To begin, we will determine the thermodynamic properties of air at the ambient heating temperature of 70 C. These are: v=20.92*10$^($ $-6)m^2/s, k = 30 * 10^(-3)W/(m * K), Pr$ [U+2061][= 0.7005].

We must determine the convective heat transfer rate using the Nusselt number:

$$\bar{h} = \frac{\overline{Nu_L} k}{L} \tag{112}$$

We can solve for the Nusselt number using the Reynolds number. The correct correlation depends on the flow regime, we can solve for the Reynolds number using:

$$Re = \frac{u_\infty L}{v} \tag{113}$$

The most likely flow regime for our application is turbulent. Therefore, we can use the following correlation to solve for the Nusselt number for a flat plate with constant heat flux:

$$Nu_x = 0.0308 Re_x^{\frac{4}{5}} Pr^{1/3} \tag{114}$$

Additionally, it is necessary to consider the process of conduction through the well plate itself, and through the culture. Similar to part 1 of this analysis, we can construct a thermal circuit:

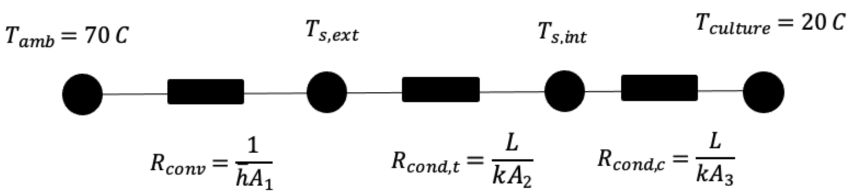


Figure 46: Thermal Circuit for Conduction

The values in the circuit above come from Eppendorf [6] and are the same as those utilized in the previous section in the case of the conduction components of the circuit. Solving the circuit above, we can generate the following graph relating air flow rate to time required to reach the setpoint. For this case, it is evident that a fan speed of about 1 m/s is required to reach the setpoint in under 15 minutes.

Part 4: Cooling
The cooling of this system uses a 200W thermoelectric cooling system to ensure that cooling takes place

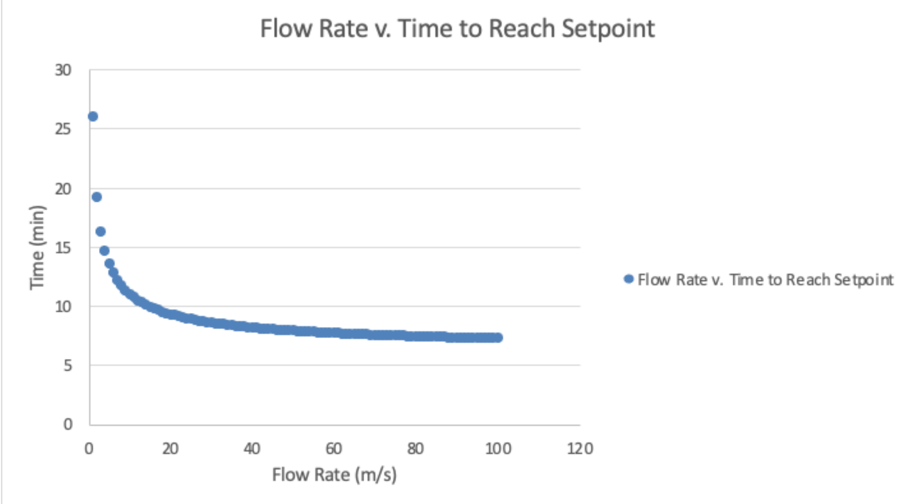


Figure 47: Time Required to meet Setpoint

quickly enough, we can perform similar calculations. First, as before, we will determine the time taken to reach an ambient temperature equal to the setpoint within the enclosure. Note that, although the cooling capacity of the selected device is 200W, 72W of that is dedicated to cooling internal components used by the device, such as motors and lights.

$$t = \frac{Q}{q} = \frac{9.83*10^3[J]}{128[\frac{J}{S}]} = 76.797[s] = 1.28[\text{ min}] \tag{115}$$

Next, we can check the heat transfer rate of the 50 mL conical tube, using the new temperature differential of 16 K, from a base culture temperature of 20 C to a desired minimum temperature of 4 C. It is only necessary to check the heat transfer rate of the conical tube, as any system capable of cooling the conical tube in sufficient time will be capable of cooling the skirted or unskirted well plate even faster.
From the analysis in part one, we can determine the heat load of the filled conical tube when the temperature differential is 16 K:

$$Q_w = 0.05[kg] * 4150\left[\frac{J}{kg*K}\right] * 16[K] = 3320[J] \tag{116}$$

$$Q_t = 0.04791[kg] * 1920\left[\frac{J}{kg*K}\right] * 16[K] = 1471.795[J] \tag{117}$$

$$Q = 3320[J] + 1471.795[J] = 4791.795[J] \tag{118}$$

Some of the calculations in part one rely on the ambient temperature within the enclosure to determine the properties of air. In these cases, it is necessary to rework the calculations to account for the difference. Specifically, the conductive heat transfer coefficients used in the thermal circuit from part one will remain unchanged. However, the convective heat transfer coefficient for a cylinder in cross flow must be reevaluated. The heat transfer rate can be found using:

$$q = hA\left(T_\infty - T_s\right) \tag{119}$$

However, for the case of external cross flow over a cylinder, special considerations need to be made to determine the convective heat transfer coefficient. The convective heat transfer coefficient can be determined using the Nusselt number and the Zukauskas relation:

$$\bar{h} = \frac{\overline{Nu_d}k}{D} \tag{120}$$

The Nusselt number can be determined using the following equation:

$$\overline{Nu_d} = CRe_D^m \Pr^n \left(\Pr \setminus \Pr_s\right)^{\frac{1}{4}} \tag{121}$$

To determine the Reynolds number used in the equation above we use the formula below, where all properties are evaluated at an ambient temperature of 4 Celsius, or approximately 277 K:

$$\text{Re}_D = \frac{VD}{v} \tag{122}$$

Additionally, the diameter of the tube is known to be 0.03 m, and the viscosity of air at ambient temperature is 13.84*10$^($−6)$m^2/s.Therefore,theReynoldsnumbercanbecalculated : FromBergmanet.al,theconstants`c'and`m'intheNusse$

From the data, the time required to reach the setpoint for a fan speed of 5 m/s is 13.60 minutes. Adding this to the time required to reach ambient temperature gives a total cooling time of 14.88 minutes.
Part 5: Conclusion
The analysis above revealed the need for a moderate speed fan to facilitate heat transfer to meet the customer need for rapid heating of cell cultures. Based on a variety of heating scenarios, it was determined that heating and cooling the 50 mL conical tube was the most demanding configuration. Based on the calculations, the climate control system will require the addition of a fan capable of generating air speeds of at least 7 m/s to heat the samples in under 15 minutes. One final note – these calculations rely on the assumption that the process of heating the enclosure to the setpoint and the process of heating the cultures to the setpoint happen one after the other, rather than concurrently. In practice, this means that the climate control system is in fact capable of heating the cultures faster than what the calculations here indicate.

The fan delivers a volumetric flow rate of 25.2 CFM, or 0.01189 cubic meters per second. Further, the fan outlet has dimensions of 1.57" by 1.57". Using this data, we can determine the air flow speed out of the fan:

$$1.57[in] * 1.57[in] * \left(\frac{2.54[\text{ cm}]}{1[\text{in}]}\right)^2 * \left(\frac{1[\text{ m}]}{100[\text{ cm}]}\right)^2 = 1.5903 * 10^{-3}\ [\text{ m}^2] \tag{123}$$

$$\frac{0.01189\left[\frac{\text{m}^3}{\text{s}}\right]}{1.5903 * 10^{-3}\,[\text{ m}^2]} = 7.48[\frac{\text{m}}{\text{s}}] \tag{124}$$

With this fan speed, the process of heating the enclosure from an ambient temperature of 20 C to 70 C will take 0.82 minutes. When the ambient temperature is 70 C, the cultures will reach a temperature of 70 C in 13.72 minutes – giving a total heating time of 14.54 minutes for a 50 mL conical tube. For smaller conical tubes or well plates this time will be reduced.
With this fan speed, the process of cooling the enclosure from an ambient temperature of 20 C to 4 C will take 1.28 minutes. When the ambient temperature is 4 C, the cultures will reach a temperature of 4 C in 11.97 minutes – giving a total cooling time of 13.25 minutes for a 50 mL conical tube. For smaller conical tubes or well plates this time will be reduced.

Gas Control: Velocity Profile
This analysis will determine the velocity profile of the tubes of the gas control system.

$$\tfrac{\partial u}{\partial x} + \tfrac{\partial u}{\partial y} + \tfrac{\partial u}{\partial z} = 0 \tag{125}$$

$$\frac{\partial v}{\partial y} = 0 \tag{126}$$

$$\frac{\partial w}{\partial z} = 0 \tag{127}$$

$$\frac{\partial u}{\partial x} = 0 \tag{128}$$

This reveals that there is no velocity in the X axis and the Y axis. Using the Navier-Strokes Equation, the equation is given:

$$\rho\left(\tfrac{\partial u}{\partial t} + u\tfrac{\partial u}{\partial x} + v\tfrac{\partial u}{\partial y} + w\tfrac{\partial u}{\partial z}\right) = \rho a_x - \tfrac{\partial p}{\partial x} + \mu\left(\tfrac{\partial^2 u}{\partial x^2} + \tfrac{\partial^2 u}{\partial y^2} + \tfrac{\partial^2 u}{\partial z^2}\right) \tag{129}$$

Since we assume steady state, acceleration is zero.

$$\frac{\partial u}{\partial t} = 0 \tag{130}$$

We obtain this value from the continuity equation:

$$\frac{\partial u}{\partial x} = 0 \tag{131}$$

Since velocity only depends on the Y axis u(y):

$$\frac{\partial u}{\partial x} = 0, \frac{\partial u}{\partial z} = 0 \tag{132}$$

Since there is no gravity in the X direction:

$$a_x = 0 \tag{133}$$

From the continuity equation, we know that the first derivative is zero. Therefore, the second derivative must also be zero.

$$\frac{\partial^2 u}{\partial x^2} = 0 \tag{134}$$

Since the velocity only depends on the Y axis u(y):

$$\frac{\partial^2 u}{\partial z^2} = 0 \tag{135}$$

After cancelling the terms above, the following equation is derived:

$$\frac{\partial P}{\partial x} = \mu \frac{\partial^2 u}{\partial y^2}$$
$$Integrating twice we obtain, u(y) = \frac{1}{2\mu}\left(\frac{\partial P}{\partial x}\right) * \left(y^2 - yD\right) \tag{136}$$

$$u(y) = \frac{1}{2\mu}\left(\frac{\partial P}{\partial x}\right) y^2 + C_1 y + C_2 \tag{137}$$

$$B \cdot C \rightarrow y = 0, u = 0 \text{ and } y = D, u = 0 \tag{138}$$

$$C_1 = -\frac{1}{2\mu}\left(\frac{\partial P}{\partial x}\right) h \tag{139}$$

$$C_2 = 0 \tag{140}$$

$$u(y) = \frac{1}{2\mu}\left(\frac{\partial P}{\partial x}\right) y^2 + \left(-\frac{1}{2\mu}\left(\frac{\partial P}{\partial x}\right) D\right) y \tag{141}$$

$$u(y) = \frac{1}{2\mu}(\frac{\partial P}{\partial x}) * (y^2 - yD) \tag{142}$$

Thus it is determined that the velocity profile will not change.

OD/FI

The speed to evaluate the vitals of all the samples in the largest well plate size, is governed by the light flash of the reader and gantry motor speed. The OD/FI reader is approximately 607.63 grams, which is around 1 pound. Therefore, there is an 80% load onto the motor, also accounting for the liquid handling mass. To find the time it takes to for the gantry to carry the OD/FI reader across the well plate, the following equation is used.

$$\frac{\text{Well plate diameter (column } * \text{ rows } + \text{ rows)}}{\text{gantry velocity speed * load velocity}} \tag{143}$$

For our OD/FI Design:

$$\frac{0.0031(24 * 16 + 2)}{0.513 * 0.6} = 61.95 \text{ seconds} \tag{144}$$

Thus, it will take a total of 61.95 seconds to analyze a 384-well plate.

Shakers: Maximum Acceleration of Shaker

This analysis will find the maximum acceleration it will take to cause spillage of the cell cultures. This analysis will also determine the maximum accelerations which the shakers will shake the cell cell culture, thus it will determine if the shaker subsystem will require a lid or not. Since there is no acceleration in the X axis

$$\frac{\partial P}{\partial x} = -\rho \cdot a_x = 0 \tag{145}$$

$$\frac{\partial P}{\partial y} = -\rho \cdot a_y \tag{146}$$

Since there is no acceleration in the Z axis

$$\frac{\partial P}{\partial z} = -\rho \cdot (a_z + g) = -\rho \cdot g \tag{147}$$

$$dP = \frac{\partial P}{\partial x} d_x + \frac{\partial P}{\partial y} d_y + \frac{\partial P}{\partial z} d_z = -\rho \cdot a_y \cdot d_y - \rho \cdot g \cdot d_z = -\rho \cdot (a_y \cdot d_y + g \cdot d_z) \tag{148}$$

$$\frac{\partial P}{\partial z} = -\rho \cdot g \rightarrow \int_{P_2}^{P_1} \partial P = \int_{Z_2}^{Z_1} -\rho \cdot g \cdot \partial z \rightarrow P_1 - P_2 = -\rho \cdot g \,(Z_1 - Z_2) \tag{149}$$

We apply the equation along a plane with constant pressure. The plane chosen is the surface of the liquid, which we know all the plane is at atmospheric pressure. Since there is constant pressure on the surface,

$$dP = 0 \tag{150}$$

$$0 = -\rho \cdot (a_y \cdot d_y + g \cdot d_z) \tag{151}$$

$$a_y \cdot d_y = -g \cdot d_z \rightarrow -\frac{a_y}{g} = \frac{d_z}{d_y}\frac{z}{y} \tag{152}$$

The volume is constant therefore we can find a relationship between the y and the rest of the values. This is represented below:

$$y = 2\frac{h_o L}{H} \tag{153}$$

$$a_y = -g \cdot \frac{Z_2 - Z_1}{Y_2 - Y_1} = -g \cdot \frac{z}{y} = -g \cdot \frac{z \cdot H}{2h_o L} \tag{154}$$

$$P_2 = \rho g \left(Z_1 - Z_2\right) \tag{155}$$

$$y = 2\frac{h_o L}{H} = 2\frac{(4mm)(6.49mm)}{10.3mm} = 5.39mm \tag{156}$$

$$a_y = -g \cdot \frac{z}{y} = -9.81\frac{m}{s^2}\left(\frac{10.3mm}{5.39mm}\right) = 18.745 \text{ m/s}^2 \tag{157}$$

Thus, it was found that the maximum acceleration that will cause the cell cultures to spill over is 18.745 m / s^2.

To ensure that the shakers will not spill over, calculations at the maximum acceleration for the shakers were found for linear, orbital, and double orbital motions as shown below:

For linear motion:

$$v = \tfrac{10900\text{RPM}}{60} * 2\pi * 0.012 \text{ m} = 14.4963\tfrac{\text{m}}{\text{s}} \tag{158}$$

$$\alpha = \frac{\pi(10900\text{RPM})}{1(30)} = 1141.445\frac{\text{rad}}{\text{s}^2} \tag{159}$$

$$a = \alpha r = 1141.445\frac{\text{rad}}{\text{s}^2} * 0.012 \text{ m} = 13.69\frac{\text{m}}{\text{s}^2} \tag{160}$$

For orbital and double orbital motion:

$$\alpha = \frac{\pi(13900\text{RPM})}{1(30)} = 1455.6 \tag{161}$$

$$a = \alpha r = 1455.6\frac{\text{rad}}{\text{s}^2} * 0.012 \text{ m} = 17.47\frac{\text{m}}{\text{s}^2} \tag{162}$$

Thus, since the maximum acceleration that the shakers can reach in linear, orbital, and double orbital motions are less than the the maximum acceleration to cause spillage of the cell cultures, the shakers do not require a lid.

O. Non-Critical Analysis

Enclosure The enclosure subsystem does not have any non-critical analyses since the rest of the parts in the system, the gantry, are off the shelf, thus they have already been tested in a lab environment.

Liquid Handling
An analysis to determine the time to fill 384 well plates were conducted as follows:

$$\text{well volume } = 105\mu L \rightarrow 0.34 \text{ second per well } \rightarrow 130.56 \text{ seconds} \tag{163}$$

$$\frac{(\text{ well diameter })(\text{ wells })}{\text{Gantry velocity}} = \frac{0.0031 \times 384}{0.513} = 2.3 \text{ seconds} \tag{164}$$

Therefore, the time it will take to fill 384 well plates is 132.86 seconds

User Interface
The user interface subsystem does not have any non-critical analyses since the rest of the parts in the system are off the shelf, thus they have already been tested in a lab environment.

Climate Control
The climate control subsystem does not have any non-critical analyses since the rest of the parts in the system are off the shelf, thus they have already been tested in a lab environment.

Gas Control
The gas control subsystem does not have any non-critical analyses since the rest of the parts in the system are off the shelf, thus they have already been tested in a lab environment.
OD/FI
There are two areas for the OD/FI reader that could possibly fail first. The first engineering analysis will cover bolt shear, where the OD/FI reader is connected to the gantry. Considering the stainless steel $\frac{1}{4}$-20 screw, the yield strength is 215 MPa [38]. The tensile area for the screw is 0.0318 in2 or 20.52 mm2 [25]. The mass of the whole OD/FI reader is 607.63 grams, or 5.96 N. Figure 48 visually shows the bolt in shear.

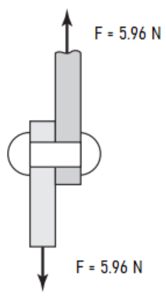


Figure 48: Bolt Shear in OD/FI Reader Mount

To calculate the shear force on the bolt, equation was used:

$$\tau = \frac{F}{A} = \frac{5.96N}{20.52} = 0.290\text{MPa} \tag{165}$$

By considering the tensile strength of the bolt, the factor of safety Is calculated as 741.4, from equation , by diving the yield strength by the shear force. This proves to be of no concern during operation.

$$n = \frac{S_y}{\sigma} = \frac{215}{0.290} = 741.4 \tag{166}$$

Another engineering analysis is performed for the light mount onto the OD/FI reader, as seen in 49. The mass of the light mount is 39.64 grams, or 0.399 N. The cross-section under analysis is the smallest area under stress, where the first screw is located.
The distance from the smallest cross-section to the center of mass of the mount is 30.03 mm. the stress can be calculated as:

$$\sigma = \frac{F}{A} = \frac{0.389N}{38.93} = 0.001MPa \tag{167}$$

The bending stress can also be considered. By using figure and the following equations, the bending stress is calculated as:

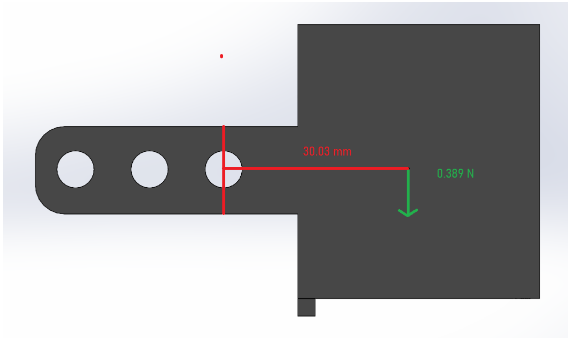


Figure 49: Beam Stress in Light Mount

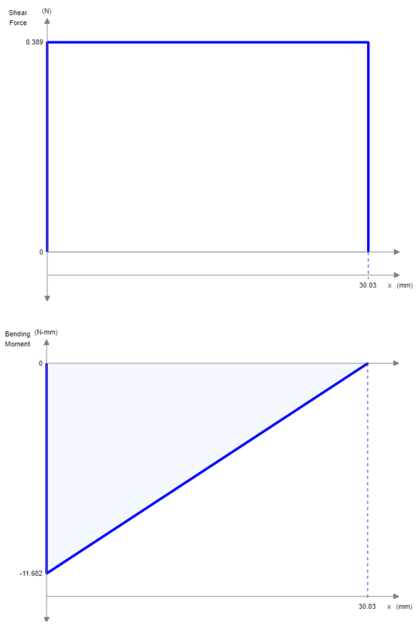


Figure 50: Shear and Bending Diagram

$$\sigma_x = \frac{My}{I} = \frac{11.68*7.5}{965.38} = 0.902\text{MPa}$$
$$y = \frac{h}{2} = 7.5 \text{ mm}$$
$$M = F*x = 11.68 \text{ N} * \text{ mm}$$
$$I = \frac{bh^3}{12} - \frac{\pi r^4}{2} = \frac{4.5*15^3}{12} - \frac{\pi*3.175^4}{2} = 965.38 \text{ mm\^{}4} \tag{168}$$

Since the bending stress has a higher stress than the uniformly distributed stress, the bending stress will be considered for the factor of safety. With a yield strength of 48.2 MPa for abs [14], the factor of safety is calculated as:

$$n = \frac{S_y}{\sigma} = \frac{48.2}{0.902} = 53.42 \tag{169}$$

Shakers

This section will conduct a strength analysis to ensure that the stress of the well tubes on the shaker tray will not cause failure. This analysis will be done similar to the material selection of the shaker trays, which was chosen to be steel.From article 'Interferometric Volume Measurement in Microplates'[18], the upper limit of the mass of a filled well tube is 80 g. Gravitational constant is 9.81 m/s. Area of well tubes, from a top-down view is 706.66 $\text{mm}^2 = 0.00070686m^2$.

Thus, the minimum stress required is

$$\sigma = \frac{\text{F}}{\text{A}} = \frac{0.08\text{kg} * 9.81\frac{\text{m}}{\text{s}^2}}{0.00070686\text{m}^2} = 11102.7\text{MPa} \tag{170}$$

P. Iterative Cycle of Design for Enclosure

The enclosure subsystem experienced significant design changes between the primary design report and the final design report. Many of these changes were completed after further analysis and research on the strength and requirements of the enclosure subsystem for our micro-bioreactor were done. Firstly, the greatest design change was the complete removal of 80/20 aluminum bars from the enclosure framing on walls, floor, and ceiling. In fact, while in the initial design, the enclosure system consisted of approximately 50% 80/20, the only 80/20 in our entire micro-bioreactor design is now found in the liquid handling and ODFI gantry subsystems. The reason behind this design change was to decrease cost as 80/20 aluminum bars tend to fall on the more expensive side. In addition, 80/20 and 80/20 attachments are primarily used for prototyping reasons, therefore, many times after many cycles of use or time passed, the attachments begin to loosen. Instead of using the 80/20 in our new designs, we decided to attach the outer steel plates, insulation plates, and inner steel plates together using rivets decreasing our overall costs and creating a stronger support system more simply.

Another design change between our initial PDR and final FDR submission is the type of steel used for our enclosure walls. While initially we used carbon steel plates, the new design uses 3mm and 2mm A36 steel sheet metal plates. This design change was done after some research in the yield strengths and cost of both steel types. It was found that A36 steel had nearly the same overall strength while sold at a much lower cost. Therefore, our new design once again decreases the cost of the overall Micro-bioreactor system tying back to our hedgehog concept of compactness and energy and cost efficiency.

Finally, another way our enclosure subsystem design improved to better reflect that hedgehog concept was through the alteration of the overall enclosure dimensions and exterior appearance. In our original design, we have a footprint of approximately 520x650mm when including all exterior component and subsystems. Now, by rearranging and reevaluating each subsystem and their components, the new design increased in overall height but decreased the footprint to a 500x500mm square improving overall compactness.

Q. Functional Surfaces

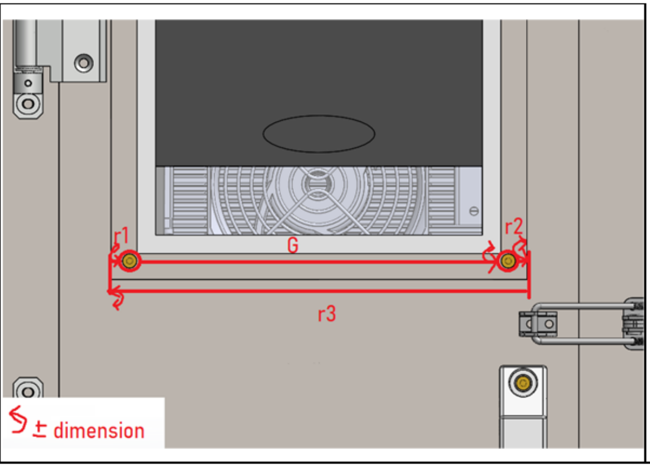
Location	Subsystem	Significance
Screw hole alignment to attach the front door of the assembly	Enclosure	The two holes must be aligned in order for the door to attach to the assembly. If the placement is off, then this can compromise the sealing of the entire enclosure
Solenoid Valve	Gas Control	The solenoid valves must have a gap as they must be able to enter into the enclosure to function properly. The clearance allows for an easy fitting for the sealant.
Screw hole alignment on top of the enclosure	Enclosure	The two holes must be aligned in order for the top lid of the enclosure to attach properly without compromising the sealing of the enclosure.
Screw hole alignment on bottom edge of the enclosure	Enclosure	The two holes must be alighed in order for the bottom lid of the enclosure to attach properly without compromising the sealing of the enclosure
Screw hole alignment on bottom face of the enclosure	Enclosure	The two holes must be alighed in order for the bottom lid of the enclosure to attach properly without compromising the sealing of the enclosure
Gantry housing mount inside of the enclosure	Enclosure	A gap must be located here in order for the gantry to sit comfotably on its mount with any disruption.
Liquid handling and ODFI mount	Enclosure	The two holes must be aligned properly in order for the OD/FI and liquid handling to be installed properly.
Pipette and disposable tip	Liquid Handling	There must be interference in order for the disposable tip of the pipette to function without slippage.
PMT Detector mount	OD/FI	There must be a gap between the PMT detector and ODFI chassis do the PMT can slide in with ease.
FI filter cube mount	OD/FI	There must be a gap between the filter cube and whole ODFI chassis in order for the cube to fit in properly.
FI filter bracket mount	OD/FI	The two holes must be aligned properly in order for the OD/FI to be mounted correctly onto the Chassis.
Well Plate Holder	Shakers	There must be a gap between the well plate mount and well plate so the well plate can be removed and changed easily.
Shaker Spring Conjunction	Shakers	There must be a small gap in order for movement between the well plate and the forced vibration to occur.
Shaker Spring Holder	Shakers	There must be a small gap in order for movement between the well plate and the forced vibration to occur from the spring.
Shaker Motor placement	Shakers	There must be a gap with the motor head pointed in the specified direction in order for the proper movement to occur for the forced vibration.

]

Figure 51: Functional Surfaces

R. Tolerance Loops

Tolerance Loop One



Vector Name	Nominal Dimension	Tolerances		Reference
r1	7.580	+Δx1	0.1270	Machining Handbook
		-Δx1	0.1270	
G	196.330	+Δx2	0.5100	
		-Δx2	0.5100	
r2	7.580	+Δx3	0.1270	Machining Handbook
		-Δx3	0.1270	
r3	211.488	+Δx4	0.2540	Machining Handbook
		-Δx4	0.2540	
		+Δx5		
		-Δx5		
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

Figure 52: Tolerance Loop One [24]

The functional surface being studied in tolerance loop one is Screw hole alignment to attach the front door of the assembly. The interaction between these two can be seen in Figure 52. The general vector equation that dictates the dimensions shown in tolerance loop one is given in the following equation. All dimensions are in millimeters.

$$\left(\vec{r_1} \pm \overrightarrow{\Delta r_1}\right) + \left(\vec{r_2} \pm \overrightarrow{\Delta r_2}\right) + (\vec{G} \pm \overrightarrow{\Delta G}) - \left(\vec{r_3} \pm \overrightarrow{\Delta r_3}\right) = \vec{0} \tag{171}$$

The equation for the minimum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

$$\begin{gathered} G_{\min} = -(r_1 + \Delta r_1) - (r_2 + \Delta r_2) + (r_3 - \Delta r_3) = 0 \\ G_{\min} = -(7.58 + .127) - (7.58 + .127) + (211.488 - .2540) = 195.82 \text{ mm} \end{gathered} \tag{172}$$

The equation for the maximum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values plus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vector to consider the worst-case scenario.

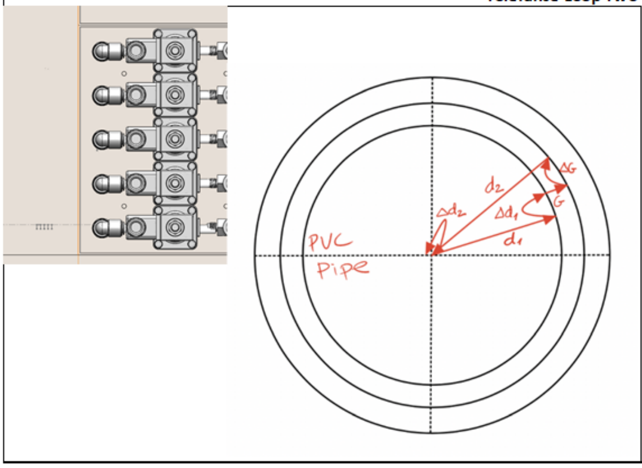
$$\begin{gathered} G_{\max} = -(r_1 - \Delta r_1) - (r_2 - \Delta r_2) + (r_3 + \Delta r_3) = 0 \\ G_{\max =} - (7.58 - .127) - (7.58 - .127) + (211.488 + .2540) = 196.84 \text{ mm} \end{gathered} \tag{173}$$

The gap and the tolerance for the gap can be calculated by using equal distribution:

$$\begin{gathered} \pm \Delta G = \frac{G_{\max} - G_{\min}}{2} = 0.51 \text{ mm} \\ G = \frac{G_{\max} + G_{\min}}{2} = 196.33 \text{ mm} \end{gathered} \tag{174}$$

Tolerance Loop Two

Tolerance Loop Two



Vector Name	(cm) Dimension	Tolerances		Reference
d1	4.445	+Δx1	0.0292	Solenoid Manufacturer's Handbook
		-Δx1	0.0165	
G	0.155	+Δx2	0.0457	
		-Δx2	0.0457	
d2	4.600	+Δx3	0.0165	Solenoid Manufacturer's Handbook
		-Δx3	0.0165	
		+Δx4		
		-Δx4		
		+Δx5		
		-Δx5		
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

]

Figure 53: Tolerance Loop Two [24]

The functional surface being studied in tolerance loop two is the Solenoid Valve. The interaction between these two can be seen in Figure 53. The general vector equation that dictates the dimensions shown in tolerance loop one is given in equation below. All dimensions are in millimeters.

$$\left(\overrightarrow{d_1} \pm \overrightarrow{\Delta d_1}\right) + (\vec{G} \pm \overrightarrow{\Delta G}) - \left(\overrightarrow{d_2} \pm \overrightarrow{\Delta d_2}\right) = \vec{0} \tag{175}$$

The equation for the minimum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

$$\begin{aligned} G_{\min} &= -(d_1 + \Delta d_1) + (d_2 - \Delta d_2) = 0 \\ G_{\min} &= -(4.445 + .0292) + (4.6 - .0165) = 0.1093 \text{ mm} \end{aligned} \tag{176}$$

The equation for the maximum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values plus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vector to consider the worst-case scenario.

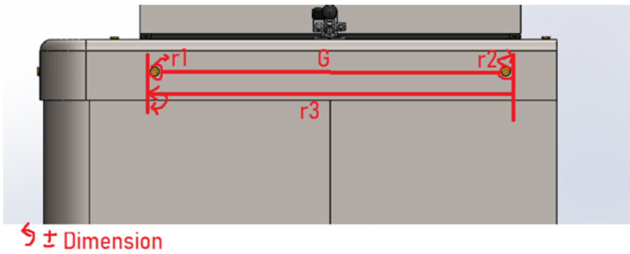
$$\begin{aligned} G_{\max} &= -(d_1 - \Delta d_1) + (d_2 + \Delta d_2) = 0 \\ G_{\max=} & - (4.445 - .0292) + (4.6 + .0165) = 0.2007 \text{ mm} \end{aligned} \tag{177}$$

The gap and the tolerance for the gap can be calculated by using equal distribution:

$$\begin{aligned} \pm\Delta G &= \tfrac{G_{\max} - G_{\min}}{2} = 0.0457 \text{ mm} \\ G &= \tfrac{G_{\max} + G_{\min}}{2} = 0.155 \text{ mm} \end{aligned} \tag{178}$$

Tolerance Loop Three

Tolerance Loop Three



Vector Name	Nominal Dimension	Tolerances		Reference
r1	7.580	+Δx1	0.1270	Machining Handbook
		-Δx1	0.1270	
G	298.388	+Δx2	0.5080	
		-Δx2	0.5080	
r2	7.580	+Δx1	0.1270	Machining Handbook
		-Δx1	0.1270	
r3	313.545	+Δx4	0.2540	
		-Δx4	0.2540	
		+Δx5		
		-Δx5		
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

]

Figure 54: Tolerance Loop Three [24]

The functional surface being studied in tolerance loop three is the screw hole alignment on top of the enclosure. The interaction between these two can be seen in Figure 54. The general vector equation that dictates the dimensions shown in tolerance loop one is given in equation below. All dimensions are in millimeters.

$$\left(\vec{r_1} \pm \overrightarrow{\Delta r_1}\right) + \left(\vec{r_2} \pm \overline{\Delta r_2}\right) + (\vec{G} \pm \overrightarrow{\Delta G}) - \left(\vec{r_3} \pm \overrightarrow{\Delta r_3}\right) = \vec{0} \tag{179}$$

The equation for the minimum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

$$\begin{aligned} G_{\min} &= -(r_1 + \Delta r_1) - (r_2 + \Delta r_2) + (r_3 - \Delta r_3) = 0 \\ G_{\min} &= -(7.58 + .127) - (7.58 + .127) + (313.545 - .2540) = 297.877 \text{ mm} \end{aligned} \tag{180}$$

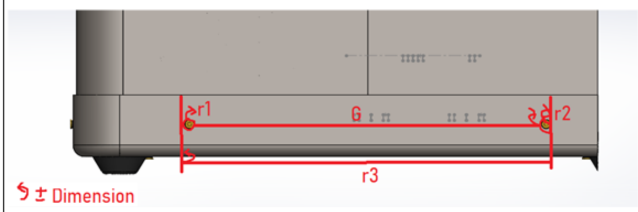
The equation for the maximum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values plus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vector to consider the worst-case scenario.

$$\begin{aligned} G_{\max} &= -(r_1 - \Delta r_1) - (r_2 - \Delta r_2) + (r_3 + \Delta r_3) = 0 \\ G_{\max=} &- (7.58 - .127) - (7.58 - .127) + (313.545 + .2540) = 298.893 \text{ mm} \end{aligned} \tag{181}$$

The gap and the tolerance for the gap can be calculated by using equal distribution:

$$\begin{aligned} \pm\Delta G &= \tfrac{G_{\max} - G_{\min}}{2} = 0.508 \text{ mm} \\ G &= \tfrac{G_{\max} + G_{\min}}{2} = 298.388 \text{ mm} \end{aligned} \tag{182}$$

Tolerance Loop Four



Tolerance Loop Four				
Vector Name	Nominal Dimension	Tolerances		Reference
r1	7.580	+Δx1	0.1270	Machining Handbook
		-Δx1	0.1270	
G	298.388	+Δx2	0.5080	
		-Δx2	0.5080	
r2	7.580	+Δx1	0.1270	Machining Handbook
		-Δx1	0.1270	
r3	313.545	+Δx4	0.2540	Machining Handbook
		-Δx4	0.2540	
		+Δx5		
		-Δx5		
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

]

Figure 55: Tolerance Loop Four [24]

The functional surface being studied in tolerance loop four is screw hole alignment on bottom edge of the enclosure. The interaction between these two can be seen in Figure 55. The general vector equation that dictates the dimensions shown in tolerance loop one is given in equation below. All dimensions are in millimeters.

$$\left(\vec{r_1} \pm \overrightarrow{\Delta r_1}\right) + \left(\vec{r_2} \pm \overrightarrow{\Delta r_2}\right) + (\vec{G} \pm \overrightarrow{\Delta G}) - \left(\vec{r_3} \pm \overrightarrow{\Delta r_3}\right) = \vec{0} \tag{183}$$

The equation for the minimum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

$$\begin{aligned} G_{\min} &= -(r_1 + \Delta r_1) - (r_2 + \Delta r_2) + (r_3 - \Delta r_3) = 0 \\ G_{\min} &= -(7.58 + .127) - (7.58 + .127) + (313.545 - .2540) = 297.877 \text{ mm} \end{aligned} \tag{184}$$

The equation for the maximum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values plus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vector to consider the worst-case scenario.

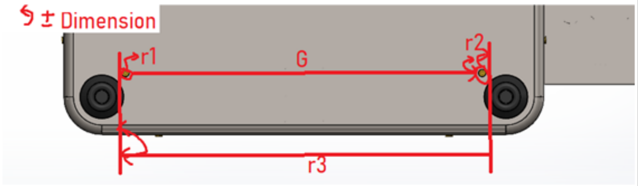
$$\begin{aligned} G_{\max} &= -(r_1 - \Delta r_1) - (r_2 - \Delta r_2) + (r_3 + \Delta r_3) = 0 \\ G_{\max=} &- (7.58 - .127) - (7.58 - .127) + (313.545 + .2540) = 298.893 \text{ mm} \end{aligned} \tag{185}$$

The gap and the tolerance for the gap can be calculated by using equal distribution:

$$\begin{aligned} \pm\Delta G &= \frac{G_{\max} - G_{\min}}{2} = 0.508 \text{ mm} \\ G &= \frac{G_{\max} + G_{\min}}{2} = 298.388 \text{ mm} \end{aligned} \tag{186}$$

Tolerance Loop Five

Tolerance Loop Five



Vector Name	Nominal Dimension	Tolerances		Reference
r1	7.580	+Δx1	0.1270	Machining Handbook
		-Δx1	0.1270	
G	298.388	+Δx2	0.5080	
		-Δx2	0.5080	
r2	7.580	+Δx1	0.1270	Machining Handbook
		-Δx1	0.1270	
r3	313.545	+Δx4	0.2540	Machining Handbook
		-Δx4	0.2540	
		+Δx5		
		-Δx5		
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

]

Figure 56: Tolerance Loop Five [24]

The functional surface being studied in tolerance loop five is screw hole alignment on bottom face of the enclosure. The interaction between these two can be seen in Figure 56. The general vector equation that dictates the dimensions shown in tolerance loop one is given in equation below. All dimensions are in millimeters.

$$\left(\vec{r_1} \pm \overrightarrow{\Delta r_1}\right) + \left(\vec{r_2} \pm \overline{\Delta r_2}\right) + (\vec{G} \pm \overrightarrow{\Delta G}) - \left(\vec{r_3} \pm \overrightarrow{\Delta r_3}\right) = \vec{0} \tag{187}$$

The equation for the minimum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

$$\begin{aligned} G_{\text{min}} &= -(r_1 + \Delta r_1) - (r_2 + \Delta r_2) + (r_3 - \Delta r_3) = 0 \\ G_{\text{min}} &= -(7.58 + .127) - (7.58 + .127) + (313.545 - .2540) = 297.877 \text{ mm} \end{aligned} \tag{188}$$

The equation for the maximum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values plus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vector to consider the worst-case scenario.

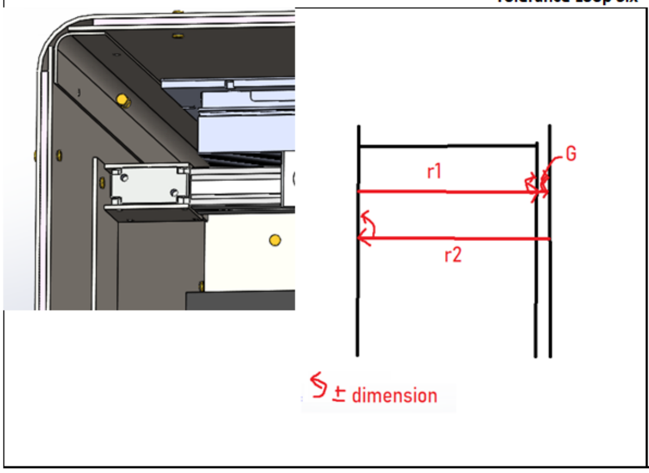
$$\begin{aligned} G_{\text{max}} &= -(r_1 - \Delta r_1) - (r_2 - \Delta r_2) + (r_3 + \Delta r_3) = 0 \\ G_{\text{max}=} &- (7.58 - .127) - (7.58 - .127) + (313.545 + .2540) = 298.893 \text{ mm} \end{aligned} \tag{189}$$

The gap and the tolerance for the gap can be calculated by using equal distribution:

$$\begin{aligned} \pm\Delta G &= \tfrac{G_{\text{max}} - G_{\text{min}}}{2} = 0.508 \text{ mm} \\ G &= \tfrac{G_{\text{max}} + G_{\text{min}}}{2} = 298.388 \text{ mm} \end{aligned} \tag{190}$$

Tolerance Loop Six

Tolerance Loop Six



Vector Name	Nominal Dimension	Tolerances		Reference
r1	25.460	+Δx1	0.0200	MacronDynamics Handbook
		-Δx1	0.0200	
G	0.450	+Δx2	0.2130	
		-Δx2	0.2130	
r2	26.000	+Δx3	0.1270	Machining Handbook
		-Δx3	0.1270	
		+Δx4		
		-Δx4		
		+Δx5		
		-Δx5		
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

Figure 57: Tolerance Loop Six [24]

The functional surface being studied in tolerance loop six is gantry housing mount inside of the enclosure. The interaction between these two can be seen in Figure 57. The general vector equation that dictates the dimensions shown in tolerance loop one is given in equation below. All dimensions are in millimeters.

$$\left(\vec{r_1} \pm \overrightarrow{\Delta r_1}\right) + (\vec{G} \pm \overrightarrow{\Delta G}) - \left(\vec{r_2} \pm \overrightarrow{\Delta r_2}\right) = \vec{0} \tag{191}$$

The equation for the minimum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

$$\begin{gathered} G_{\min} = -\left(r_1 + \Delta r_1\right) + \left(r_2 - \Delta r_2\right) = 0 \\ G_{\min} = -(25.46 + .02) + (26 - .127) = 0.213 \text{ mm} \end{gathered} \tag{192}$$

The equation for the maximum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values plus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vector to consider the worst-case scenario.

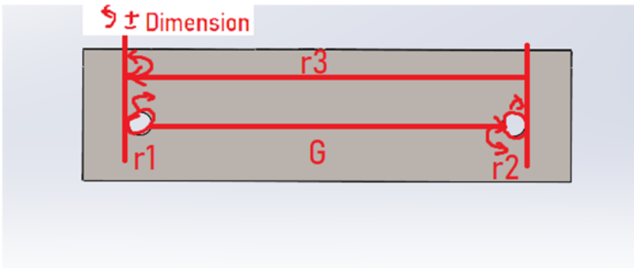
$$\begin{gathered} G_{\max} = -\left(r_1 - \Delta r_1\right) + \left(r_2 + \Delta r_2\right) = 0 \\ G_{\max=} -(25.46 - .02) + (26 + .127) = 0.687 \text{ mm} \end{gathered} \tag{193}$$

The gap and the tolerance for the gap can be calculated by using equal distribution:

$$\begin{gathered} \pm\Delta G = \frac{G_{\max} - G_{\min}}{2} = 0.213 \text{ mm} \\ G = \frac{G_{\max} + G_{\min}}{2} = 0.45 \text{ mm} \end{gathered} \tag{194}$$

Tolerance Loop Seven

Tolerance Loop Seven



Vector Name	Nominal Dimension	Tolerances		Reference
r1	7.580	+Δx1	0.1270	Machining Handbook
		-Δx1	0.1270	
G	39.702	+Δx2	0.5080	
		-Δx2	0.5080	
r2	7.580	+Δx1	0.1270	Machining Handbook
		-Δx1	0.1270	
r3	54.862	+Δx4	0.2540	Machining Handbook
		-Δx4	0.2540	
		+Δx5		
		-Δx5		
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

]

Figure 58: Tolerance Loop Seven [24]

The functional surface being studied in tolerance loop seven is liquid handling and OD/FI mount. The interaction between these two can be seen in Figure 58. The general vector equation that dictates the dimensions shown in tolerance loop one is given in equation below. All dimensions are in millimeters.

$$\left(\vec{r_1} \pm \overrightarrow{\Delta r_1}\right) + \left(\vec{r_2} \pm \overrightarrow{\Delta r_2}\right) + (\vec{G} \pm \overrightarrow{\Delta G}) - \left(\vec{r_3} \pm \overrightarrow{\Delta r_3}\right) = \vec{0} \tag{195}$$

The equation for the minimum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

$$\begin{aligned} G_{\min} &= -(r_1 + \Delta r_1) - (r_2 + \Delta r_2) + (r_3 - \Delta r_3) = 0 \\ G_{\min} &= -(7.58 + .127) - (7.58 + .127) + (54.862 - .2540) = 39.194 \text{ mm} \end{aligned} \tag{196}$$

The equation for the maximum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values plus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vector to consider the worst-case scenario.

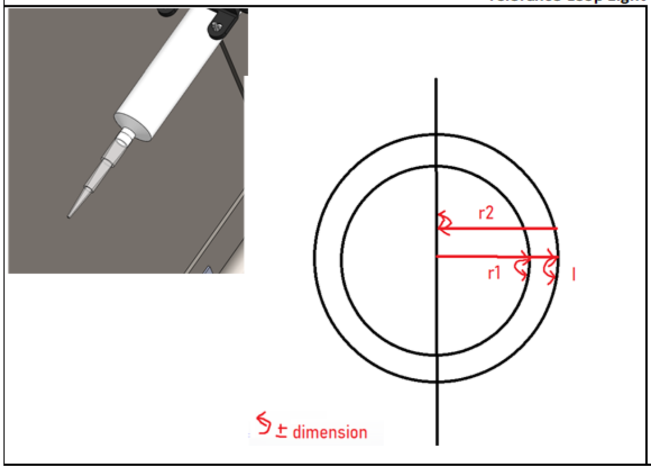
$$\begin{aligned} G_{\max} &= -(r_1 - \Delta r_1) - (r_2 - \Delta r_2) + (r_3 + \Delta r_3) = 0 \\ G_{\max=} &- (7.58 - .127) - (7.58 - .127) + (58.862 + .2540) = 40.21 \text{ mm} \end{aligned} \tag{197}$$

The gap and the tolerance for the gap can be calculated by using equal distribution:

$$\begin{aligned} \pm\Delta G &= \tfrac{G_{\max} - G_{\min}}{2} = 0.508 \text{ mm} \\ G &= \tfrac{G_{\max} + G_{\min}}{2} = 39.702 \text{ mm} \end{aligned} \tag{198}$$

Tolerance Loop Eight

Tolerance Loop Eight



Vector Name	Nominal Dimension	Tolerances		Reference
r1	7.000	+Δx1	0.0200	Manufacturer's Handbook
		-Δx1	0.0200	
I	0.370	+Δx2	0.1000	
		-Δx2	0.1000	
r2	6.900	+Δx3	0.0200	Manufacturer's Handbook
		-Δx3	0.0200	
		+Δx4		
		-Δx4		
		+Δx5		
		-Δx5		
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

]

Figure 59: Tolerance Loop Eight [24]

The functional surface being studied in tolerance loop eight is pipette and disposable tip. An interference is necessary in order to maintain the seal during functional use. The interaction between these two can be seen in Figure 59. The general vector equation that dictates the dimensions shown in tolerance loop one is given in equation below. All dimensions are in millimeters.

$$\left(\overrightarrow{r_1} \pm \overline{\Delta r_1}\right) + (\vec{I} \pm \overrightarrow{\Delta I}) - \left(\overrightarrow{r_2} \pm \overline{\Delta r_2}\right) = \overrightarrow{0} \tag{199}$$

The equation for the minimum interference can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vectors to consider the worst-case scenario.

$$\begin{aligned} I_{\min} &= -\left(r_1 - \Delta r_1\right) + \left(r_2 + \Delta r_2\right) = 0 \\ I_{\min} &= -(7 - .02) + (6.9 + .02) = -0.06 \text{ mm} \end{aligned} \tag{200}$$

The equation for the maximum interference can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

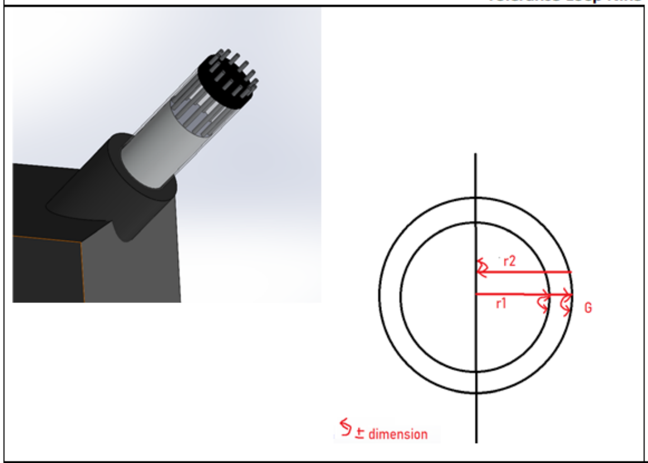
$$\begin{aligned} I_{\max} &= -\left(r_1 + \Delta r_1\right) + \left(r_2 - \Delta r_2\right) = 0 \\ I_{\max} &= -(7 + .02) + (6.9 - .02) = -0.14 \text{ mm} \end{aligned} \tag{201}$$

Using equal distribution, the interference tolerance for the interference can be found as:

$$\begin{aligned} \pm \Delta I &= \tfrac{I_{\max} - I_{\min}}{2} = 0.1 \text{ mm} \\ I &= \tfrac{I_{\max} + I_{\min}}{2} = 0.37 \text{ mm} \end{aligned} \tag{202}$$

Tolerance Loop Nine

Tolerance Loop Nine



Vector Name	Nominal Dimension	Tolerances		Reference
r1	14.000	+Δx1	0.3000	PMT Manufacturer's Handbook
		-Δx1	0.3000	
G	0.500	+Δx2	0.3500	
		-Δx2	0.3500	
r2	14.500	+Δx3	0.0500	3D Printing Tolerance
		-Δx3	0.0500	
		+Δx4		
		-Δx4		
		+Δx5		
		-Δx5		
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

]

Figure 60: Tolerance Loop Nine [24]

The functional surface being studied in tolerance loop nine is PMT Detector mount. The interaction between these two can be seen in Figure 60. The general vector equation that dictates the dimensions shown in tolerance loop one is given in equation below. All dimensions are in millimeters.

$$\left(\vec{r_1} \pm \overrightarrow{\Delta r_1}\right) + (\vec{G} \pm \overrightarrow{\Delta G}) - \left(\vec{r_2} \pm \overrightarrow{\Delta r_2}\right) = \vec{0} \tag{203}$$

The equation for the minimum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

$$\begin{gathered} G_{\min} = -(r_1 + \Delta r_1) + (r_2 - \Delta r_2) = 0 \\ G_{\min} = -(14 + .3) + (14.5 - .05) = 0.15 \text{ mm} \end{gathered} \tag{204}$$

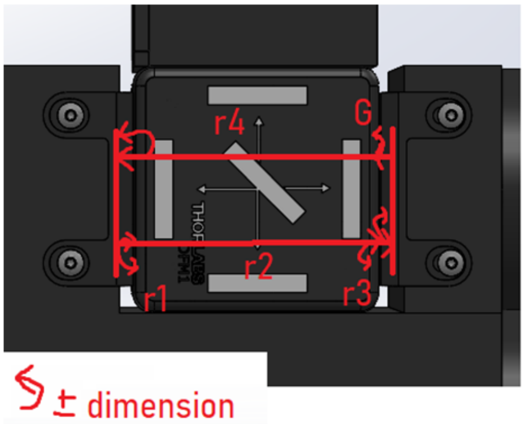
The equation for the maximum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values plus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vector to consider the worst-case scenario.

$$\begin{gathered} G_{\max} = -(r_1 - \Delta r_1) + (r_2 + \Delta r_2) = 0 \\ G_{\max=} - (14 + .3) + (14.5 - .05) = 0.85 \text{ mm} \end{gathered} \tag{205}$$

The gap and the tolerance for the gap can be calculated by using equal distribution:

$$\begin{gathered} \pm\Delta G = \frac{G_{\max} - G_{\min}}{2} = 0.35 \text{ mm} \\ G = \frac{G_{\max} + G_{\min}}{2} = 0.5 \text{ mm} \end{gathered} \tag{206}$$

Tolerance Loop Ten



Vector Name	Nominal Dimension	Tolerances		Reference
r1	2.800	+Δx1	0.0200	
		-Δx1	0.0200	
G	0.400	+Δx2	0.1100	
		-Δx2	0.1100	
r2	50.800	+Δx3	0.0200	
		-Δx3	0.0200	
r3	2.800	+Δx4	0.0200	
		-Δx4	0.0200	
r4	56.800	+Δx5	0.0500	3D Printing Tolerance
		-Δx5	0.0500	
		+Δx6		
		-Δx6		
		+Δx7		
		-Δx7		
		+Δx8		
		-Δx8		
		+Δx9		
		-Δx9		
		+Δx10		
		-Δx10		
		+Δx11		
		-Δx11		
		+Δx12		
		-Δx12		

]

Figure 61: Tolerance Loop Ten [24]

The functional surface being studied in tolerance loop ten is FI filter cube mount. The interaction between these two can be seen in Figure 61. The general vector equation that dictates the dimensions shown in tolerance loop one is given in equation below. All dimensions are in millimeters.

$$\left(\vec{r_1} \pm \overrightarrow{\Delta r_1}\right) + \left(\vec{r_2} \pm \overline{\Delta r_2}\right) + \left(\vec{r_3} \pm \overrightarrow{\Delta r_3}\right) + (\vec{G} \pm \overrightarrow{\Delta G}) - \left(\vec{r_4} \pm \overrightarrow{\Delta 4}\right) = \vec{0} \tag{207}$$

The equation for the minimum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values minus its tolerance. Tolerances were added to the positive vectors and the tolerances were subtracted from the negative vectors to consider the worst-case scenario.

$$\begin{gathered} G_{\text{min}} = -\left(r_1 + \Delta r_1\right) + \left(r_2 + \Delta r_2\right) + \left(r_3 + \Delta r_3\right) + \left(r_4 - \Delta r_4\right) = 0 \\ G_{\text{min}} = -(2.8 + .02) - (50.8 + .02) - (2.8 + .02) + (56.8 - .05) = 0.29 \text{ mm} \end{gathered} \tag{208}$$

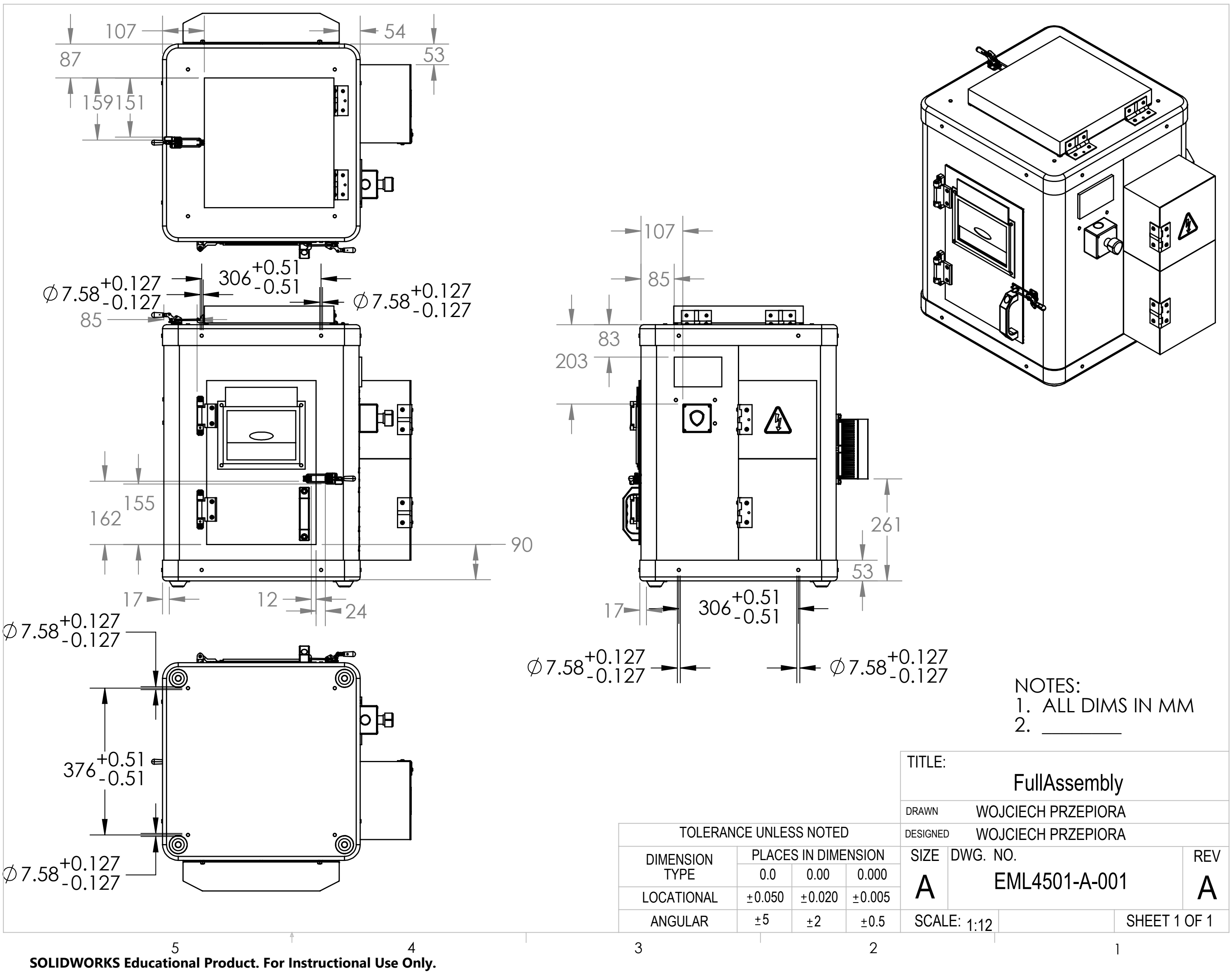
The equation for the maximum gap clearance can be found using vector equation below. Due to the nominal value of the gap, which accounts for its nominal values plus its tolerance. Tolerances were subtracted from the positive vectors and the tolerances were added to the negative vector to consider the worst-case scenario.

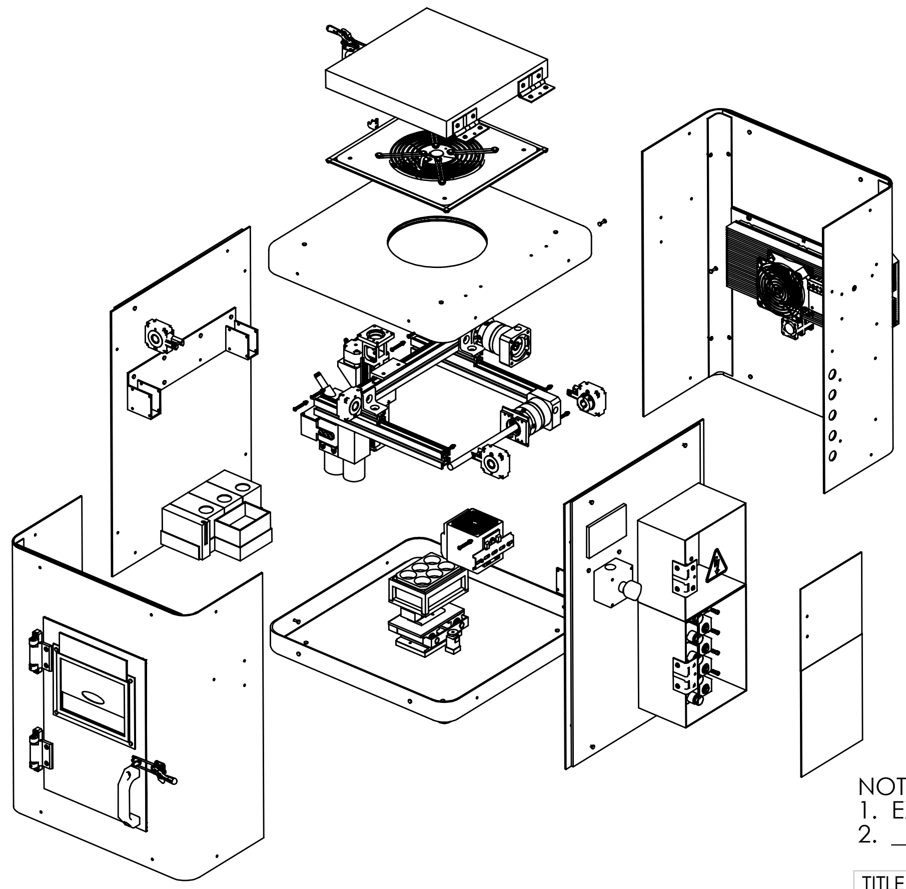
$$\begin{gathered} G_{\text{max}} = -\left(r_1 - \Delta r_1\right) + \left(r_2 - \Delta r_2\right) + \left(r_3 - \Delta r_3\right) + \left(r_4 + \Delta r_4\right) = 0 \\ G_{\text{max=}} - (2.8 - .02) - (50.8 - .02) - (2.8 - .02) + (56.8 + .05) = 0.51 \text{ mm} \end{gathered} \tag{209}$$

The gap and the tolerance for the gap can be calculated by using equal distribution:

$$\begin{gathered} \pm\Delta G = \frac{G_{\text{max}} - G_{\text{min}}}{2} = 0.11 \text{ mm} \\ G = \frac{G_{\text{max}} + G_{\text{min}}}{2} = 0.4 \text{ mm} \end{gathered} \tag{210}$$

G. Detailed Drawings



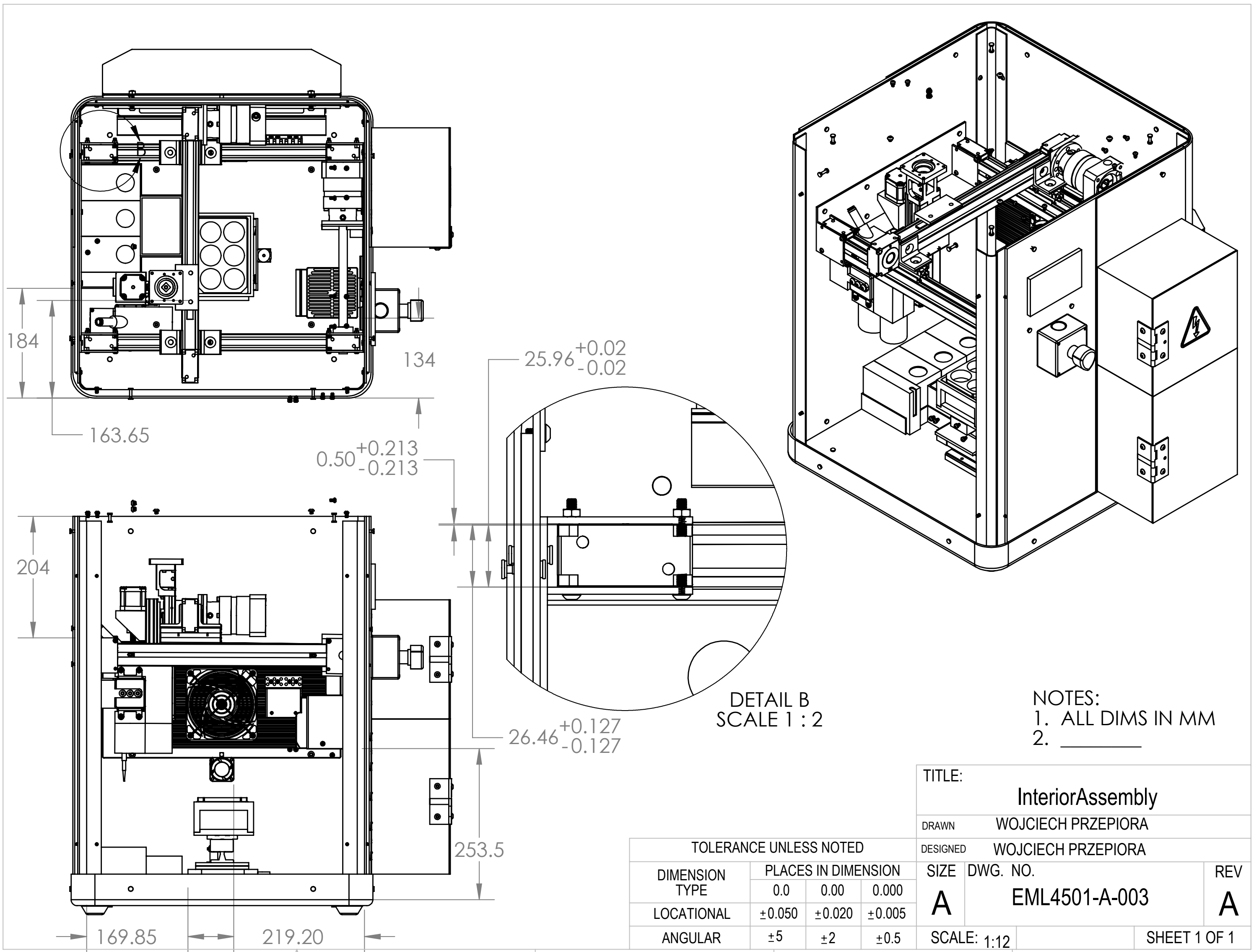


NOTES:
1. EXPLODED VIEW OF INTERIOR
2. ________

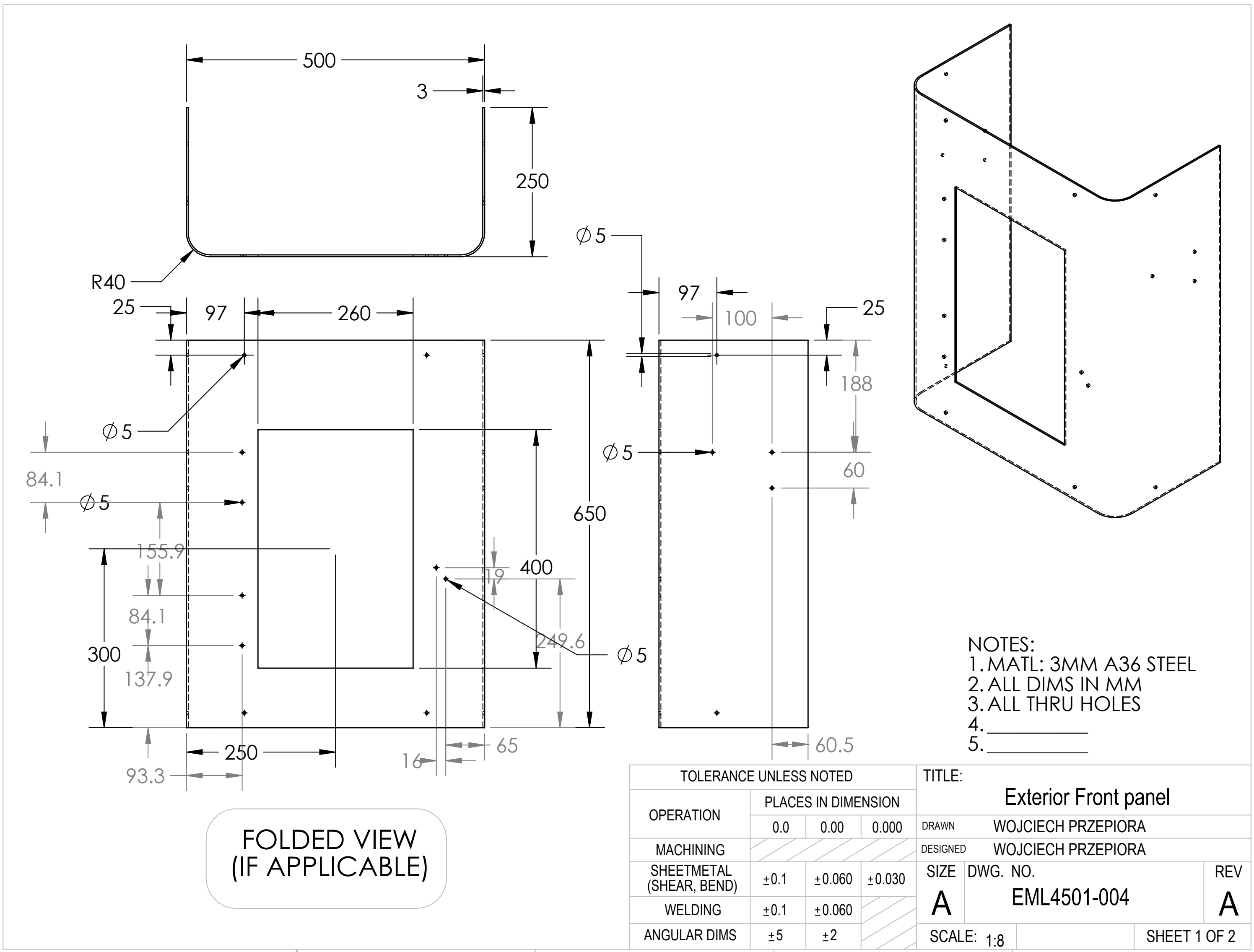
TITLE:	FullAssemblyExploded			
DRAWN	WOJCIECH PRZEPIORA			
DESIGNED	WOJCIECH PRZEPIORA			
SIZE	DWG. NO.		REV	
A	EML4501-A-002		A	
SCALE: 1:48		SHEET 1 OF 1		

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

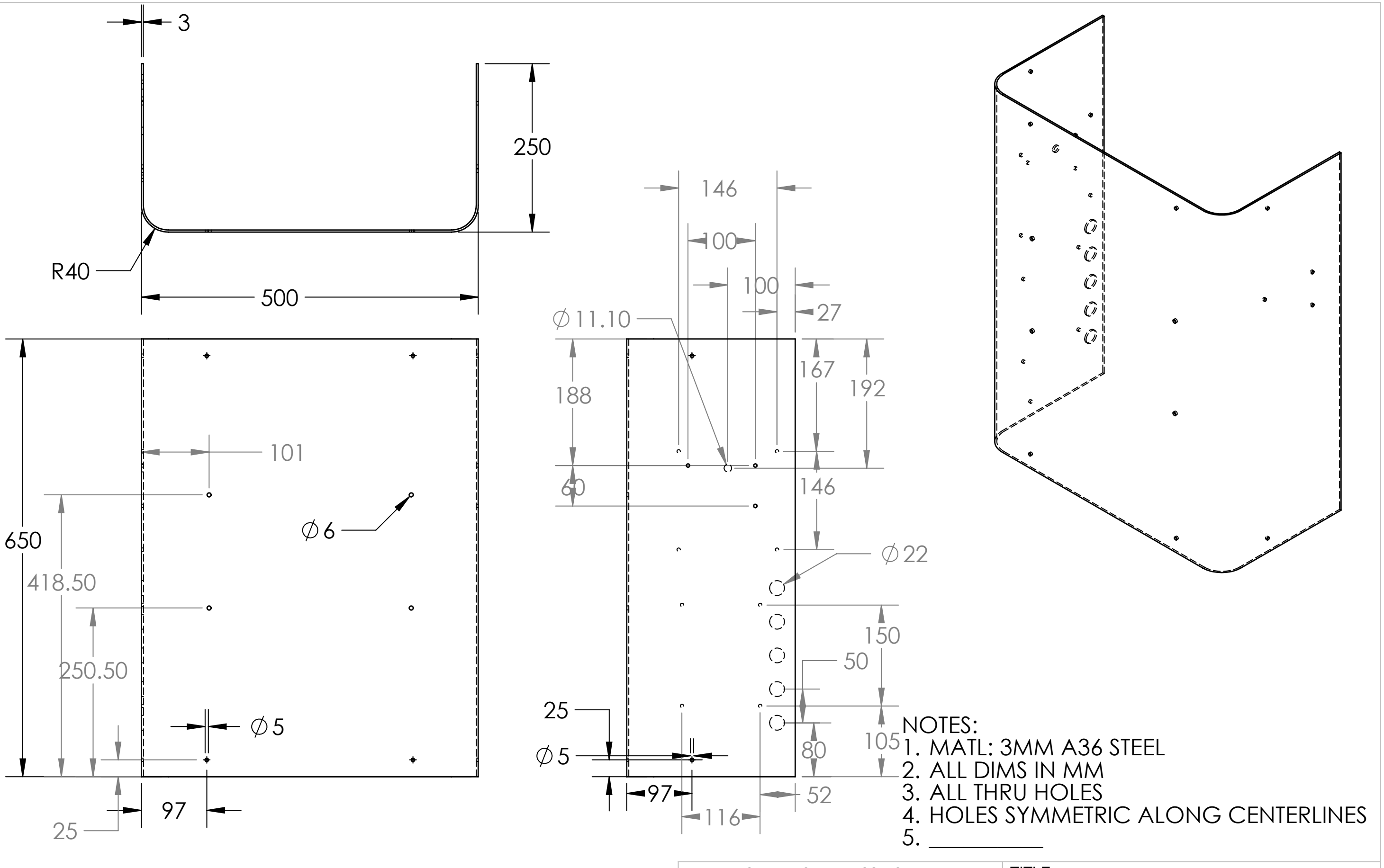
5 4 3 2 1



SOLIDWORKS Educational Product. For Instructional Use Only.



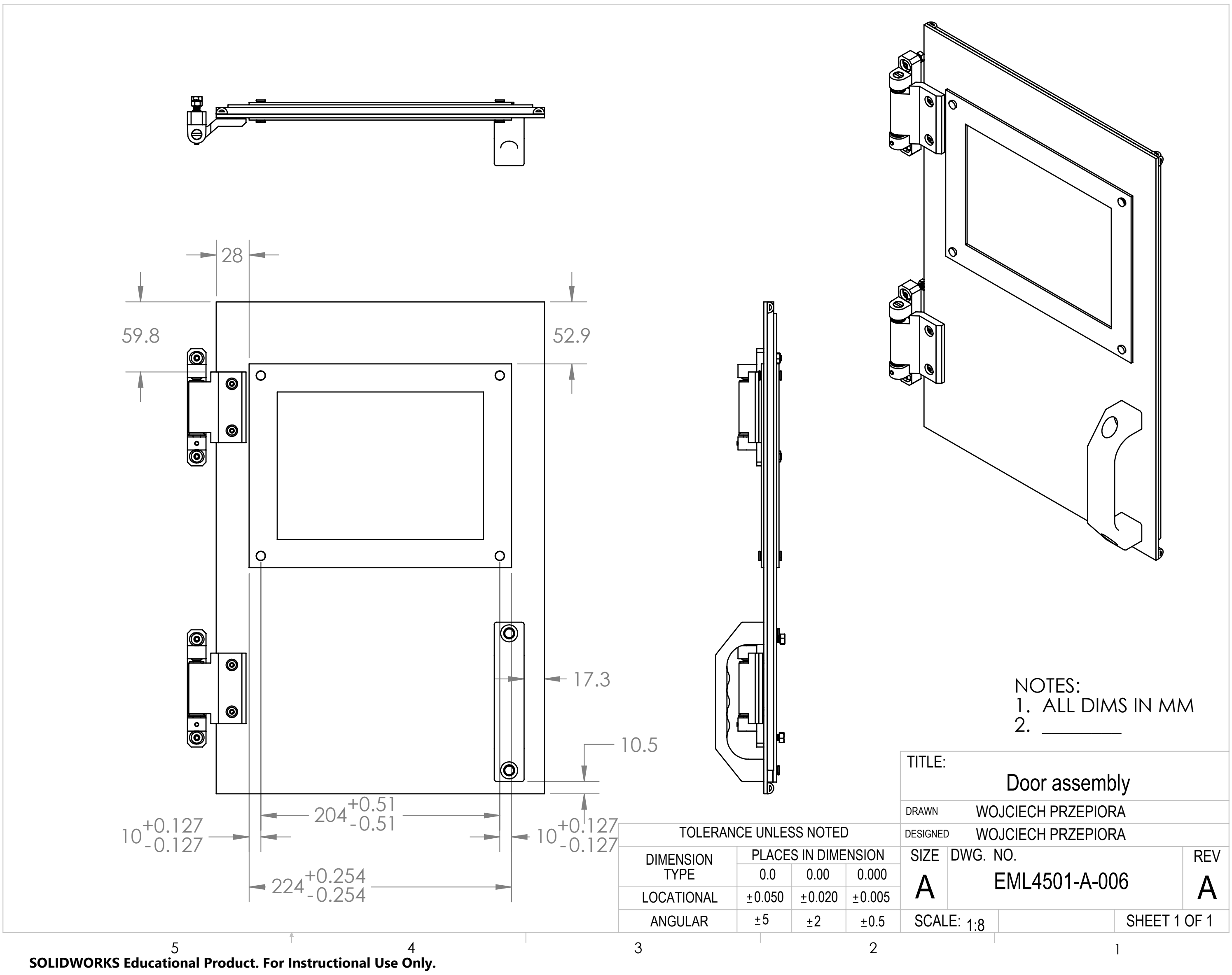
SOLIDWORKS Educational Product. For Instructional Use Only.



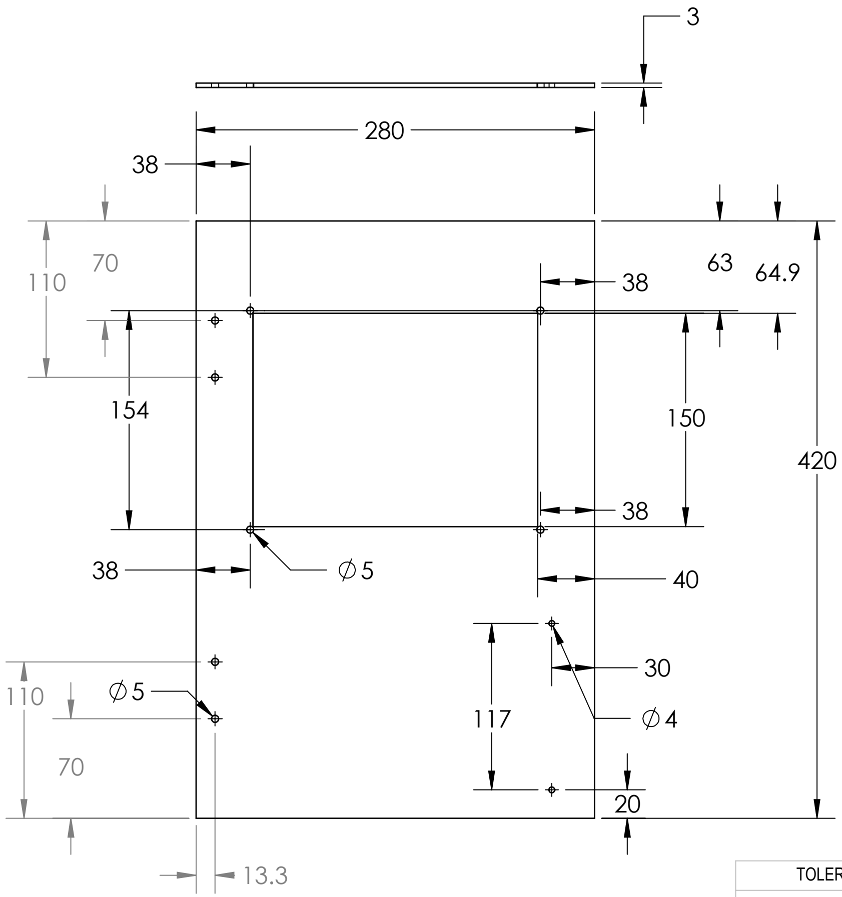
NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. HOLES SYMMETRIC ALONG CENTERLINES
5. __________

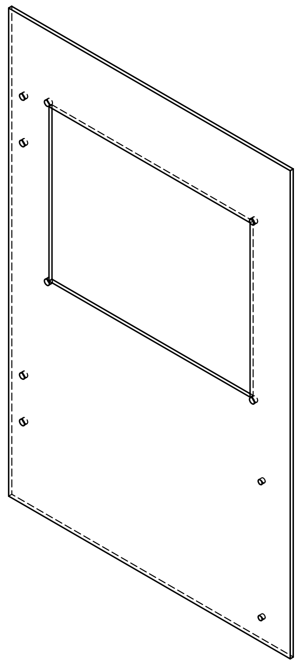
TOLERANCE UNLESS NOTED				TITLE: Exterior Back Panel
OPERATION	PLACES IN DIMENSION			DRAWN WOJCIECH PRZEPIORA
	0.0	0.00	0.000	DESIGNED WOJCIECH PRZEPIORA
MACHINING				SIZE A DWG. NO. EML4501-005 REV A
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030	
WELDING	±0.1	±0.060		
ANGULAR DIMS	±5	±2		SCALE: 1:8 SHEET 1 OF 2

5 4 3 2 1



28
59.8
52.9
17.3
10.5
204 +0.51 -0.51
10 +0.127 -0.127
10 +0.127 -0.127
224 +0.254 -0.254
NOTES:
1. ALL DIMS IN MM
2.
TITLE:
Door assembly
DRAWN WOJCIECH PRZEPIORA
DESIGNED WOJCIECH PRZEPIORA
TOLERANCE UNLESS NOTED
DIMENSION TYPE
PLACES IN DIMENSION
0.0
0.00
0.000
LOCATIONAL
±0.050
±0.020
±0.005
ANGULAR
±5
±2
±0.5
SIZE
A
DWG. NO.
EML4501-A-006
REV
A
SCALE: 1:8
SHEET 1 OF 1
5
4
3
2
1
SOLIDWORKS Educational Product. For Instructional Use Only.





NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. HOLES SYMMETRIC ALONG CENTERLINE
5. ___________

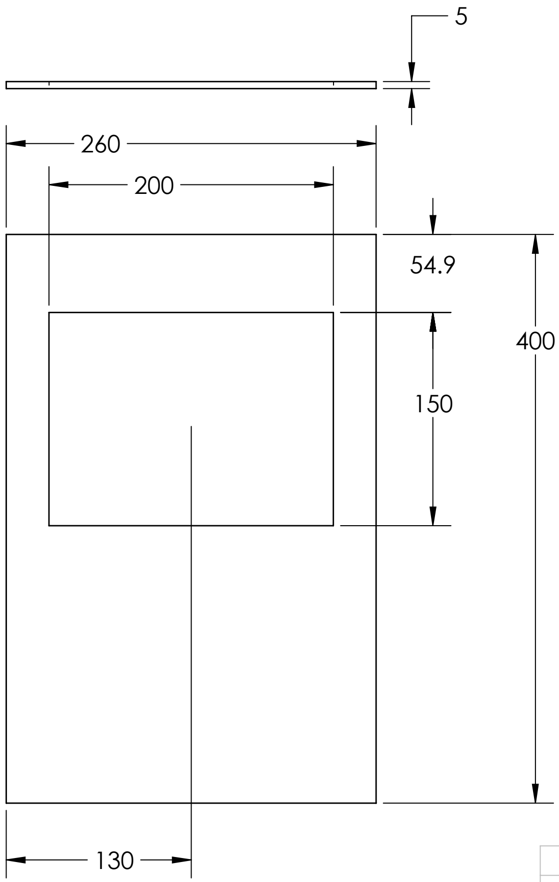
FOLDED VIEW
(IF APPLICABLE)

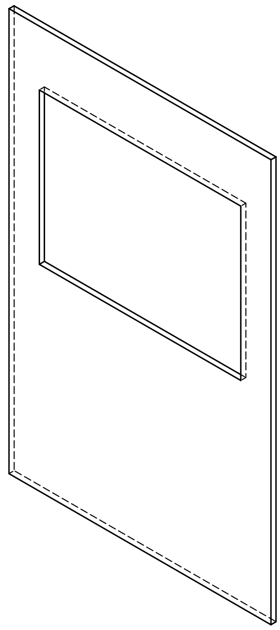
TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE:	exterior door panel	
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-007	REV A
SCALE: 1:4		SHEET 1 OF 2

5 4 3 2 1

SOLIDWORKS Educational Product. For Instructional Use Only.

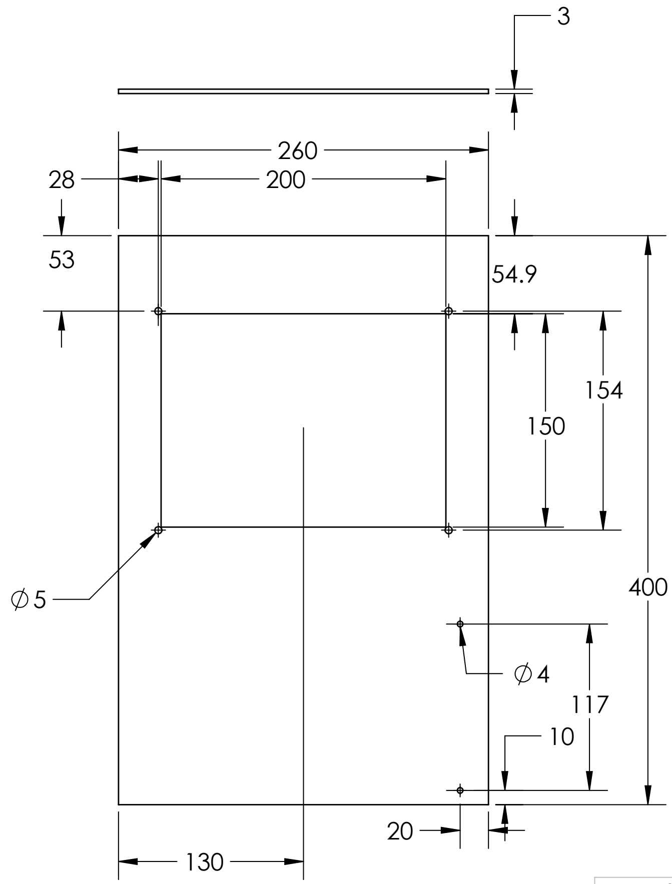


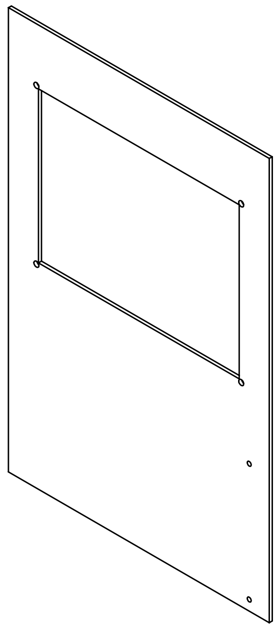


NOTES:
1. MATL: POLYURETHANE FOAM RIGID
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

TOLERANCE UNLESS NOTED				TITLE: door insulation	
OPERATION	PLACES IN DIMENSION				
	0.0	0.00	0.000	DRAWN	WOJCIECH PRZEPIORA
MACHINING	±0.050	±0.020	±0.005	DESIGNED	WOJCIECH PRZEPIORA
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE A	DWG. NO. EML4501-008 REV A
WELDING	±0.1	±0.060			
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:4	SHEET 1 OF 1

5 4 3 2 1





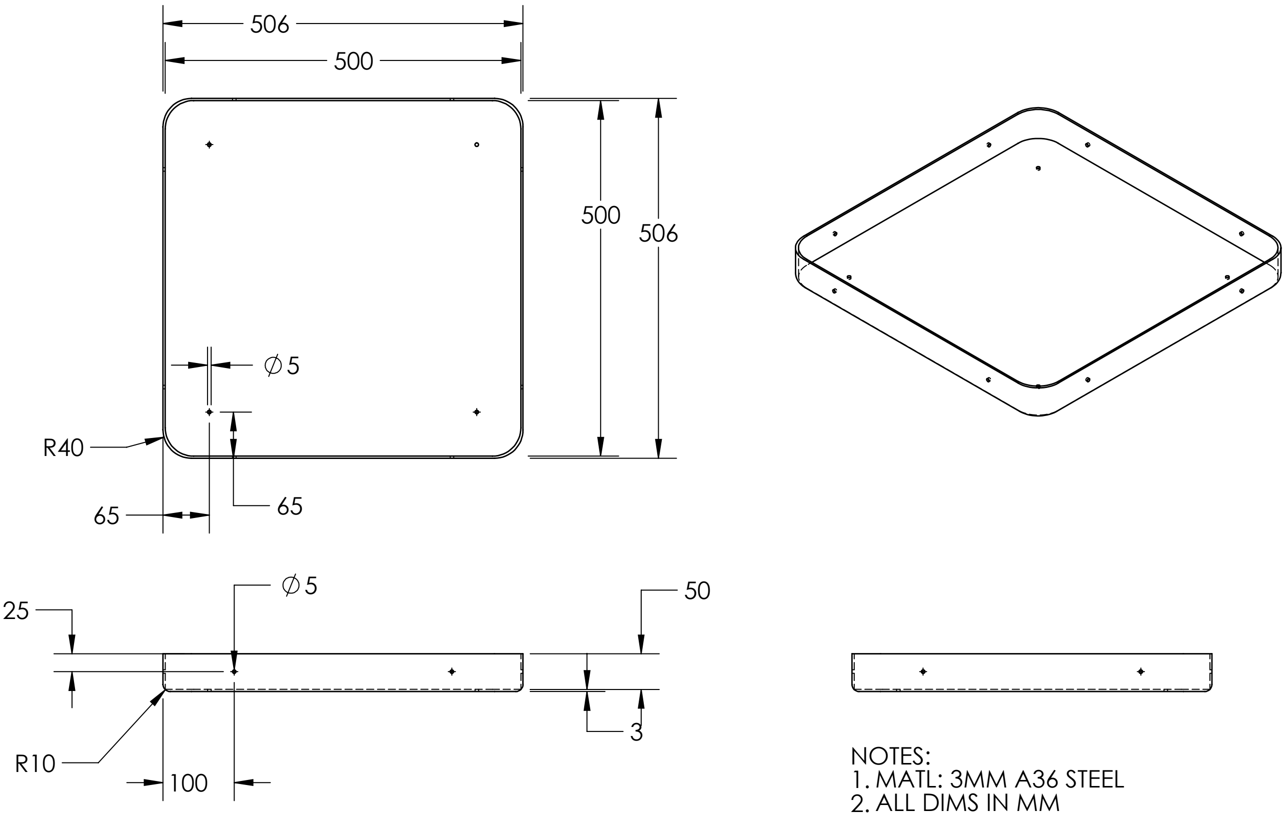
NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. ___________
5. ___________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE:	interior door panel
DRAWN	WOJCIECH PRZEPIORA
DESIGNED	WOJCIECH PRZEPIORA
SIZE	A
DWG. NO.	EML4501-009
REV	A
SCALE:	1:4
SHEET 1 OF 2	

5 4 3 2 1



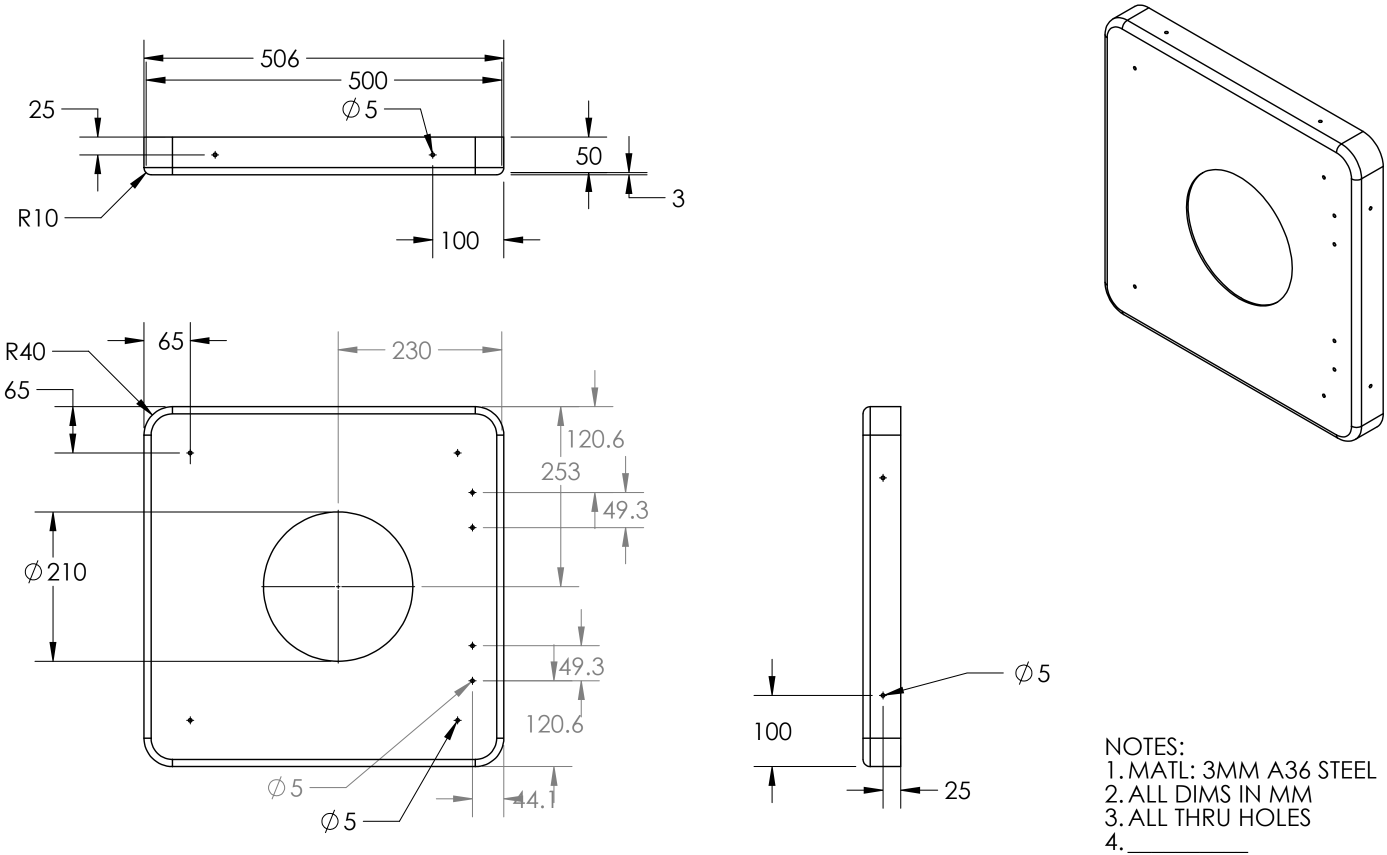
NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. HOLES SYMMETRIC ALONG CENTERLINES
5. ___________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE:	exterior bottom panel
DRAWN	WOJCIECH PRZEPIROA
DESIGNED	WOJCIECH PRZEPIORA
SIZE	A
DWG. NO.	EML4501-010
REV	A
SCALE:	1:8
SHEET 1 OF 2	

5 4 3 2 1

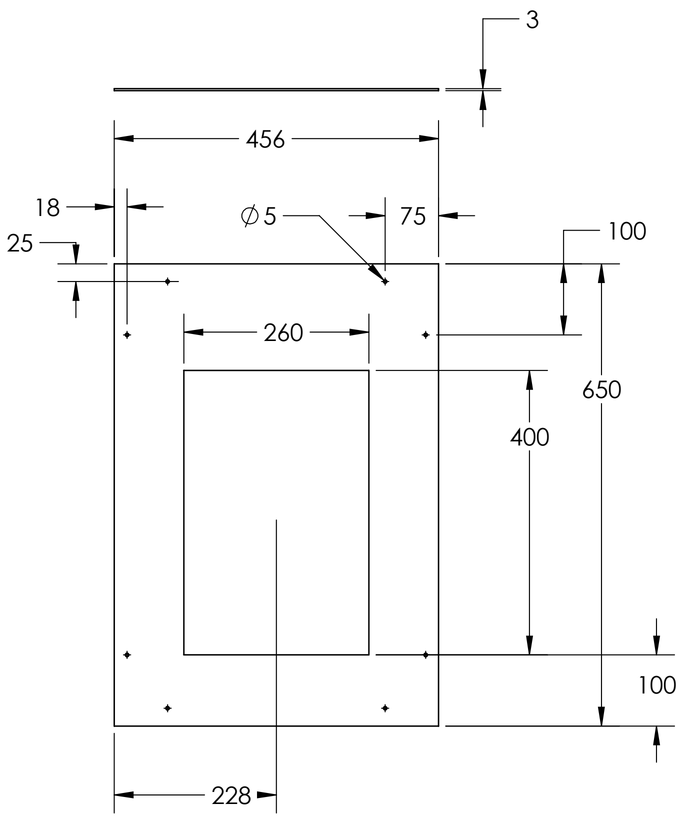


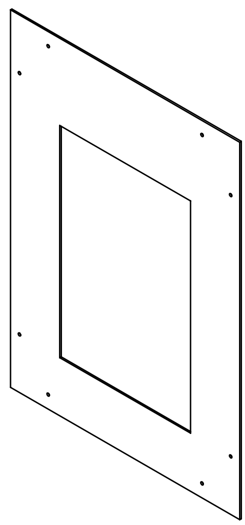
NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4.__________
5.__________

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE:	exterior top panel	
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-011	REV A
SCALE: 1:8		SHEET 1 OF 2

5 4 3 2 1





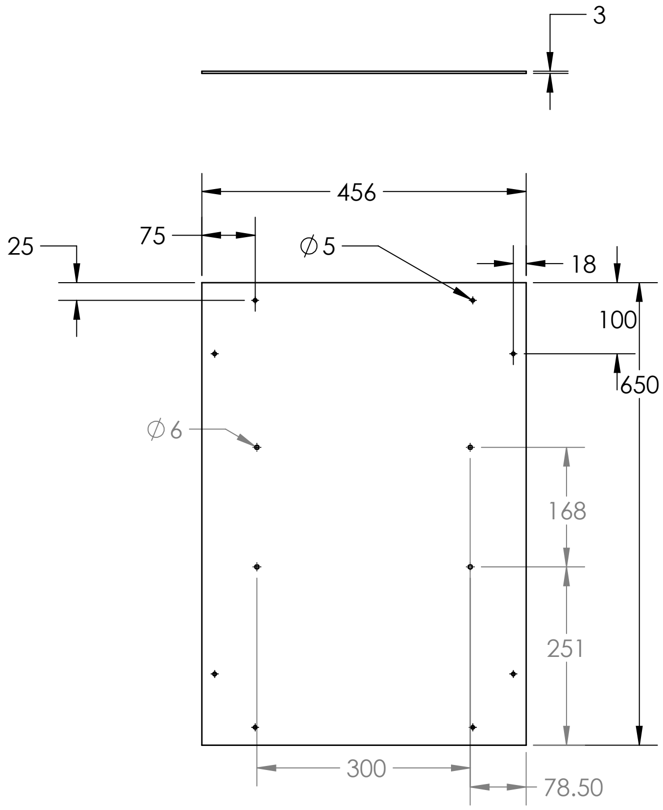
NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. ___________
5. ___________

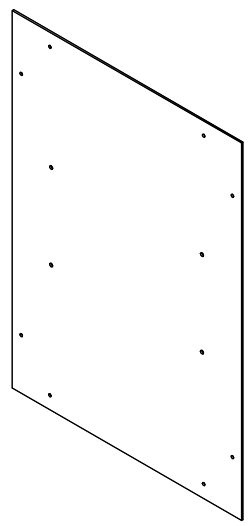
FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE:	front interior panel	
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-012	REV A
SCALE: 1:8		SHEET 1 OF 2

5 4 3 2 1





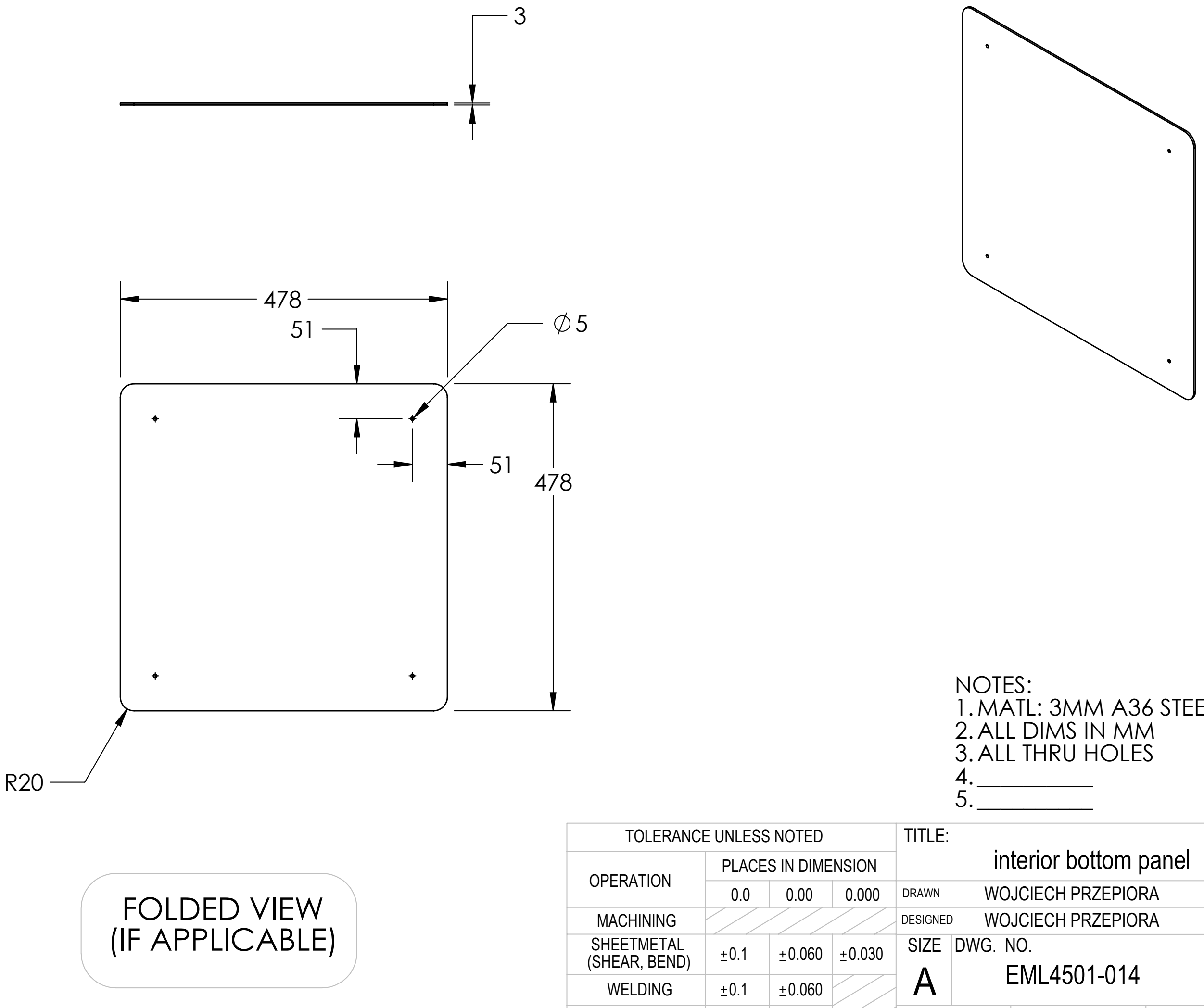
NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. ___________
5. ___________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED				TITLE: interior back panel		
OPERATION	PLACES IN DIMENSION			DRAWN	WOJCIECH PRZEPIORA	
	0.0	0.00	0.000	DESIGNED	WOJCIECH PRZEPIORA	
MACHINING				SIZE A	DWG. NO. EML4501-013	REV A
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030			
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2		SCALE: 1:8		SHEET 1 OF 2

5 4 3 2 1

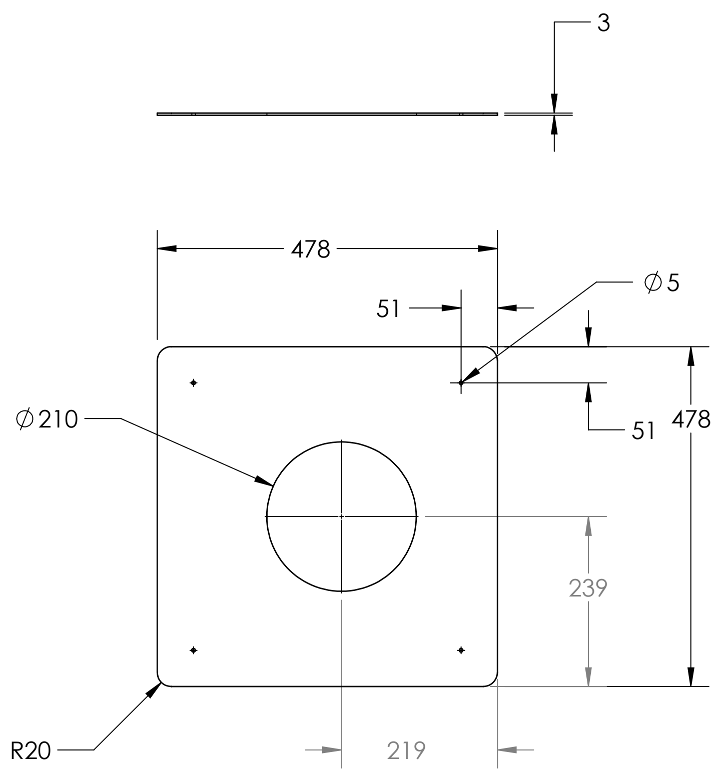
SOLIDWORKS Educational Product. For Instructional Use Only.

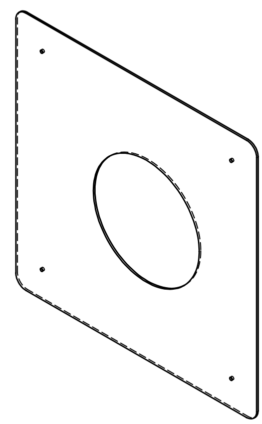


NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. ___________
5. ___________

TOLERANCE UNLESS NOTED				TITLE: interior bottom panel		
OPERATION	PLACES IN DIMENSION			DRAWN	WOJCIECH PRZEPIORA	
	0.0	0.00	0.000	DESIGNED	WOJCIECH PRZEPIORA	
MACHINING				SIZE A	DWG. NO. EML4501-014	REV A
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030			
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2		SCALE: 1:8		SHEET 1 OF 2

5 4 3 2 1





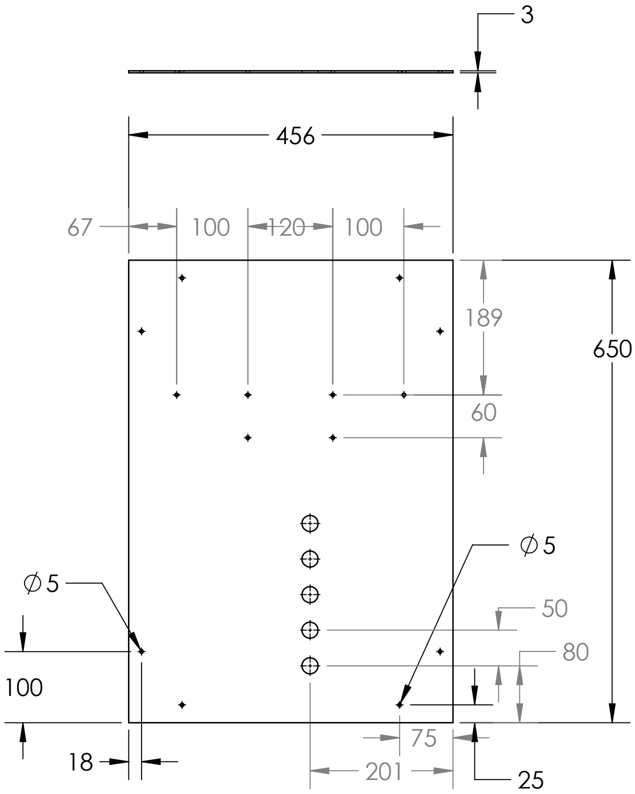
NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4.
5.

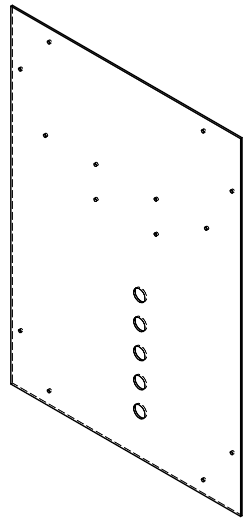
FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE: interior top panel		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-015	REV A
SCALE: 1:8		SHEET 1 OF 2

5 4 3 2 1



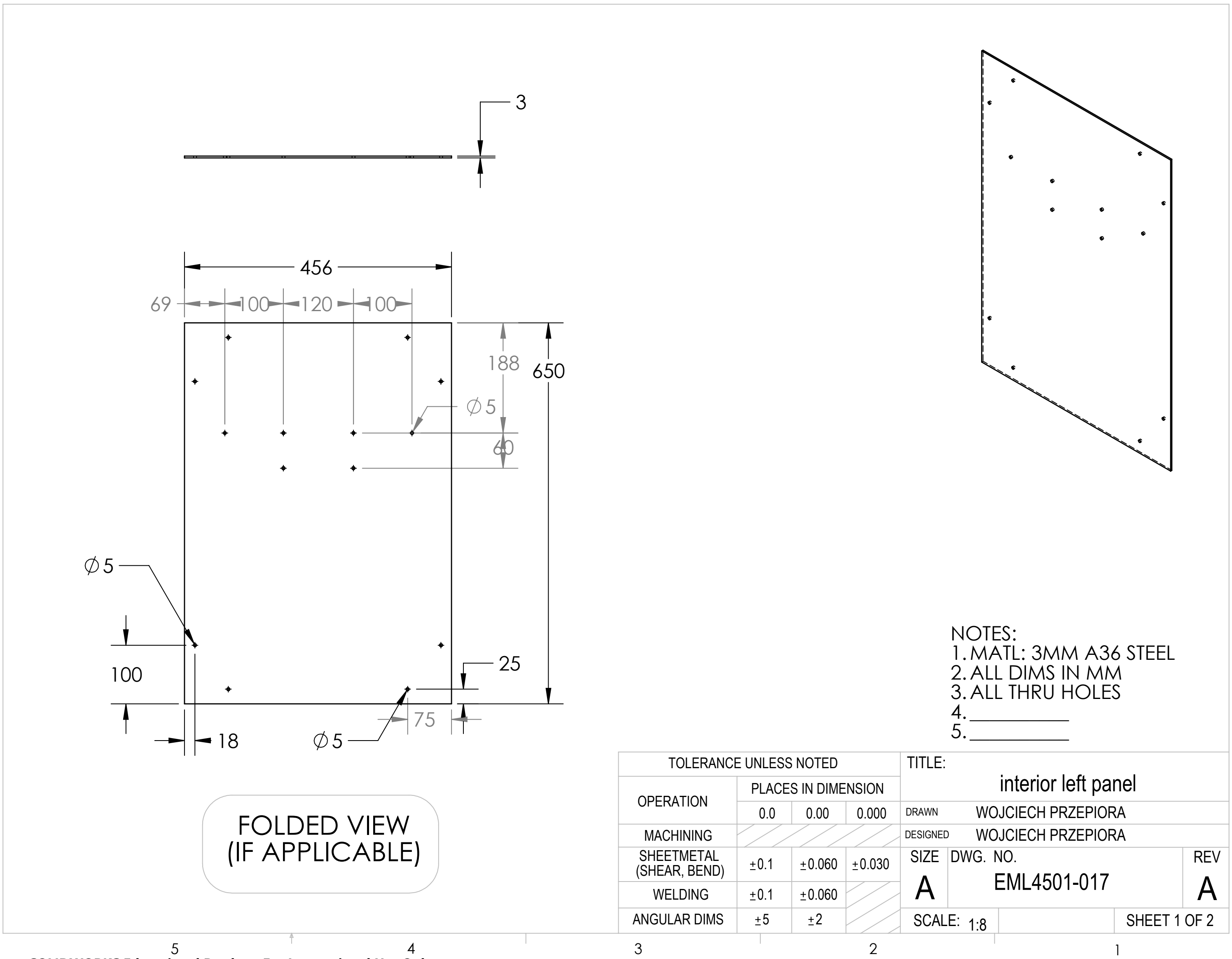


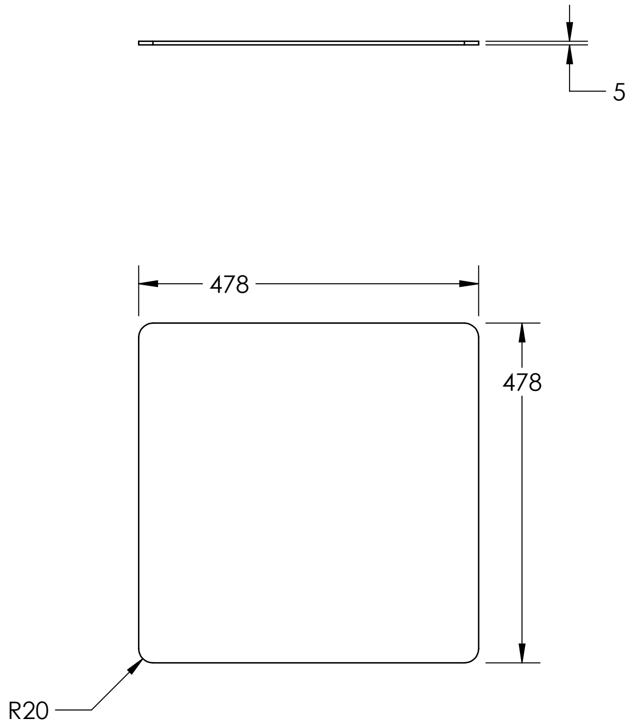
NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4.__________
5.__________

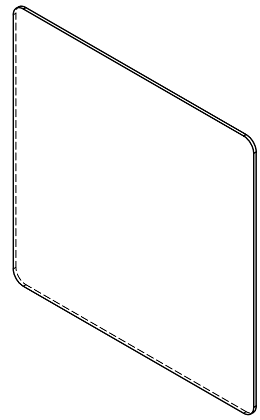
FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED				TITLE: interior right panel
OPERATION	PLACES IN DIMENSION			DRAWN WOJCIECH PRZEPIORA
	0.0	0.00	0.000	DESIGNED WOJCIECH PRZEPIORA
MACHINING				SIZE A
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030	DWG. NO. EML4501-016
WELDING	±0.1	±0.060		REV A
ANGULAR DIMS	±5	±2		SCALE: 1:8 SHEET 1 OF 2

5 4 3 2 1


3
456
69
100
120
100
188
650
∅5
60
∅5
100
25
18
75
∅5
FOLDED VIEW
(IF APPLICABLE)
NOTES:
1. MATL: 3MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4.
5.
TOLERANCE UNLESS NOTED
OPERATION
PLACES IN DIMENSION
0.0
0.00
0.000
MACHINING
SHEETMETAL (SHEAR, BEND)
±0.1
±0.060
±0.030
WELDING
±0.1
±0.060
ANGULAR DIMS
±5
±2
TITLE:
interior left panel
DRAWN WOJCIECH PRZEPIORA
DESIGNED WOJCIECH PRZEPIORA
SIZE
A
DWG. NO.
EML4501-017
REV
A
SCALE: 1:8
SHEET 1 OF 2
5
4
3
2
1

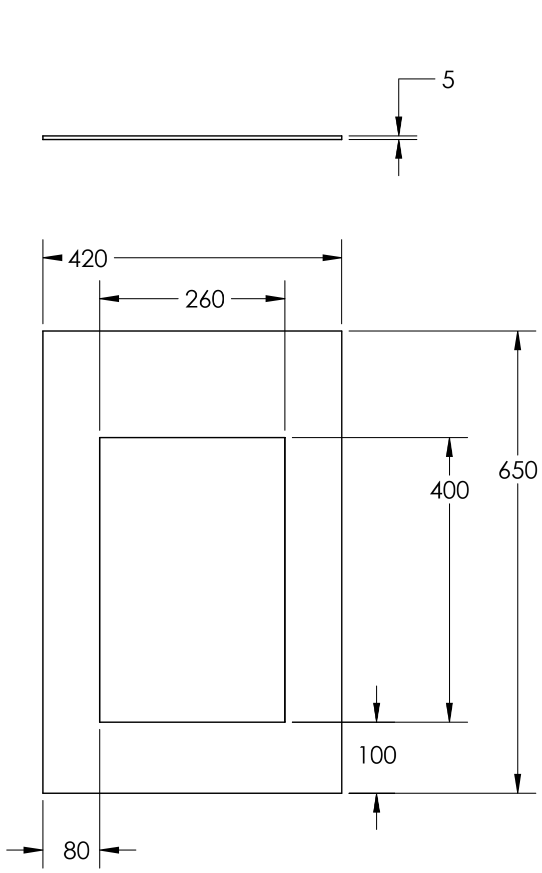


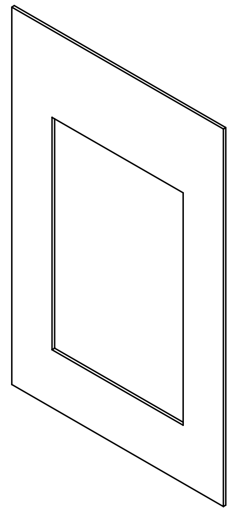


NOTES:
1. MATL: Polyurethane Foam Rigid
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

TOLERANCE UNLESS NOTED				TITLE: top & bottom insulation		
OPERATION	PLACES IN DIMENSION			DRAWN	WOJCIECH PRZEPIORA	
	0.0	0.00	0.000	DESIGNED	WOJCIECH PRZEPIORA	
MACHINING	±0.050	±0.020	±0.005	SIZE	DWG. NO.	REV
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		A	EML4501-018	A
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:8		SHEET 1 OF 1

5 4 3 2 1



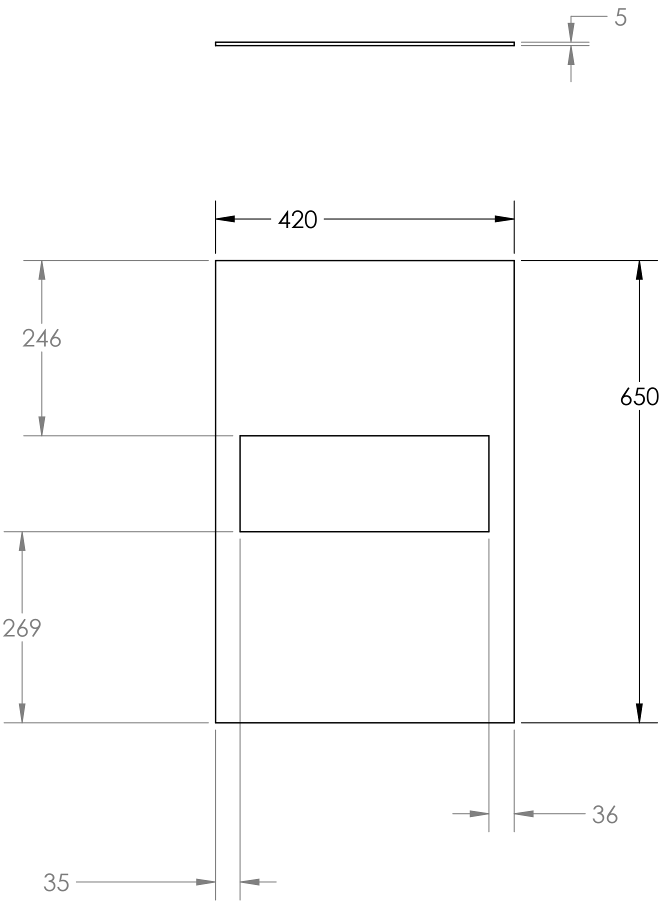


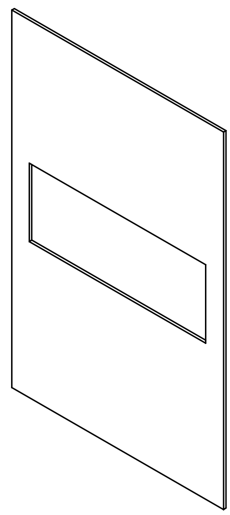
NOTES:
1. MATL: POLYURETHANE FOAM RIGID
2. ALL DIMS IN MM
3.__________
4.__________
5.__________

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE: front wall insulation		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-019	REV A
SCALE: 1:8		SHEET 1 OF 1

5 4 3 2 1

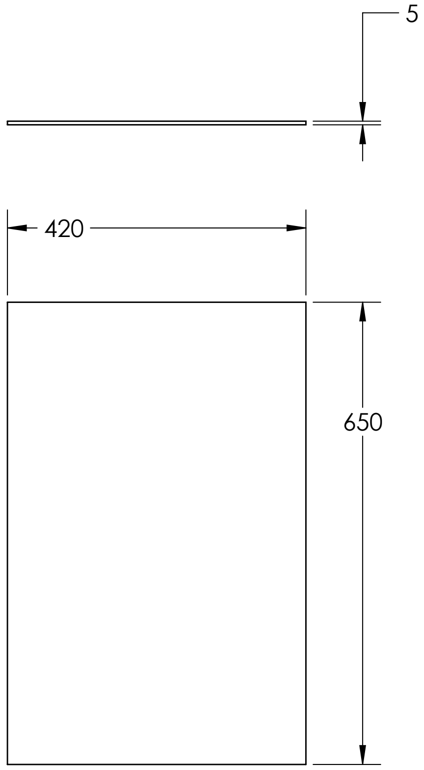


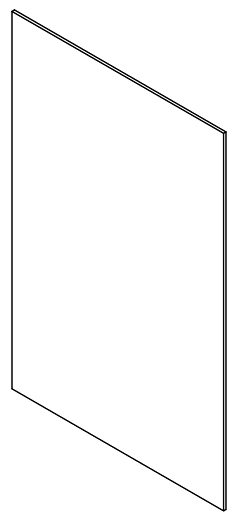


NOTES:
1. MATL: POLYURETHANE FOAM RIGID
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

TOLERANCE UNLESS NOTED				TITLE: back insulation	
OPERATION	PLACES IN DIMENSION				
	0.0	0.00	0.000	DRAWN	WOJCIECH PRZEPIORA
MACHINING	±0.050	±0.020	±0.005	DESIGNED	WOJCIECH PRZEPIORA
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE A	DWG. NO. EML4501-020 REV A
WELDING	±0.1	±0.060			
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:8	SHEET 1 OF 1

5 4 3 2 1



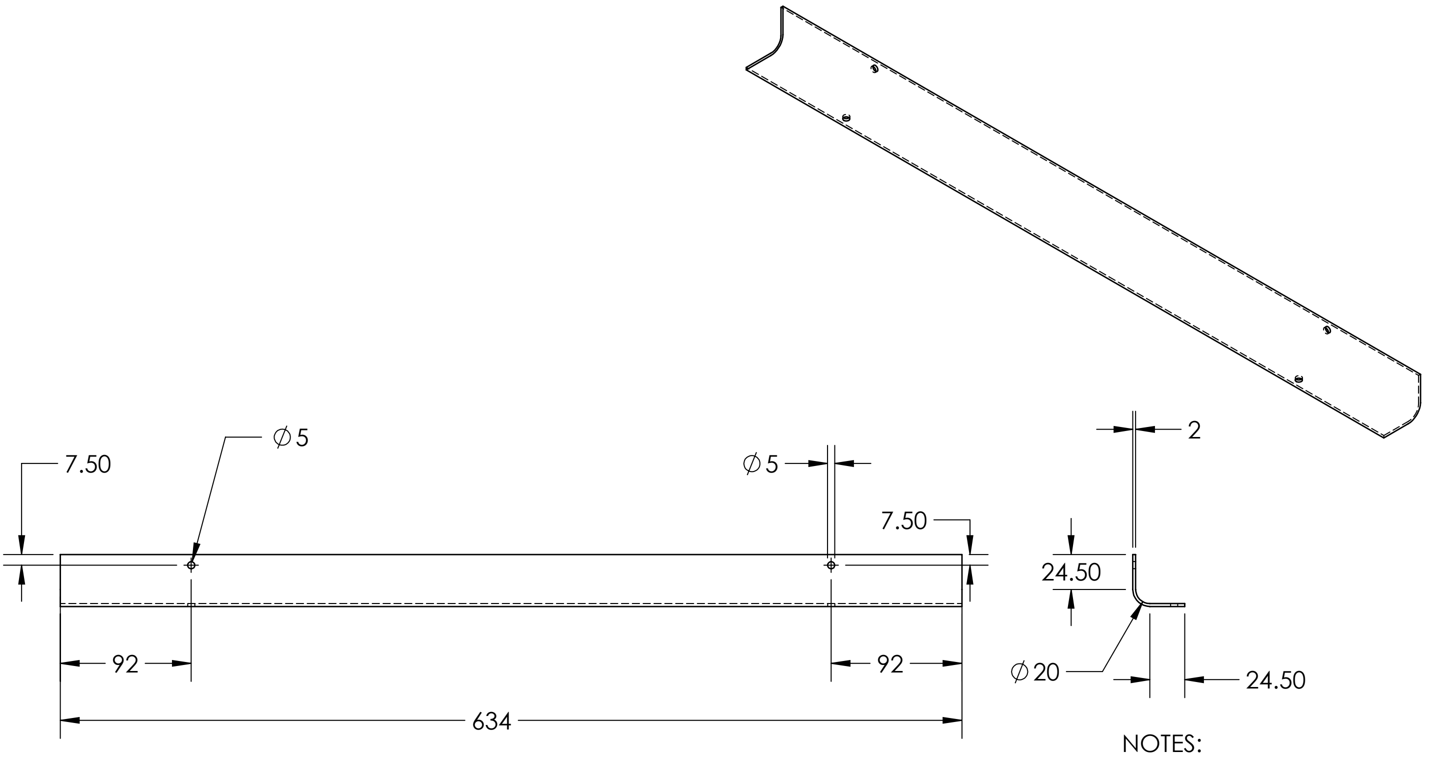


NOTES:
1. MATL: POLYURETHANE FOAM RIG
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE: left & right insulation		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-021	REV A
SCALE: 1:8		SHEET 1 OF 1

5 4 3 2 1



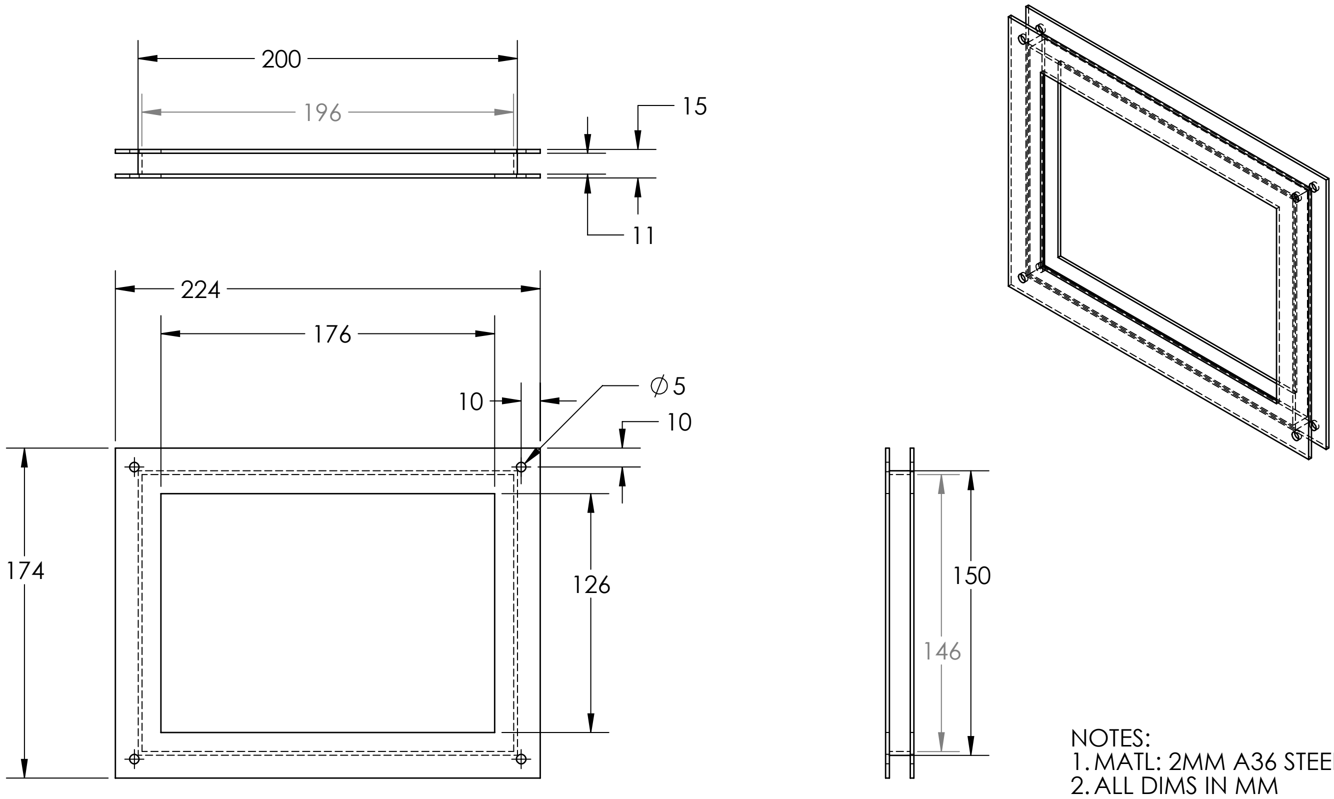
NOTES:
1. MATL: 2 MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. ___________
5. ___________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED				TITLE: interior corners		
OPERATION	PLACES IN DIMENSION			DRAWN	WOJCIECH PRZEPIORA	
	0.0	0.00	0.000	DESIGNED	WOJCIECH PRZEPIORA	
MACHINING				SIZE	DWG. NO.	REV
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030	A	EML4501-022	A
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2		SCALE: 1:8		SHEET 1 OF 2

5 4 3 2 1

SOLIDWORKS Educational Product. For Instructional Use Only.



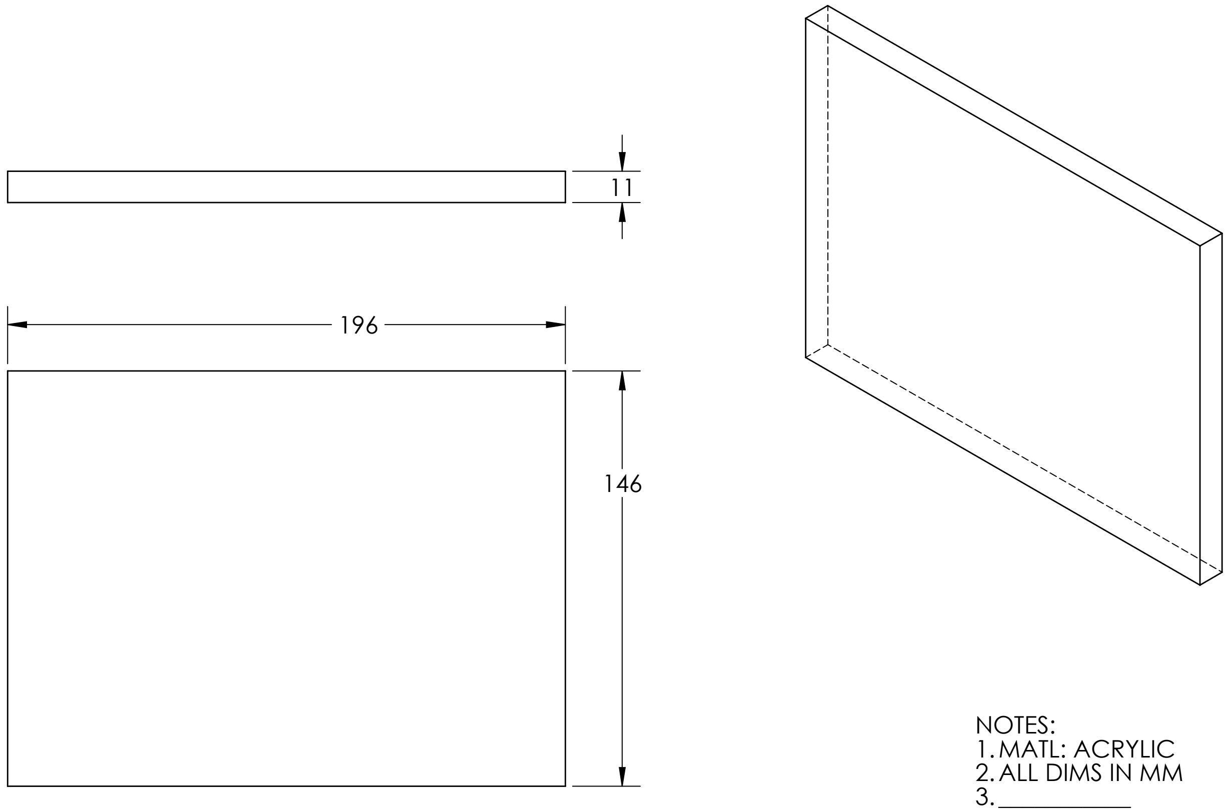
NOTES:
1. MATL: 2MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. __________
5. __________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE: Window frame		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-023	REV A
SCALE: 1:2		SHEET 1 OF 2

5 4 3 2 1



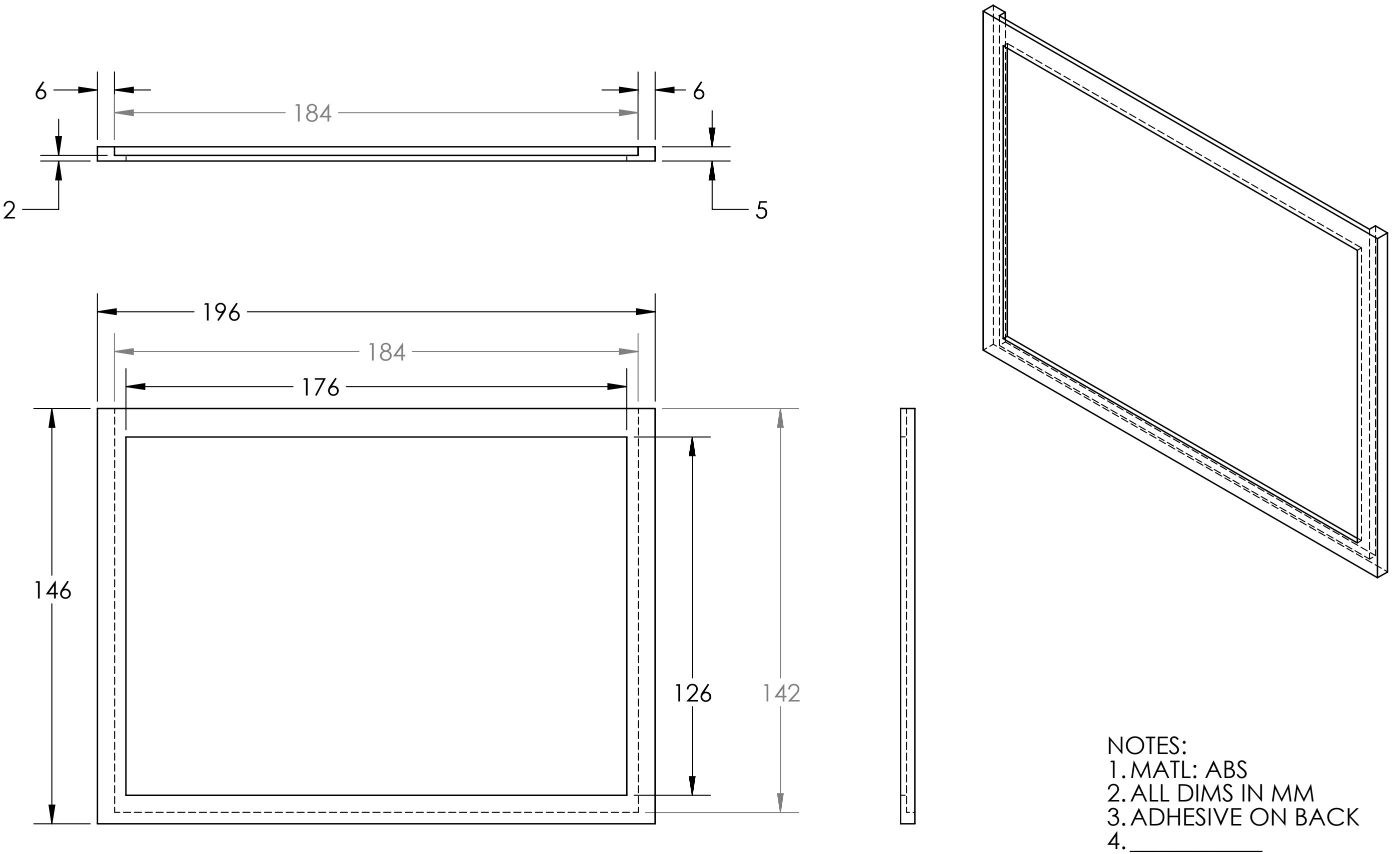
NOTES:
1. MATL: ACRYLIC
2. ALL DIMS IN MM
3. ____________
4. ____________
5. ____________

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE:	Acrylic Sheet	
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-024	REV A
SCALE: 1:2		SHEET 1 OF 1

5 4 3 2 1

SOLIDWORKS Educational Product. For Instructional Use Only.



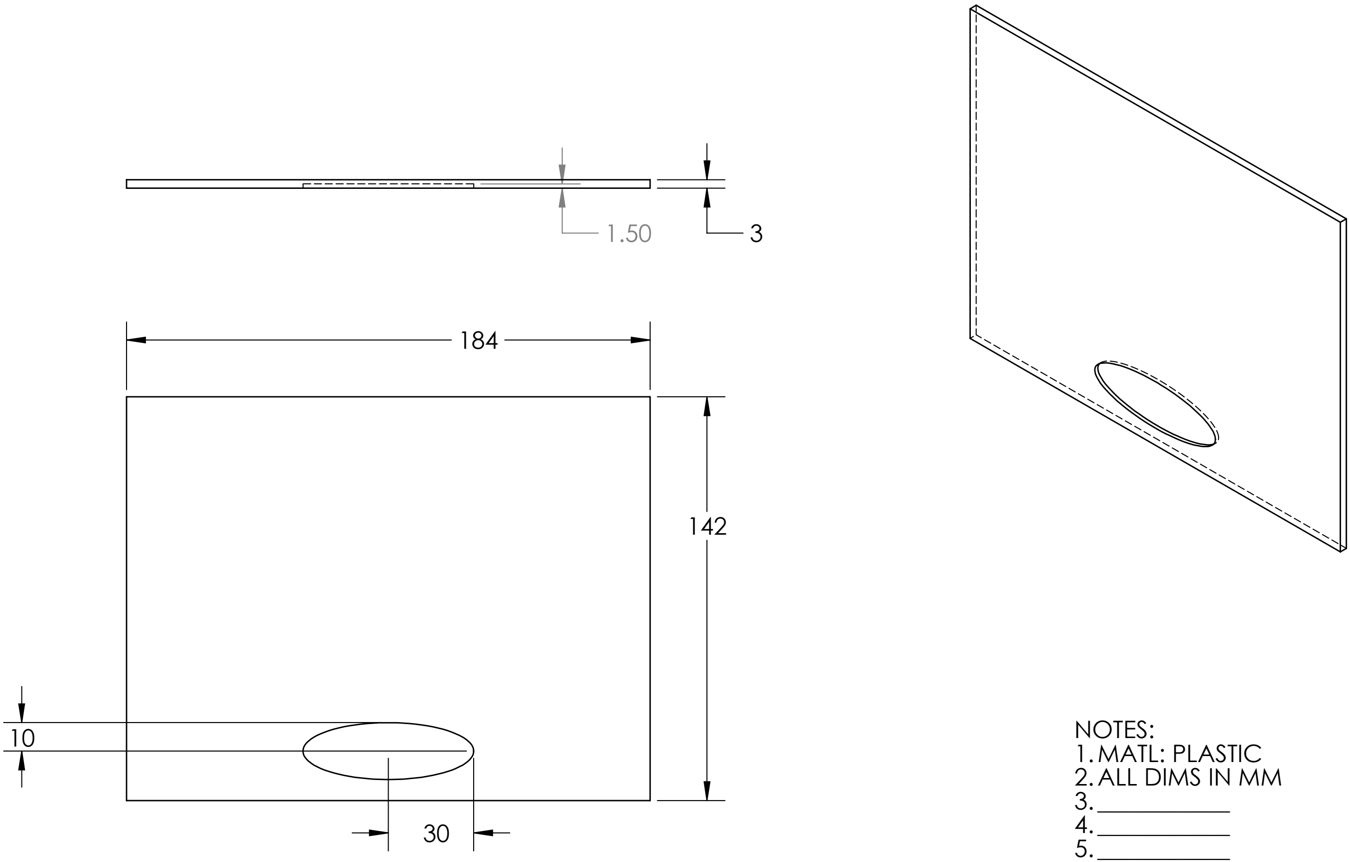
NOTES:
1. MATL: ABS
2. ALL DIMS IN MM
3. ADHESIVE ON BACK
4. ___________
5. ___________

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE:	window screen case
DRAWN	WOJCIECH PRZEPIORA
DESIGNED	WOJCIECH PRZEPIORA
SIZE A	DWG. NO. EML4501-025 — REV A
SCALE: 1:2	SHEET 1 OF 1

5 4 3 2 1

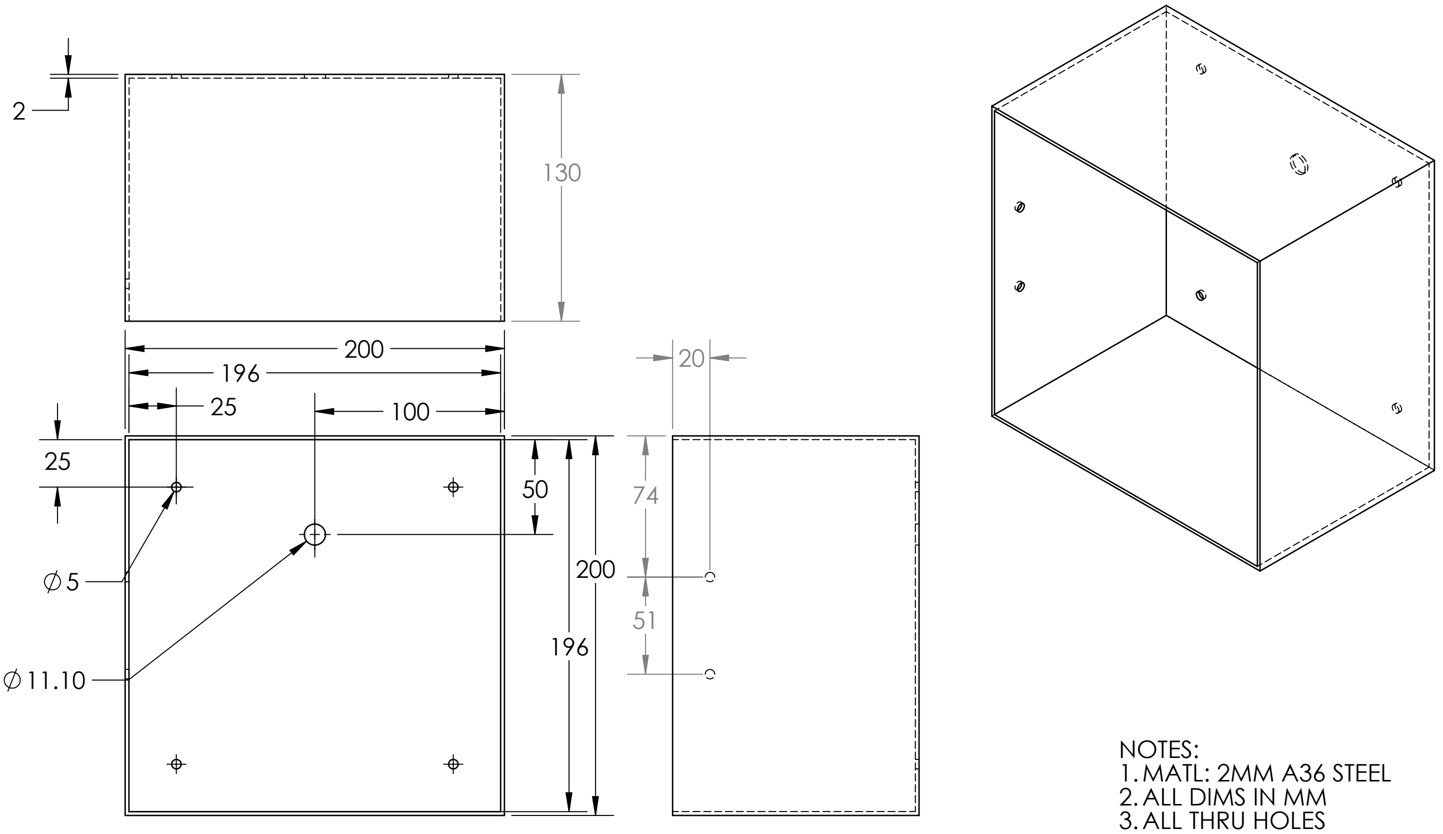
SOLIDWORKS Educational Product. For Instructional Use Only.



NOTES:
1. MATL: PLASTIC
2. ALL DIMS IN MM
3. ____________
4. ____________
5. ____________

TOLERANCE UNLESS NOTED				TITLE: Blackout Screen		
OPERATION	PLACES IN DIMENSION					
	0.0	0.00	0.000	DRAWN	WOJCIECH PRZEPIORA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	WOJCIECH PRZEPIORA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-026	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:2		SHEET 1 OF 1

5 4 3 2 1



NOTES:
1. MATL: 2MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. ___________
5. ___________

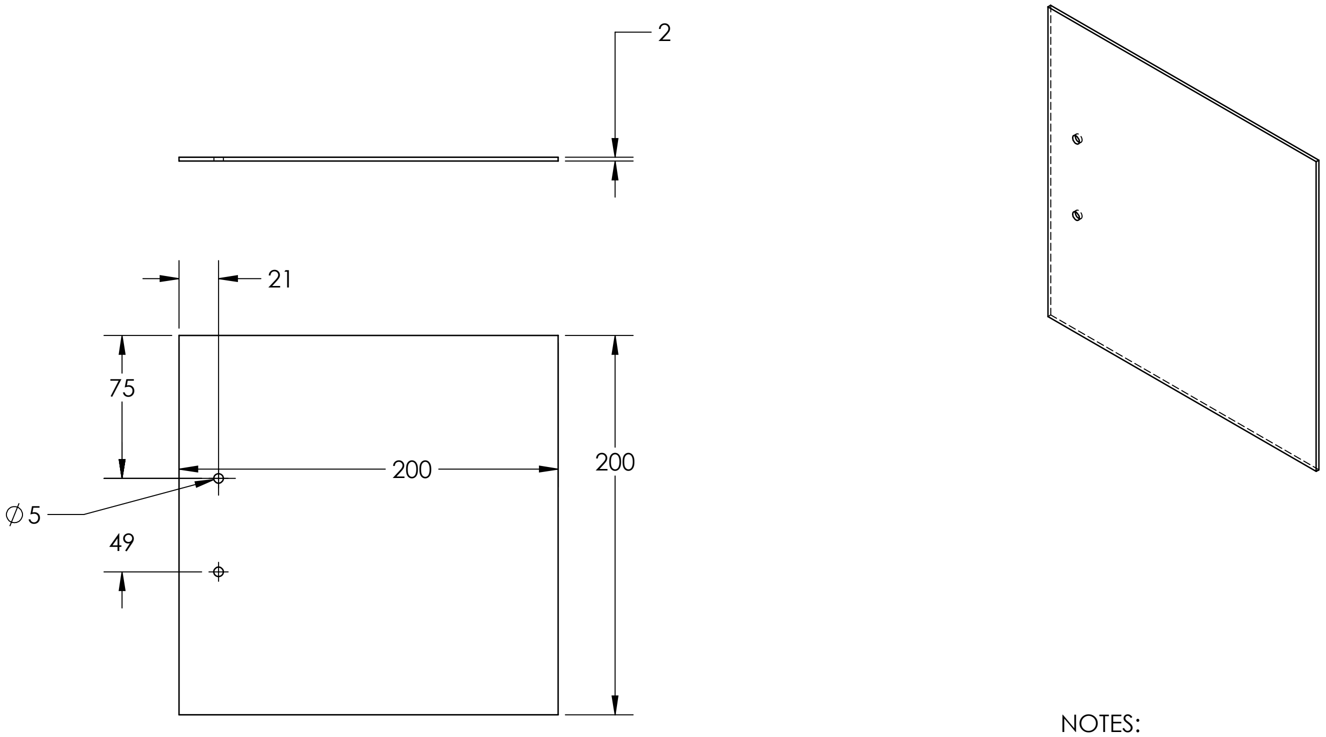
FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE: electrical box		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-027	REV A
SCALE: 1:4		SHEET 1 OF 2

5 4 3 2 1

SOLIDWORKS Educational Product. For Instructional Use Only.

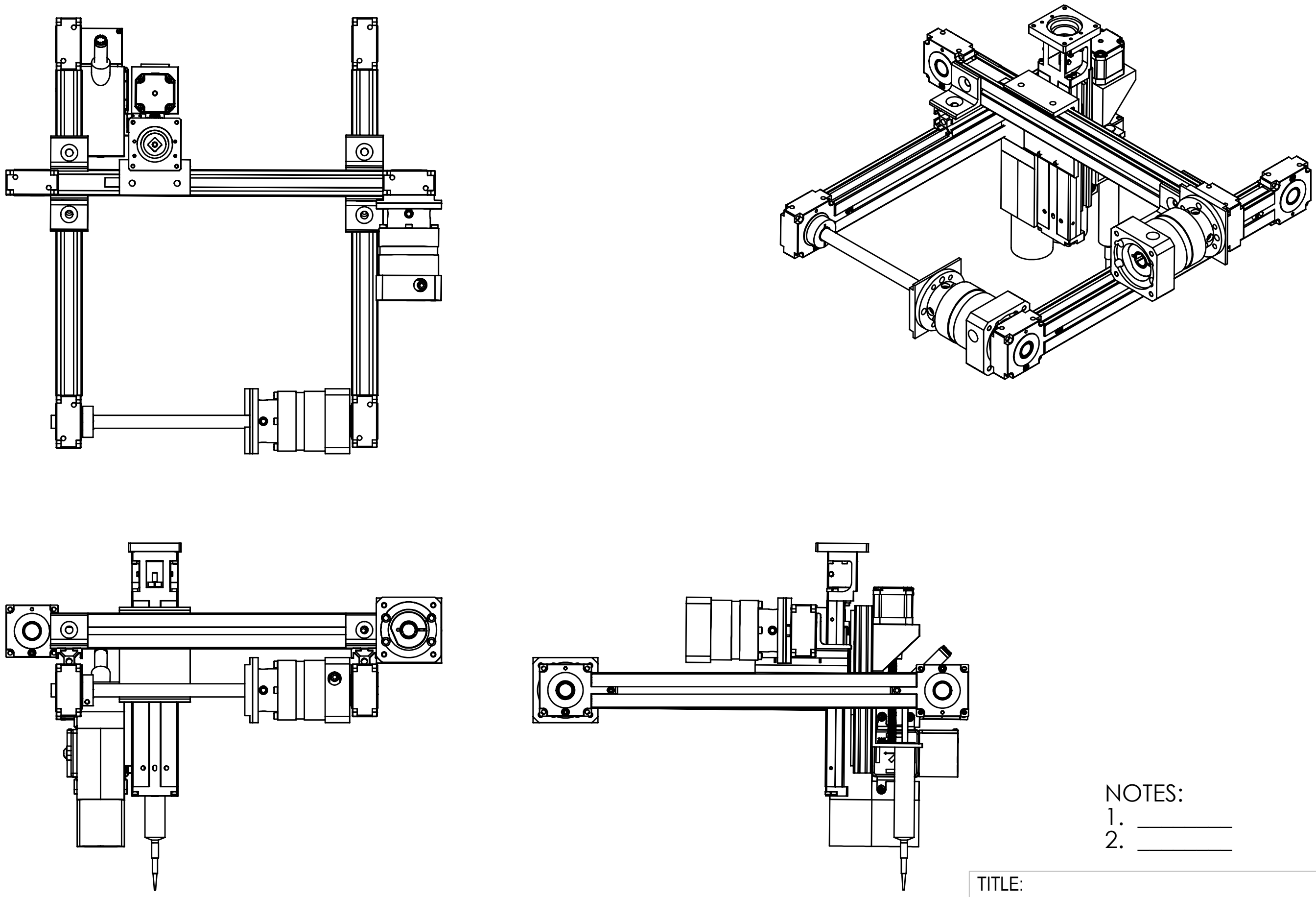


NOTES:
1. MATL: 2MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. ___________
5. ___________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED				TITLE: electrical box door	
OPERATION	PLACES IN DIMENSION				
	0.0	0.00	0.000	DRAWN	WOJCIECH PRZEPIORA
MACHINING				DESIGNED	WOJCIECH PRZEPIORA
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030	SIZE A	DWG. NO. EML4501-028 REV A
WELDING	±0.1	±0.060			
ANGULAR DIMS	±5	±2		SCALE: 1:2	SHEET 1 OF 2

5 4 3 2 1



NOTES:
1. ________
2. ________

TITLE:
Gantry, Liquid Hadeling, ODFI Assembly

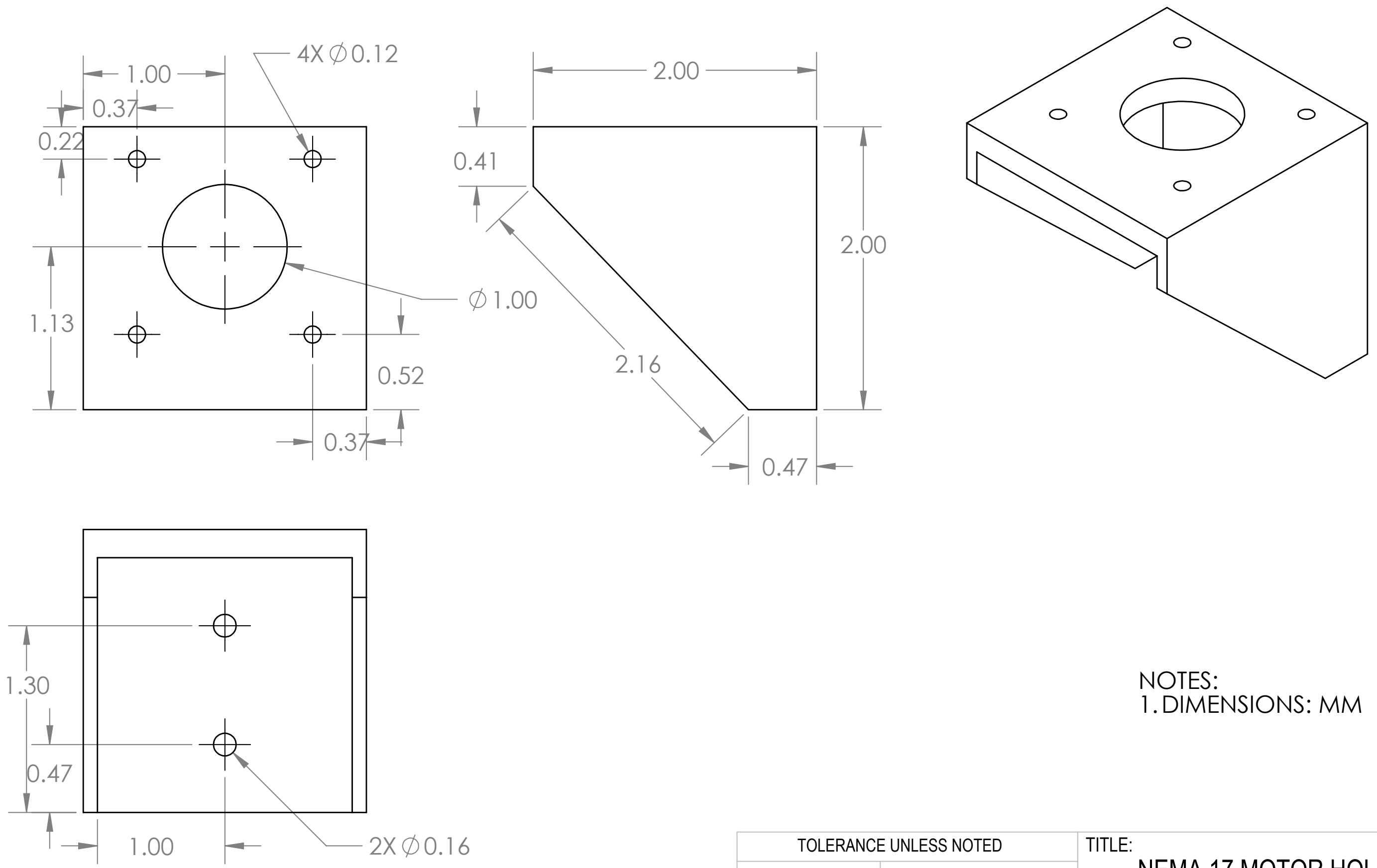
DRAWN	WOJCIECH PRZEPIORA
DESIGNED	MARCELA ABADIA

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

SIZE	DWG. NO.	REV
A	EML4501-A-029	A
SCALE: 1:8		SHEET 1 OF 1

5 4 3 2 1

SOLIDWORKS Educational Product. For Instructional Use Only.

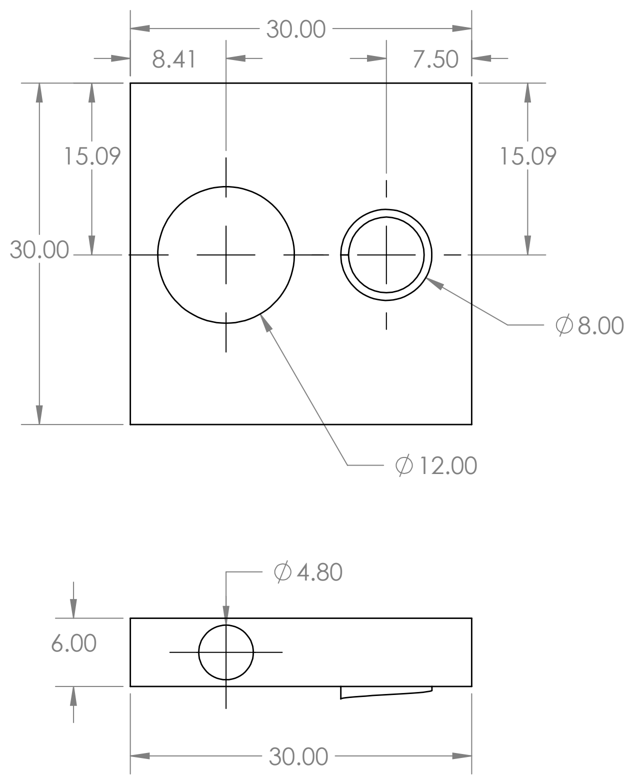


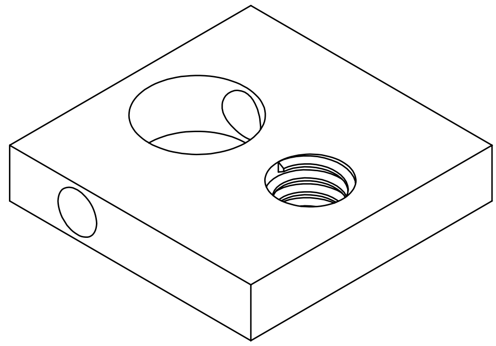
NOTES:
1. DIMENSIONS: MM

TOLERANCE UNLESS NOTED				TITLE: NEMA 17 MOTOR HOLDER		
OPERATION	PLACES IN DIMENSION			DRAWN	JOAO PEDRO DOS SANTOS	
	0.0	0.00	0.000	DESIGNED	WOJCIECH PRZEPIORA	
MACHINING	±0.050	±0.020	±0.005	SIZE	DWG. NO.	REV
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		A	EML4501-030	A
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:1		SHEET 1 OF 1

5 4 3 2 1

SOLIDWORKS Educational Product. For Instructional Use Only.

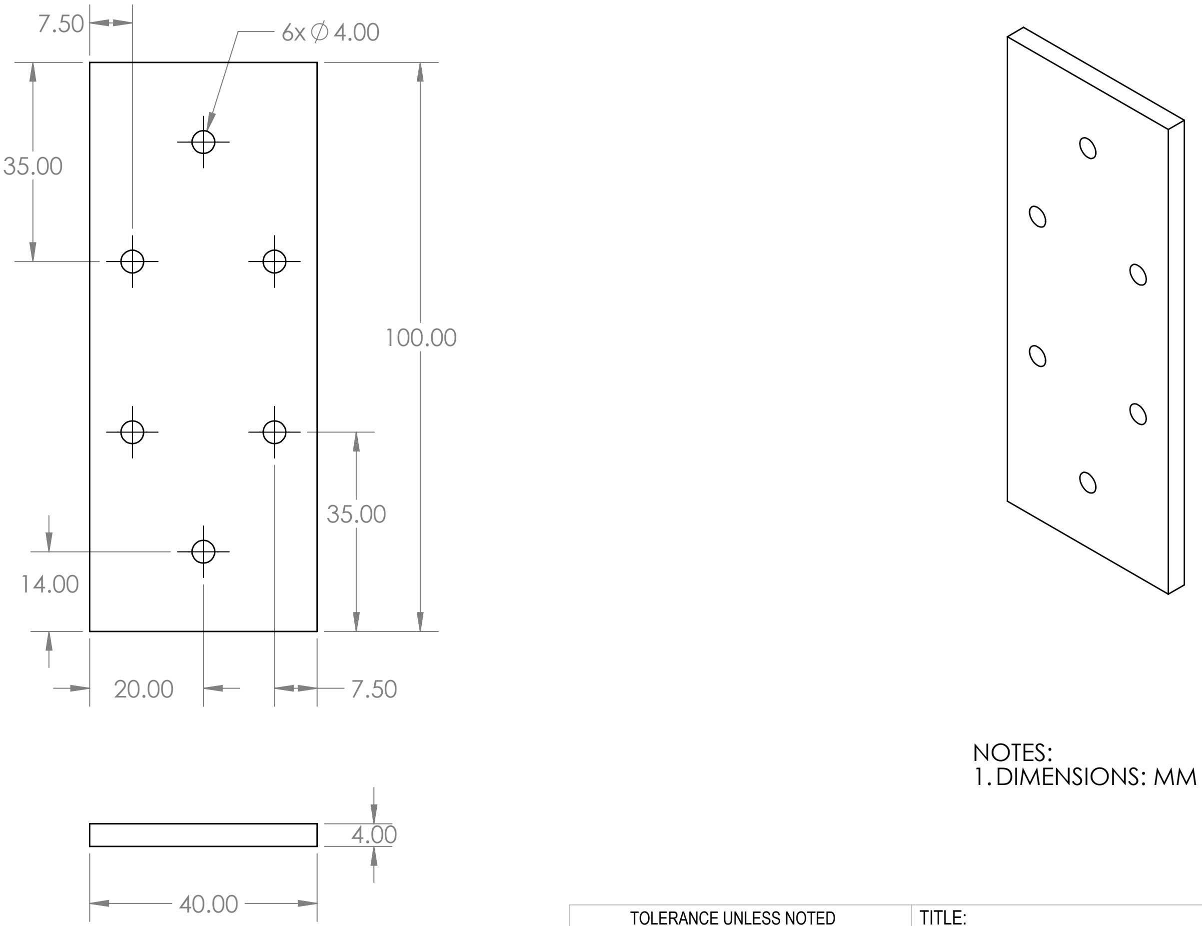




NOTES:
1. DIMENSIONS: MM

TOLERANCE UNLESS NOTED				TITLE: LEAD SCREW MOUNT		
OPERATION	PLACES IN DIMENSION			DRAWN	JOAO PEDRO DOS SANTOS	
	0.0	0.00	0.000	DESIGNED	WOJCIECH PRZEPIORA	
MACHINING	±0.050	±0.020	±0.005	SIZE A	DWG. NO. EML4501-031	REV A
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060				
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2	±0.5	SCALE: 2:1		SHEET 1 OF 1

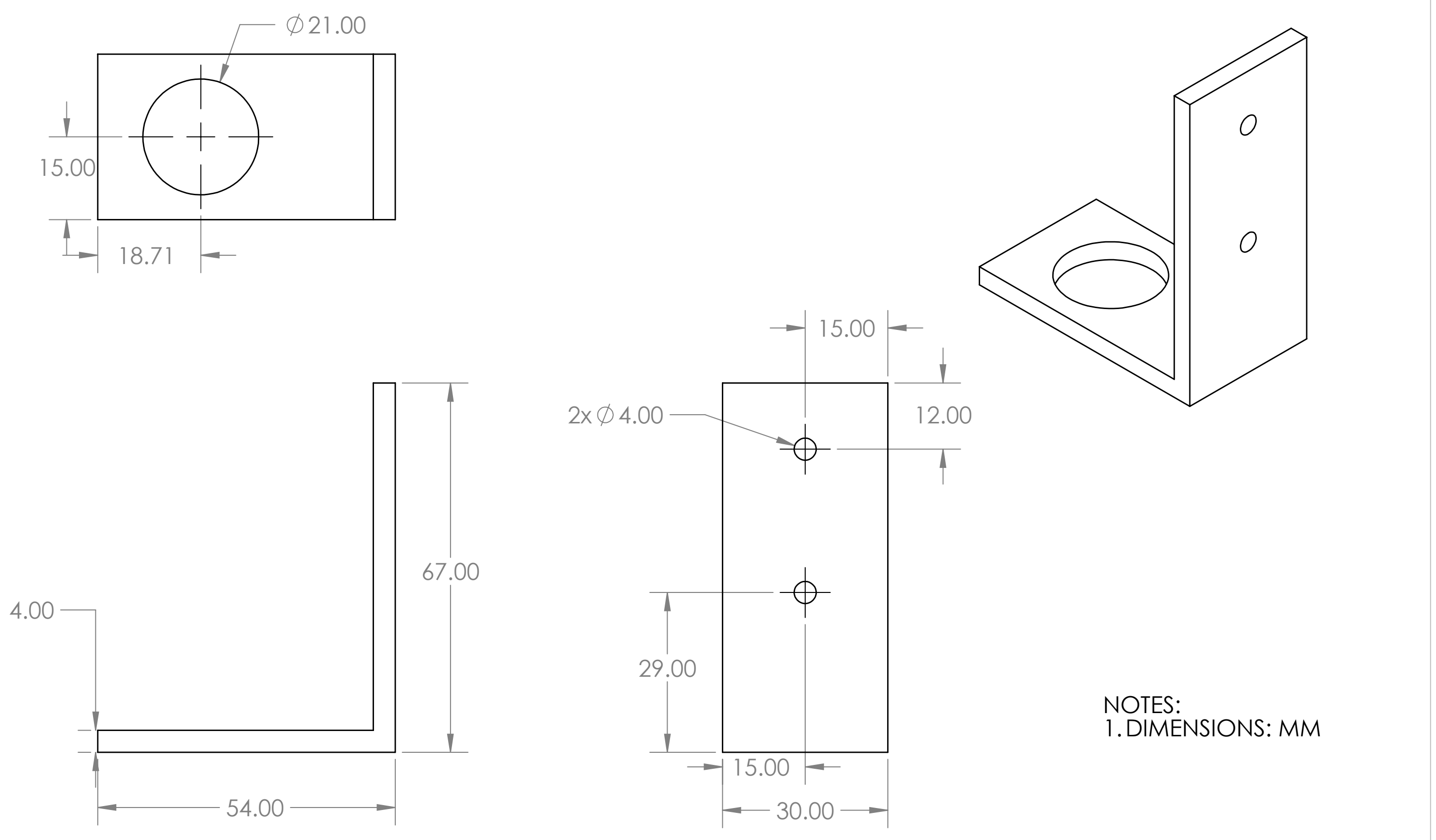
5 4 3 2 1



TOLERANCE UNLESS NOTED				TITLE: PIPETTE GANTRY MOUNT	
OPERATION	PLACES IN DIMENSION				
	0.0	0.00	0.000	DRAWN	JOAO PEDRO DOS SANTOS
MACHINING	±0.050	±0.020	±0.005	DESIGNED	WOJ CIECH PRZEPIORA
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE A	DWG. NO. EML4501-032 REV A
WELDING	±0.1	±0.060			
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:1	SHEET 1 OF 1

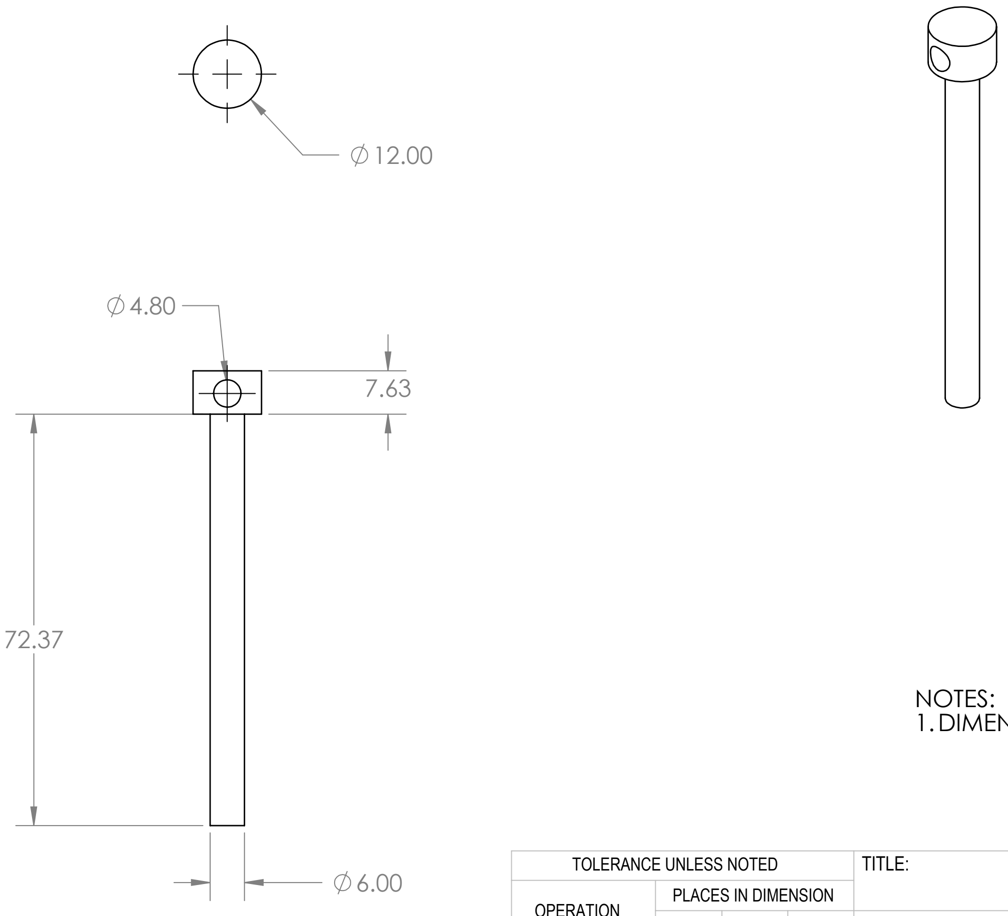
5 4 3 2 1

SOLIDWORKS Educational Product. For Instructional Use Only.



TOLERANCE UNLESS NOTED				TITLE: PIPETTE MOUNT		
OPERATION	PLACES IN DIMENSION					
	0.0	0.00	0.000	DRAWN	JOAO PEDRO DOS SANTOS	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	WOJCIECH PRZEPIORA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE A	DWG. NO. EML4501-033	REV A
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:1		SHEET 1 OF 1

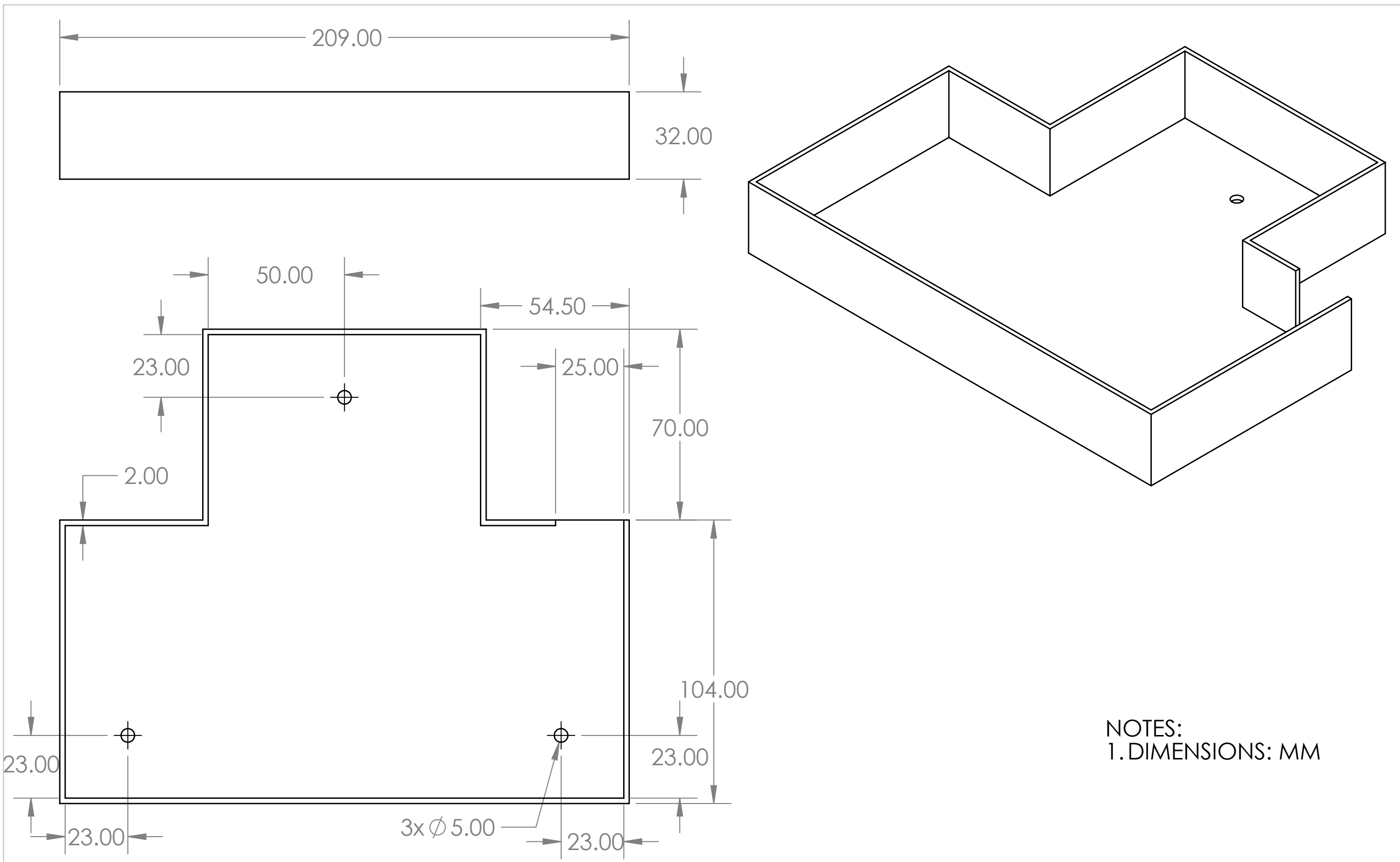
5 4 3 2 1



NOTES:
1. DIMENSIONS: MM

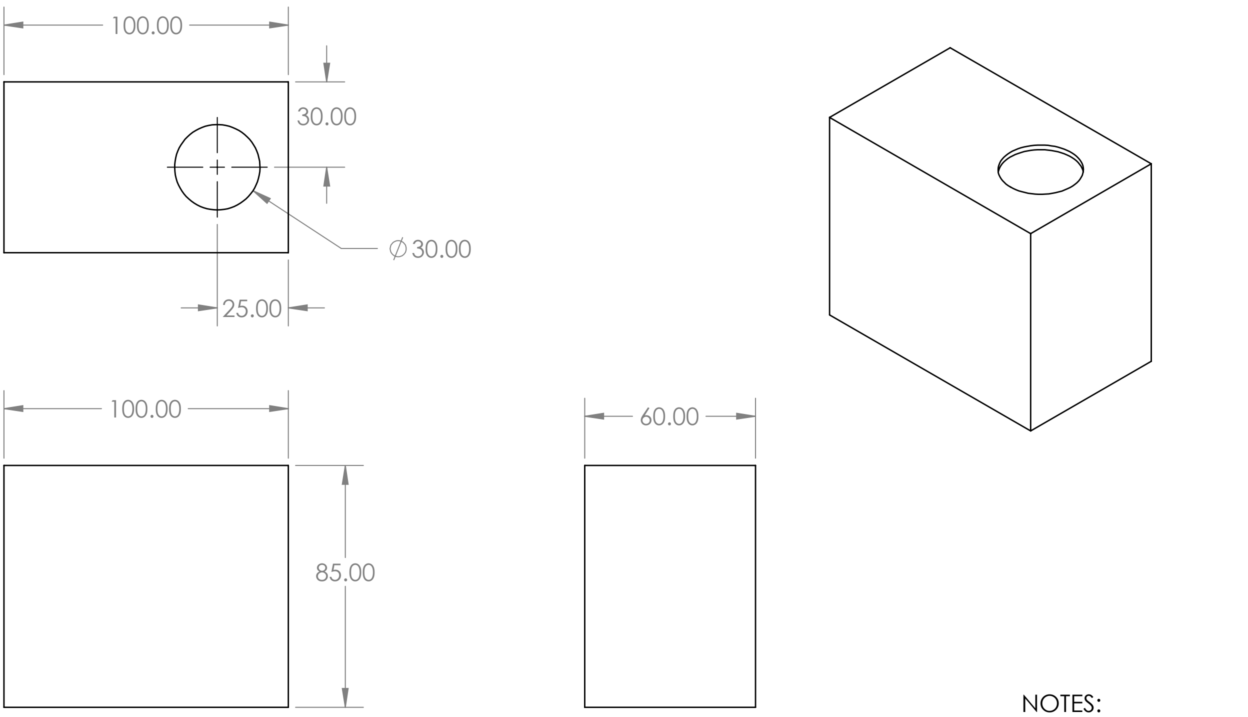
TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			PISTON		
	0.0	0.00	0.000	DRAWN	JOAO PEDRO DOS SANTOS	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	WOJ CIECH PRZEPIORA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-034	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:1		SHEET 1 OF 1

5 4 3 2 1



TOLERANCE UNLESS NOTED				TITLE: CONTAINER HOLDER	
OPERATION	PLACES IN DIMENSION				
	0.0	0.00	0.000	DRAWN	JOAO PEDRO DOS SANTOS
MACHINING	±0.050	±0.020	±0.005	DESIGNED	WOJ CIECH PRZEPIORA
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE A	DWG. NO. EML4501-035 — REV A
WELDING	±0.1	±0.060			
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:2	SHEET 1 OF 1

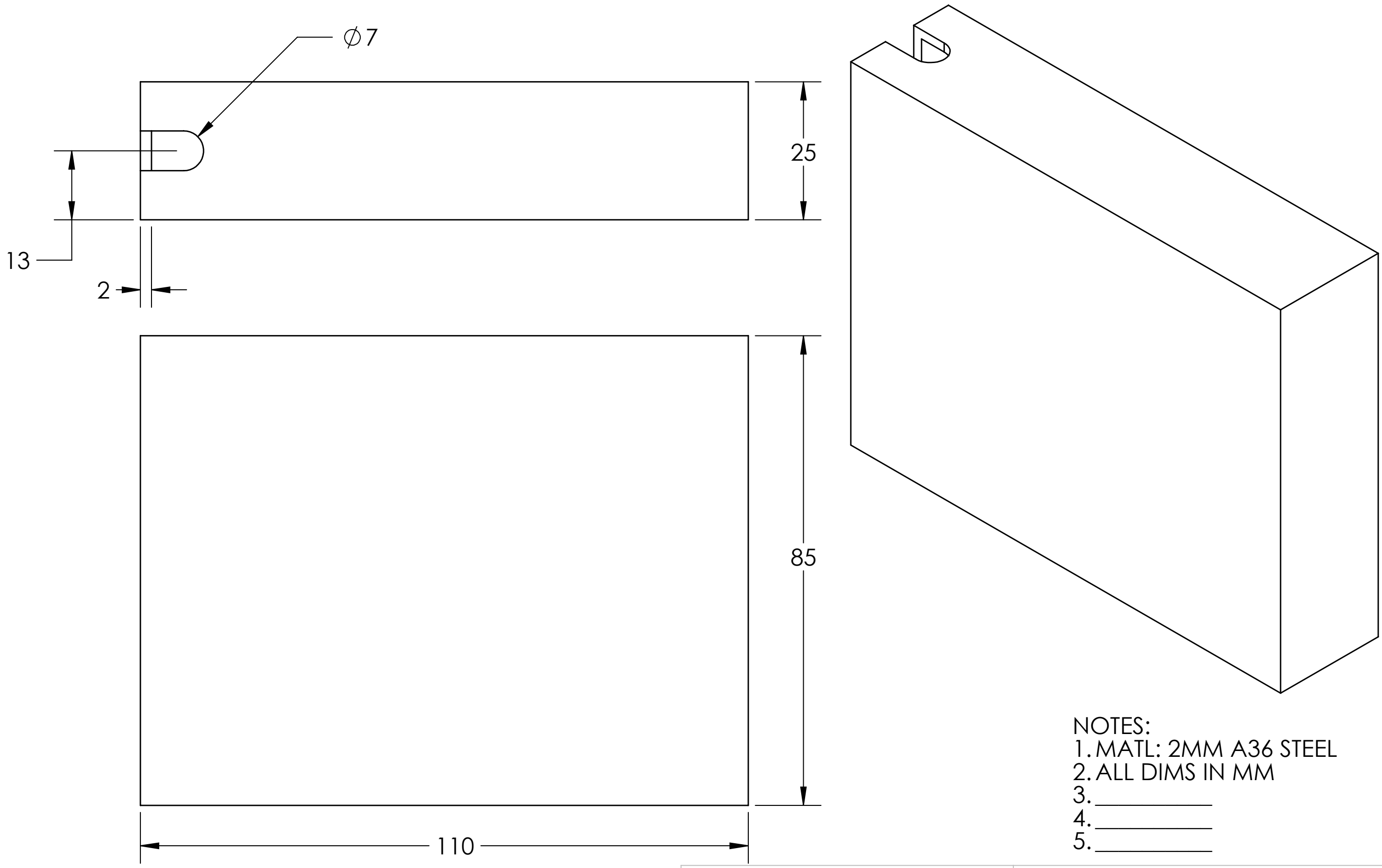
5 4 3 2 1



NOTES:
1. DIMENSIONS: MM
2. QTY: 3

TOLERANCE UNLESS NOTED				TITLE: LIQUID RESERVOIR		
OPERATION	PLACES IN DIMENSION					
	0.0	0.00	0.000	DRAWN	JOAO PEDRO DOS SANTOS	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	WOJ CIECH PRZEPIORA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE A	DWG. NO. EML4501-036	REV A
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:2		SHEET 1 OF 1

5 4 3 2 1

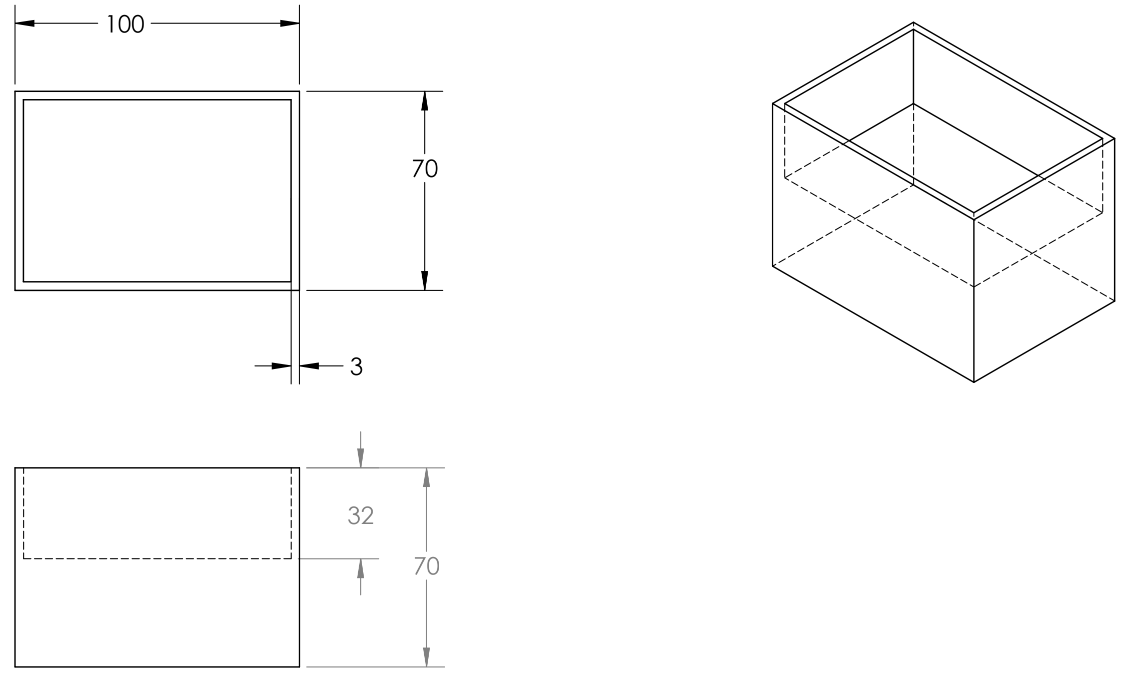


NOTES:
1. MATL: 2MM A36 STEEL
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED				TITLE: Tip disposal		
OPERATION	PLACES IN DIMENSION			DRAWN	WOJCIECH PRZEPIORA	
	0.0	0.00	0.000	DESIGNED	MARCELA ABADIA	
MACHINING				SIZE	DWG. NO.	REV
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030	A	EML4501-037	A
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2		SCALE: 1:1		SHEET 1 OF 2

5 4 3 2 1



NOTES:
1. MATL: 2MM A36 STEEL
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE: tip refill

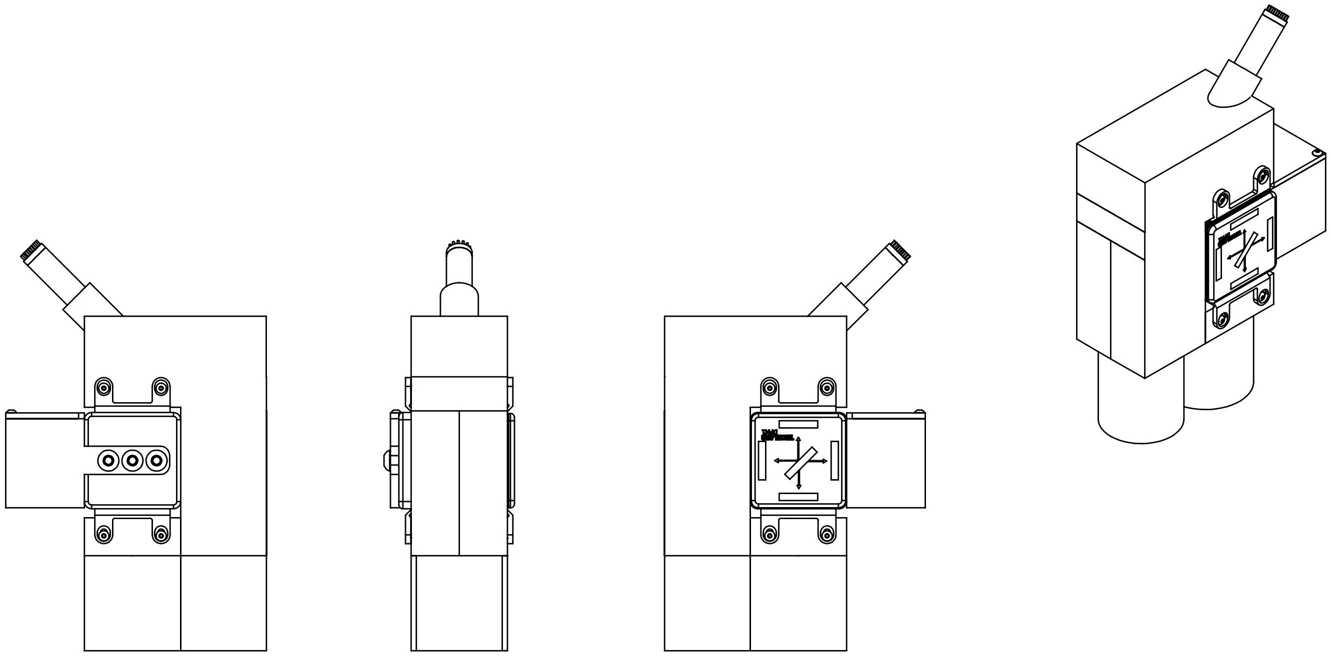
DRAWN WOJCIECH PRZEPIORA

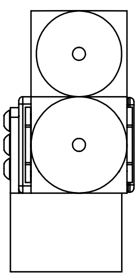
DESIGNED MARCELA ABADIA

SIZE A | DWG. NO. EML4501-038 | REV A

SCALE: 1:2 | SHEET 1 OF 2

5 4 3 2 1





NOTES:
1. ________
2. ________

TITLE: ODFI READER ASSEMBLY

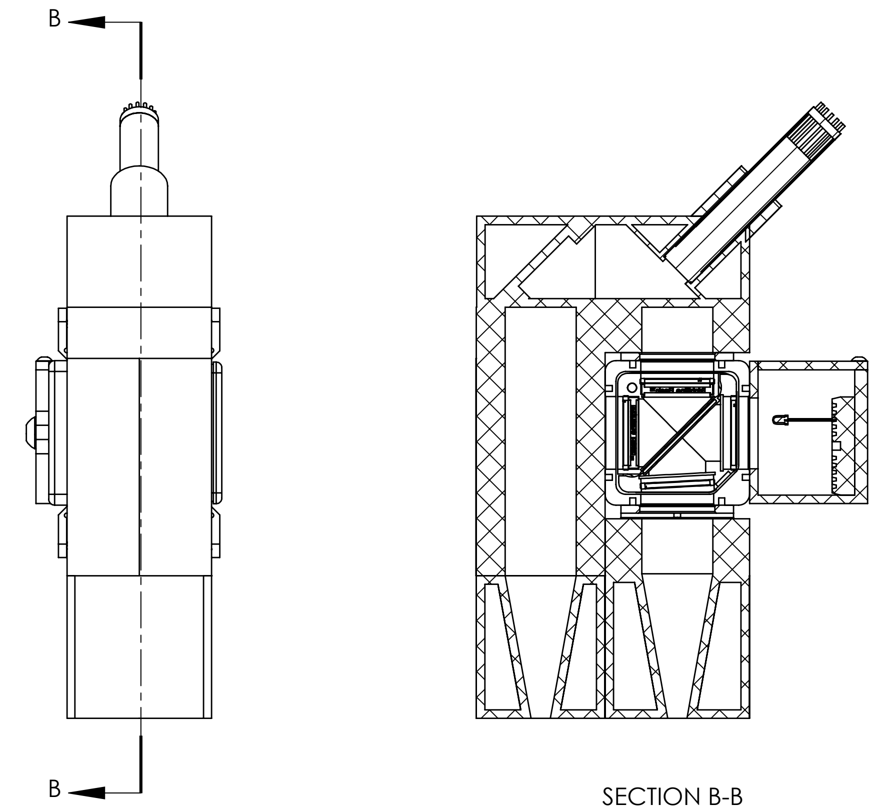
DRAWN	Brenden Modi
DESIGNED	Brenden Modi

TOLERANCE UNLESS NOTED

DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

SIZE	DWG. NO.	REV
A	EML2322L-A-039	A
SCALE: 1:4	SHEET 1 OF 3	

5 4 3 2 1

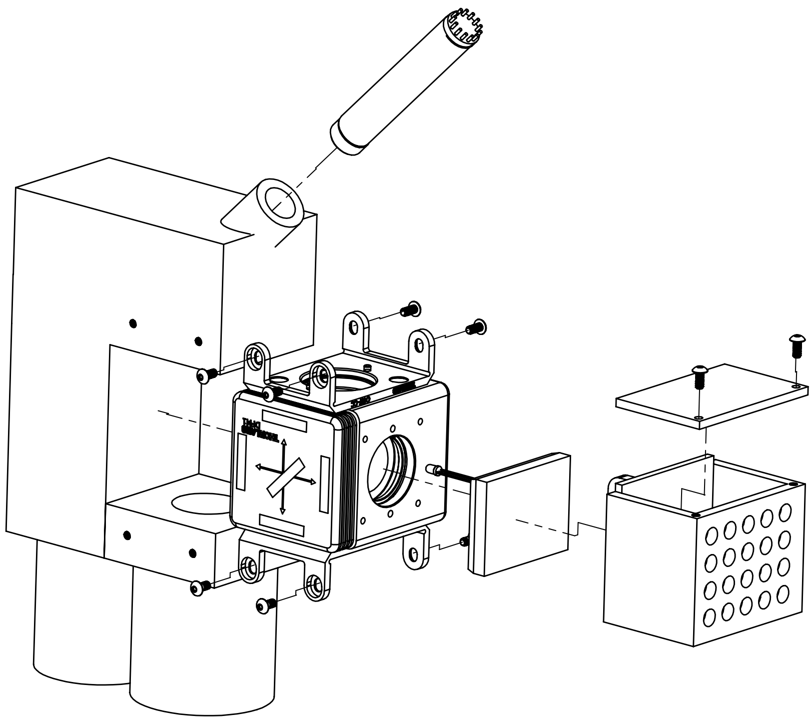


SECTION B-B
SCALE 1 : 2

NOTES:
1. ________
2. ________

TOLERANCE UNLESS NOTED				TITLE: ODFI READER ASSEMBLY
				DRAWN Brenden Modi
				DESIGNED Brenden Modi
DIMENSION TYPE	PLACES IN DIMENSION			SIZE A
	0.0	0.00	0.000	DWG. NO. EML2322L-A-040
LOCATIONAL	±0.050	±0.020	±0.005	REV A
ANGULAR	±5	±2	±0.5	SCALE: 1:4 — SHEET 2 OF 3

5 4 3 2 1



NOTES:
1. ________
2. ________

TITLE:
ODFI READER ASSEMBLY

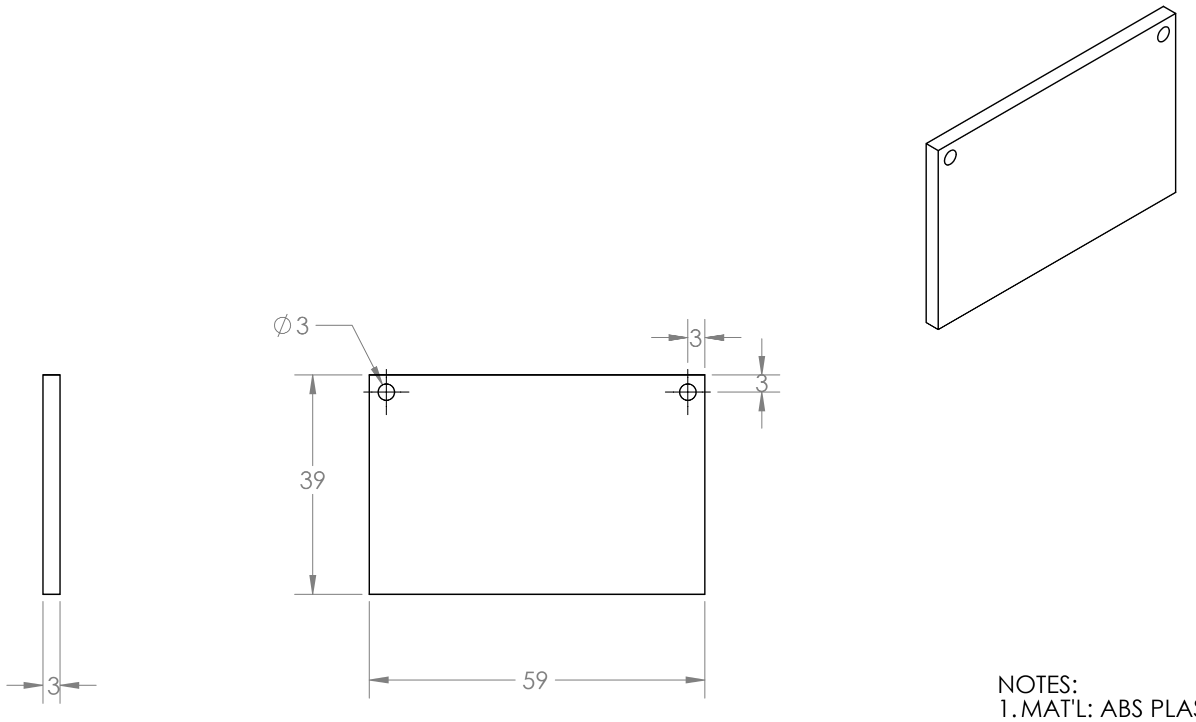
DRAWN	Brenden Modi
DESIGNED	Brenden Modi

TOLERANCE UNLESS NOTED

DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

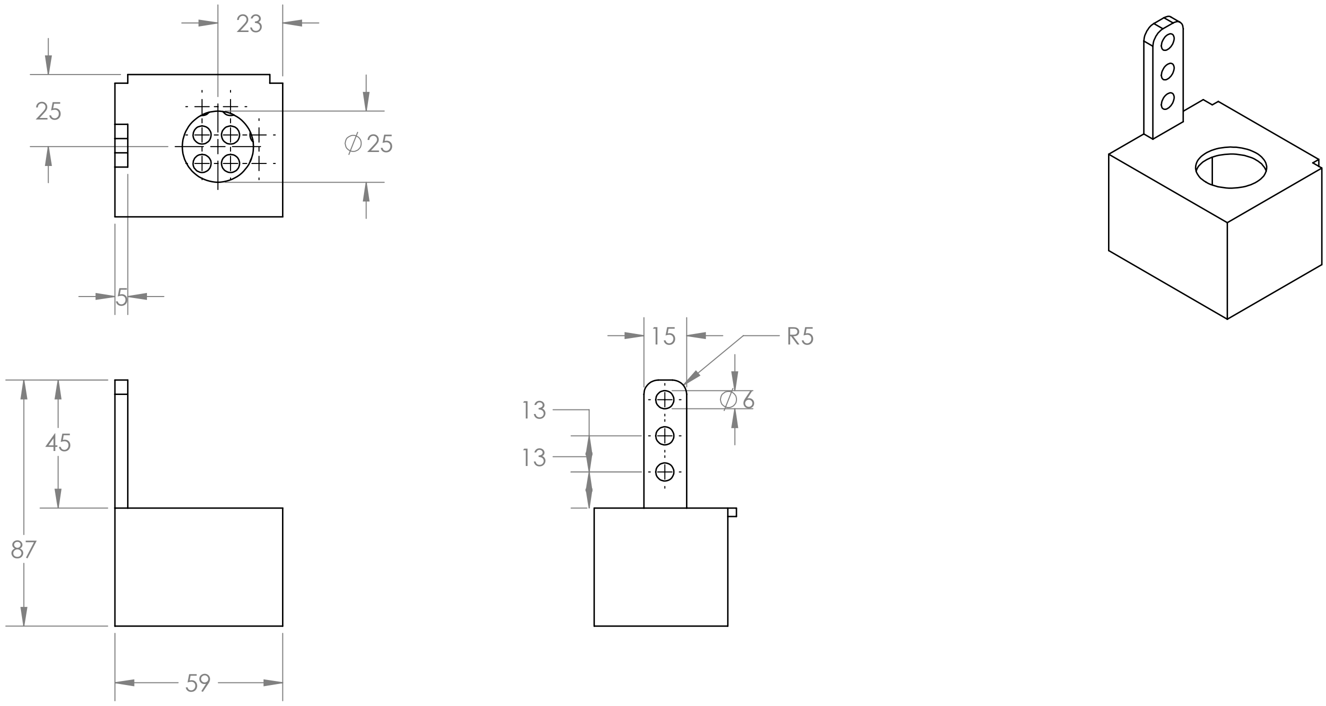
SIZE	DWG. NO.	REV
A	EML2322L-A-041	A
SCALE: 1:8		SHEET 3 OF 3

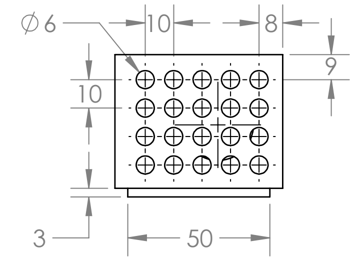
5 4 3 2 1



NOTES:
1. MAT'L: ABS PLASTIC
2. 3D PRINTED
3. ALL TOLERANCES = ±0.05
4. ALL DIMS IN MM.

TOLERANCE UNLESS NOTED				TITLE: ODFI Top Cover
OPERATION	PLACES IN DIMENSION			
	0.0	0.00	0.000	DRAWN Brenden Modi
MACHINING	±0.050	±0.020	±0.005	DESIGNED Brenden Modi
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE A / DWG. NO. EML2322L-042 / REV A
WELDING	±0.1	±0.060		
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:1 / SHEET 1 OF 3

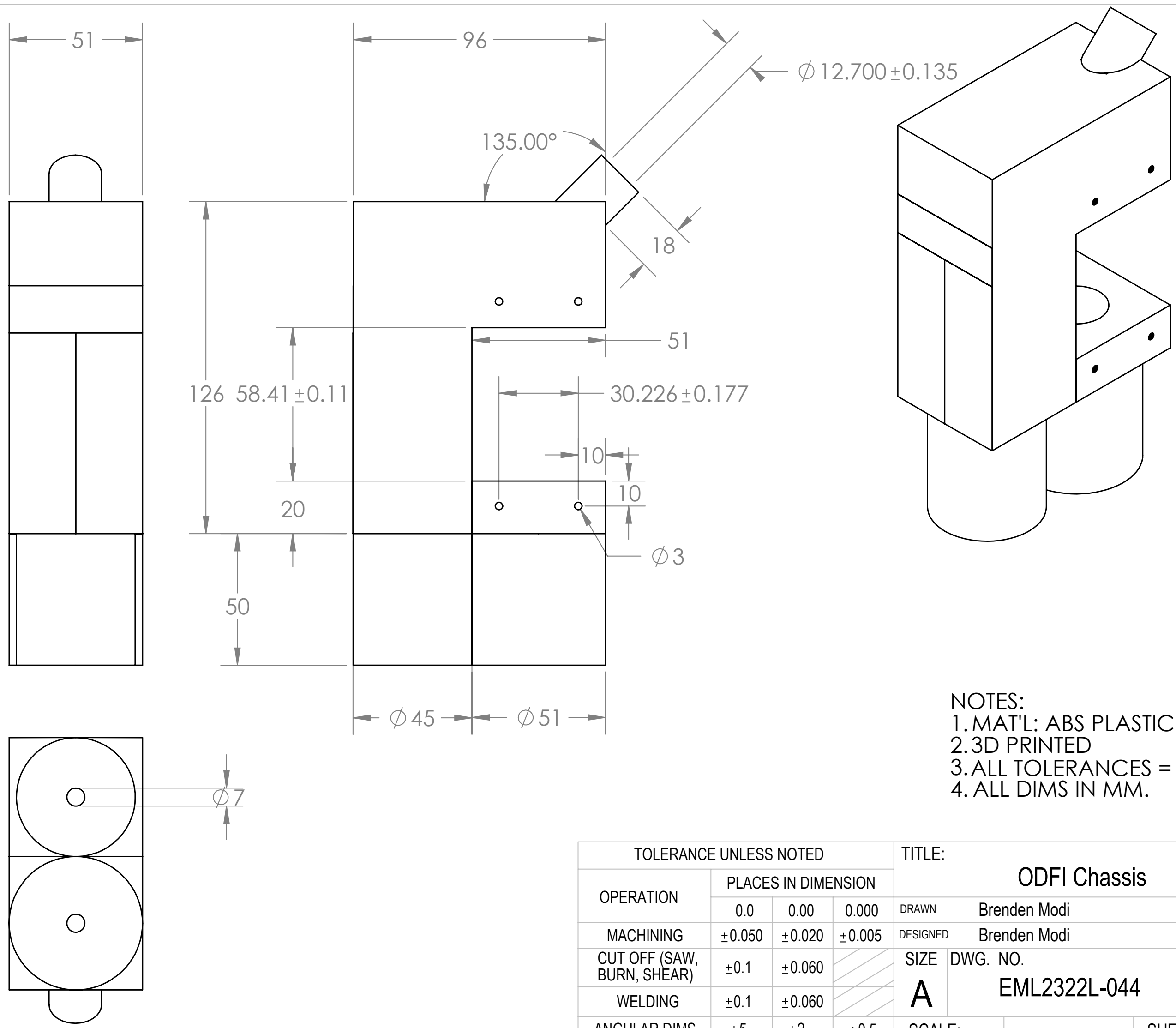




NOTES:
1. MAT'L: ABS PLASTIC
2. 3D PRINTED
3. ALL TOLERANCES = ±0.05
4. ALL DIMS IN MM.

TOLERANCE UNLESS NOTED				TITLE: ODFI Light Bracket	
OPERATION	PLACES IN DIMENSION				
	0.0	0.00	0.000	DRAWN	Brenden Modi
MACHINING	±0.050	±0.020	±0.005	DESIGNED	Brenden Modi
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE A	DWG. NO. EML2322L-043 REV A
WELDING	±0.1	±0.060			
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:2	SHEET 2 OF 3

5 4 3 2 1



NOTES:
1. MAT'L: ABS PLASTIC
2. 3D PRINTED
3. ALL TOLERANCES = ±0.05
4. ALL DIMS IN MM.

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE: ODFI Chassis

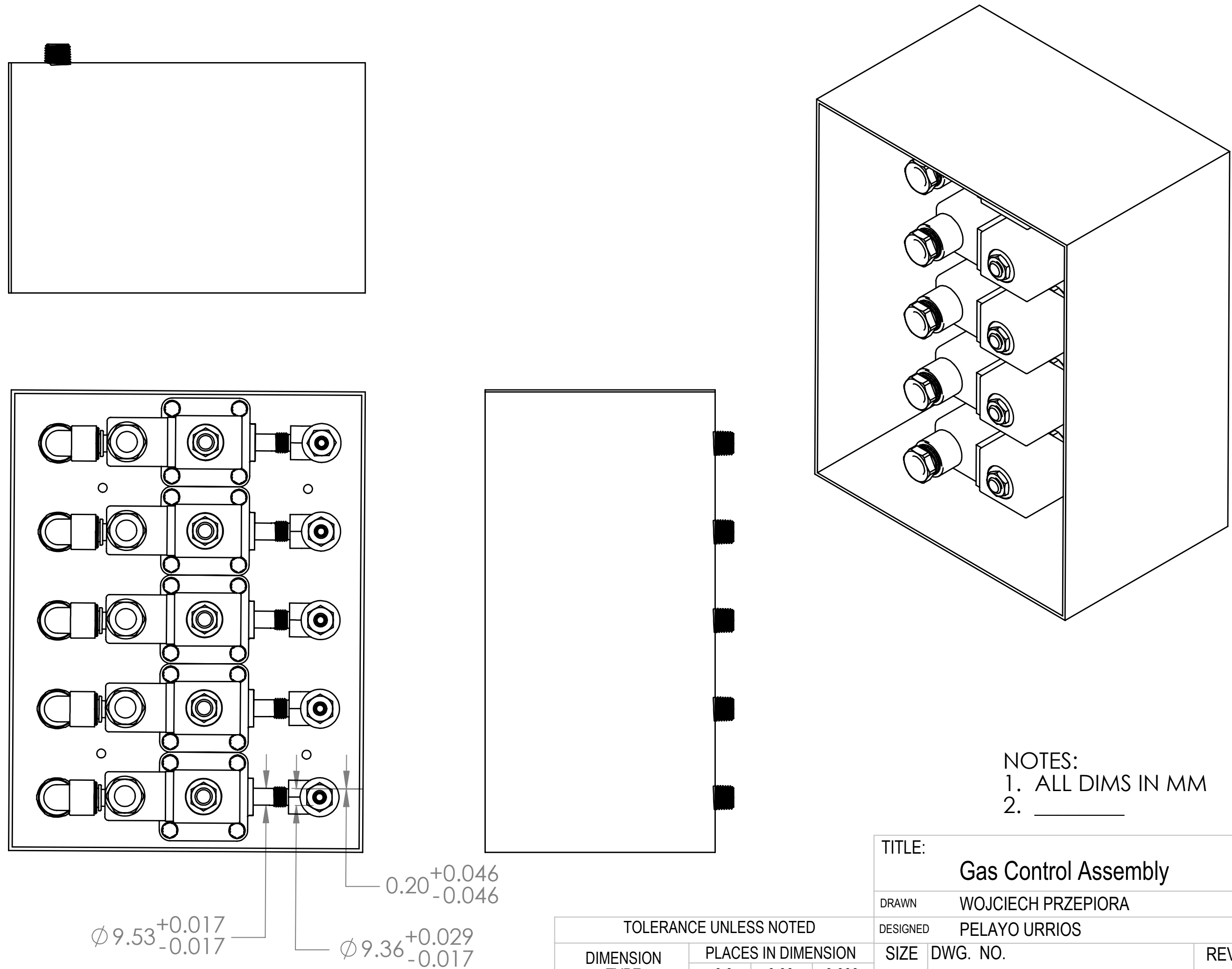
DRAWN: Brenden Modi

DESIGNED: Brenden Modi

SIZE: A | DWG. NO.: EML2322L-044 | REV: A

SCALE: 1:5 | SHEET 3 OF 3

5 4 3 2 1

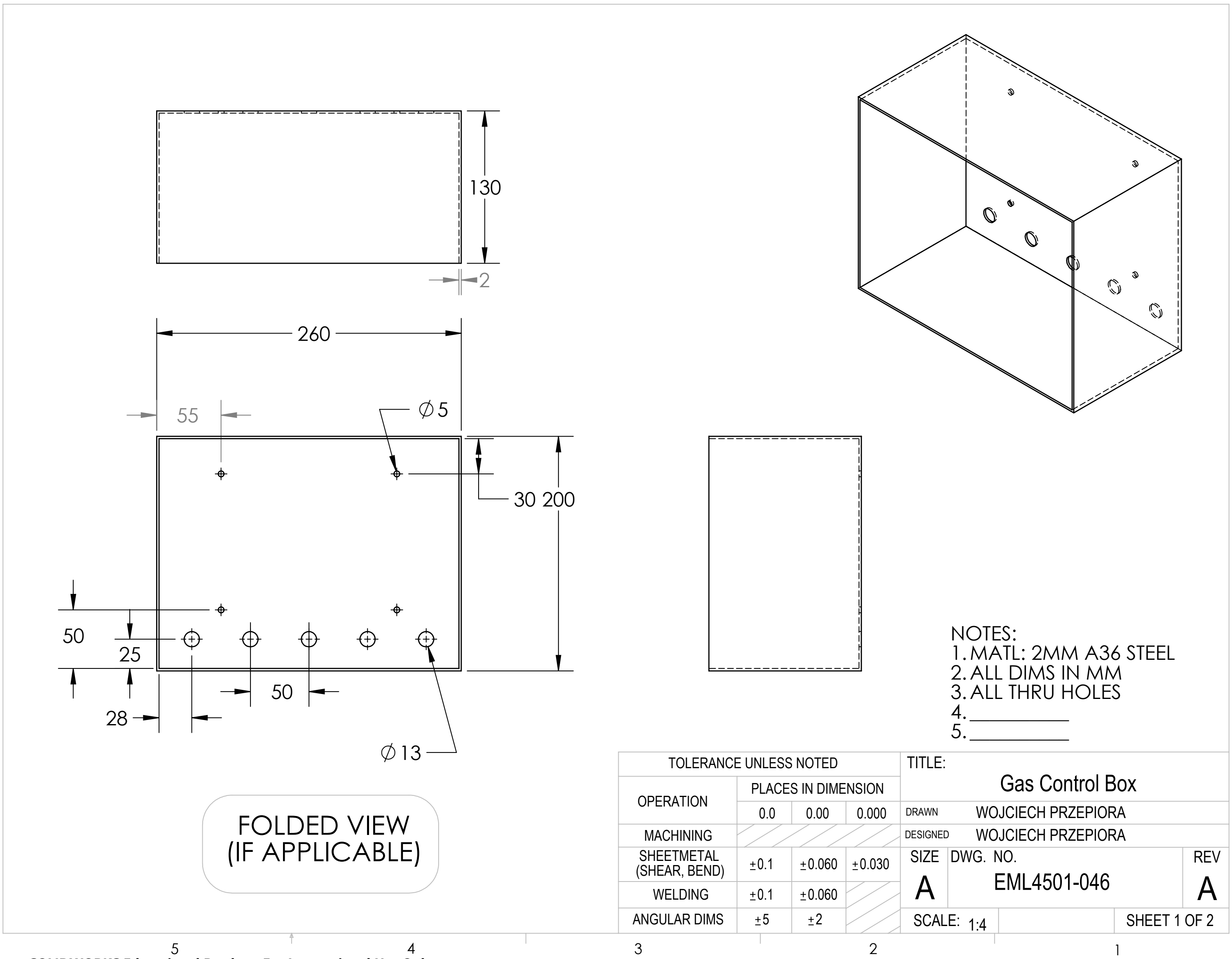


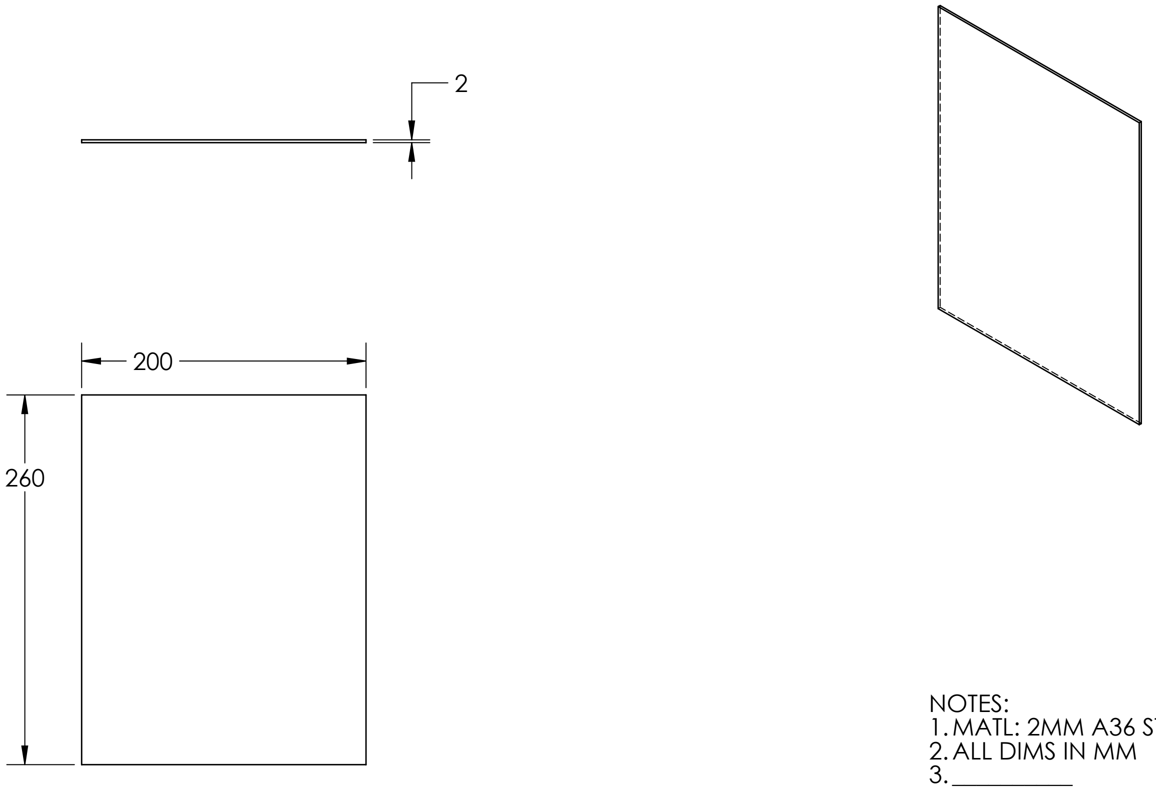
NOTES:
1. ALL DIMS IN MM
2. ________

TITLE:	Gas Control Assembly			
DRAWN	WOJCIECH PRZEPIORA			
DESIGNED	PELAYO URRIOS			
SIZE	DWG. NO.		REV	
A	EML4501-A-045		A	
SCALE: 1:4		SHEET 1 OF 1		

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

5 4 3 2 1


130
2
260
55
∅5
30 200
50
25
28
50
∅13
NOTES:
1. MATL: 2MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4.
5.
FOLDED VIEW
(IF APPLICABLE)
TOLERANCE UNLESS NOTED
OPERATION
PLACES IN DIMENSION
0.0 0.00 0.000
MACHINING
SHEETMETAL (SHEAR, BEND) ±0.1 ±0.060 ±0.030
WELDING ±0.1 ±0.060
ANGULAR DIMS ±5 ±2
TITLE:
Gas Control Box
DRAWN WOJCIECH PRZEPIORA
DESIGNED WOJCIECH PRZEPIORA
SIZE A
DWG. NO. EML4501-046
REV A
SCALE: 1:4
SHEET 1 OF 2
5 4 3 2 1



NOTES:
1. MATL: 2MM A36 STEEL
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

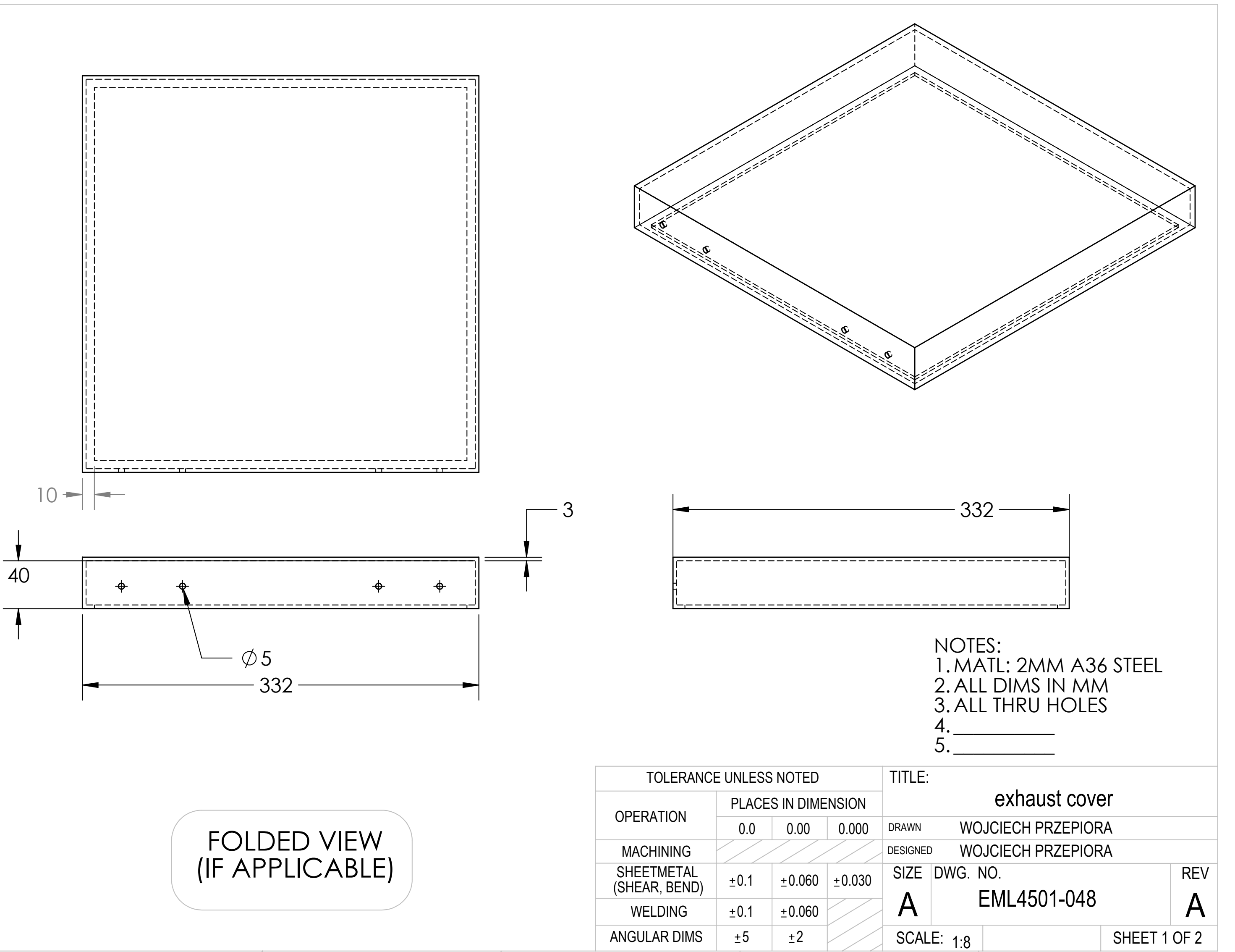
FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE: gas box door		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-047	REV A
SCALE: 1:4		SHEET 1 OF 2

5 4 3 2 1

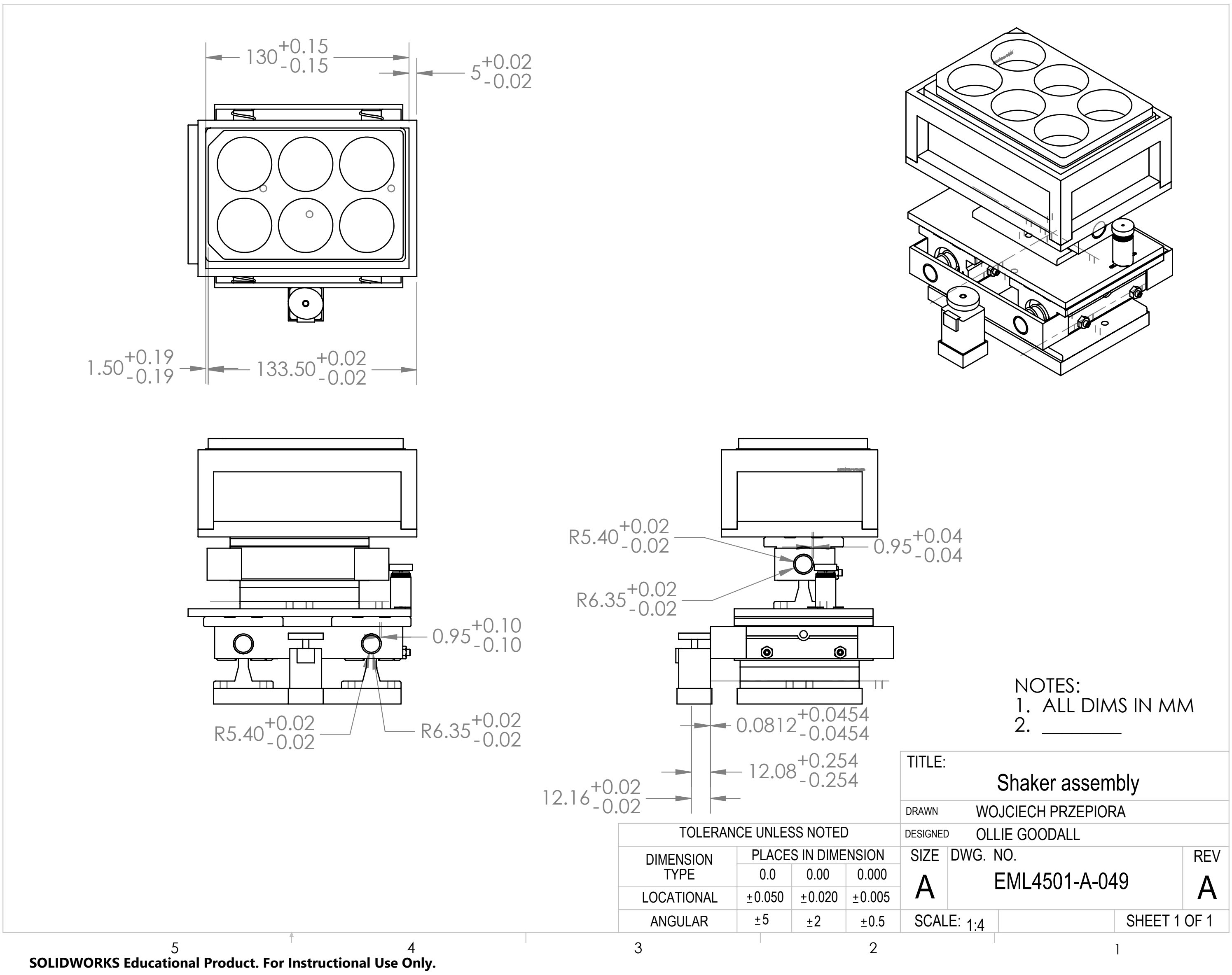
SOLIDWORKS Educational Product. For Instructional Use Only.

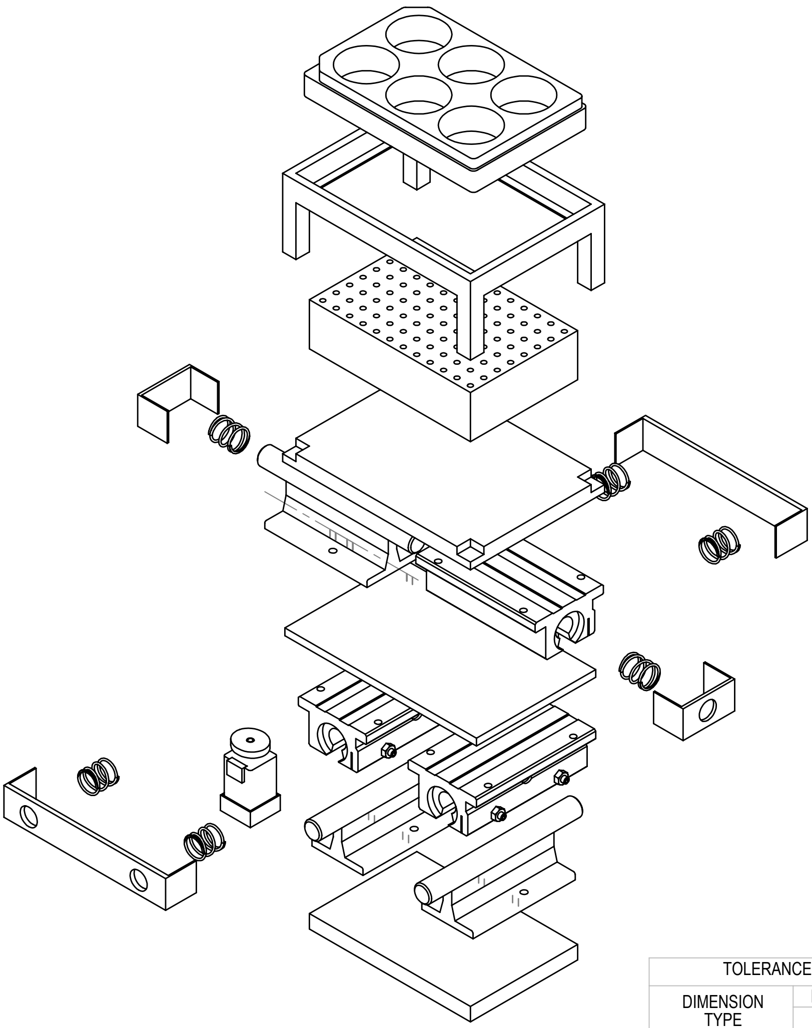


NOTES:
1. MATL: 2MM A36 STEEL
2. ALL DIMS IN MM
3. ALL THRU HOLES
4. ___________
5. ___________

TOLERANCE UNLESS NOTED				TITLE: exhaust cover
OPERATION	PLACES IN DIMENSION			DRAWN: WOJCIECH PRZEPIORA
	0.0	0.00	0.000	DESIGNED: WOJCIECH PRZEPIORA
MACHINING				SIZE: A — DWG. NO.: EML4501-048 — REV: A
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030	
WELDING	±0.1	±0.060		
ANGULAR DIMS	±5	±2		SCALE: 1:8 — SHEET 1 OF 2

5 4 3 2 1


130 +0.15 -0.15
5 +0.02 -0.02
1.50 +0.19 -0.19
133.50 +0.02 -0.02
R5.40 +0.02 -0.02
R6.35 +0.02 -0.02
0.95 +0.10 -0.10
R5.40 +0.02 -0.02
R6.35 +0.02 -0.02
R5.40 +0.02 -0.02
0.95 +0.04 -0.04
R6.35 +0.02 -0.02
0.0812 +0.0454 -0.0454
12.08 +0.254 -0.254
12.16 +0.02 -0.02
NOTES:
1. ALL DIMS IN MM
2. ________
TITLE:
Shaker assembly
DRAWN WOJCIECH PRZEPIORA
DESIGNED OLLIE GOODALL
TOLERANCE UNLESS NOTED
DIMENSION TYPE
PLACES IN DIMENSION
0.0
0.00
0.000
LOCATIONAL ±0.050 ±0.020 ±0.005
ANGULAR ±5 ±2 ±0.5
SIZE A
DWG. NO. EML4501-A-049
REV A
SCALE: 1:4
SHEET 1 OF 1
5
4
3
2
1
SOLIDWORKS Educational Product. For Instructional Use Only.



NOTES:
1. ________
2. ________

TITLE: Shaker assembly Exploded

DRAWN: WOJCIECH PRZEPIORA

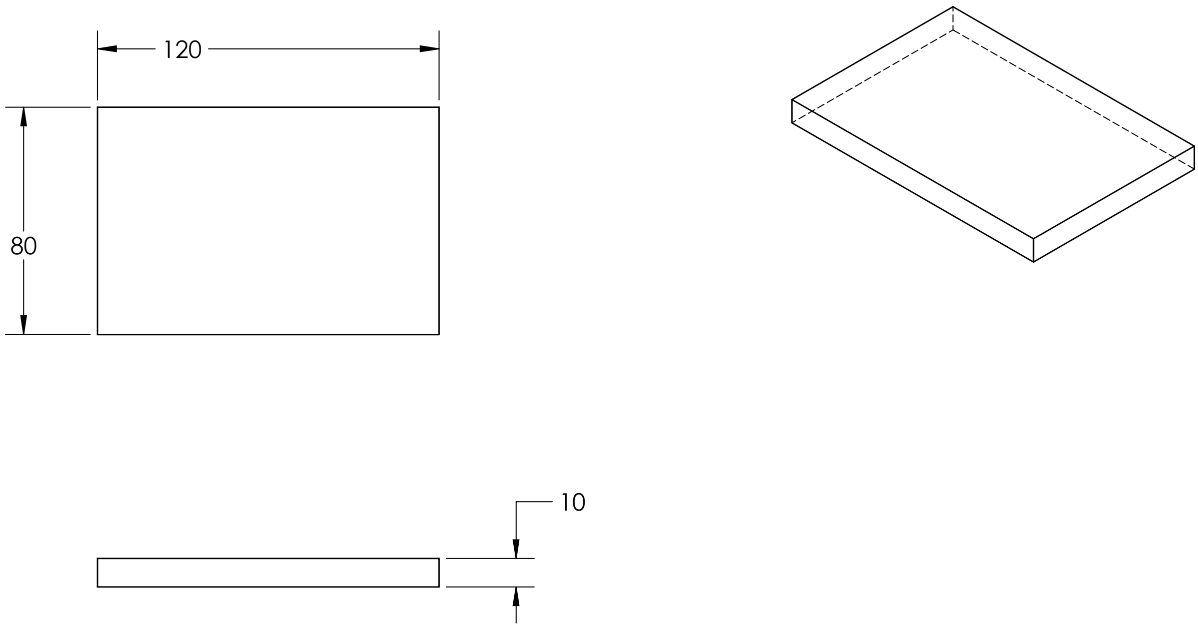
DESIGNED: OLLIE GOODALL

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

SIZE	DWG. NO.	REV
A	EML4501-A-050	A

SCALE: 1:12 SHEET 1 OF 1

5 4 3 2 1



NOTES:
1. MATL: A36 STEEL
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

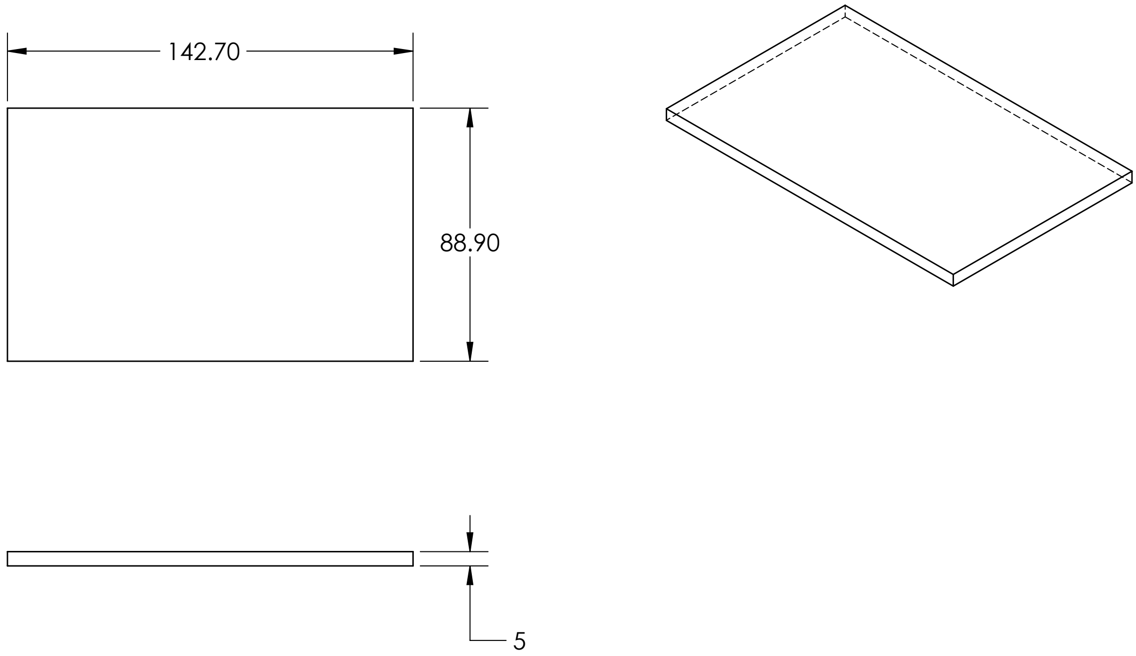
FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE:		
shaker base plate		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-051	REV A
SCALE: 1:2		SHEET 1 OF 2

5 4 3 2 1

SOLIDWORKS Educational Product. For Instructional Use Only.



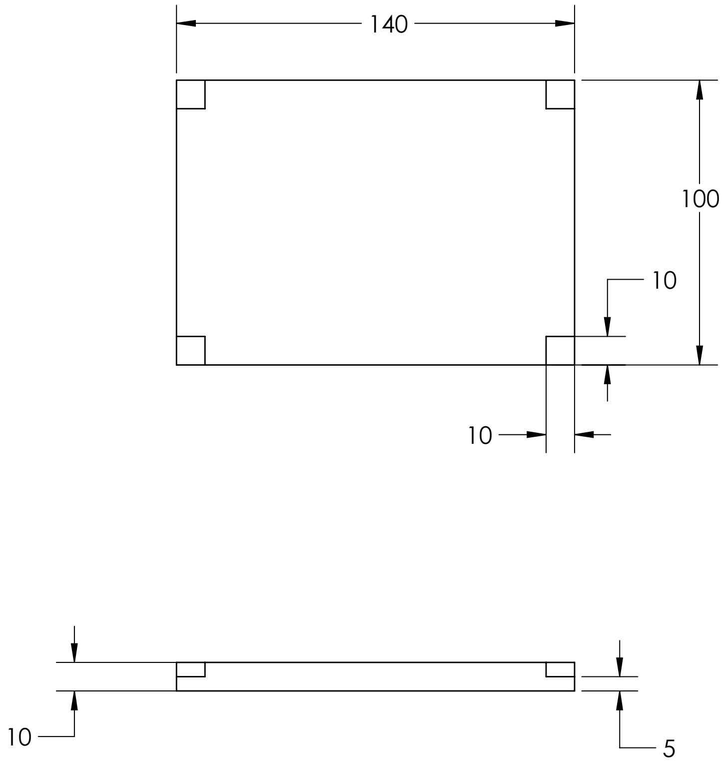
NOTES:
1. MATL: 5MM A36 STEEL
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

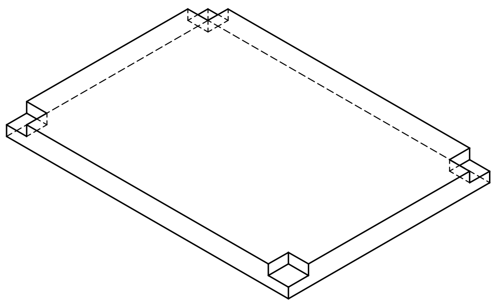
FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE: shaker middle plate		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	WOJCIECH PRZEPIORA	
SIZE A	DWG. NO. EML4501-052	REV A
SCALE: 1:2		SHEET 1 OF 2

5 4 3 2 1



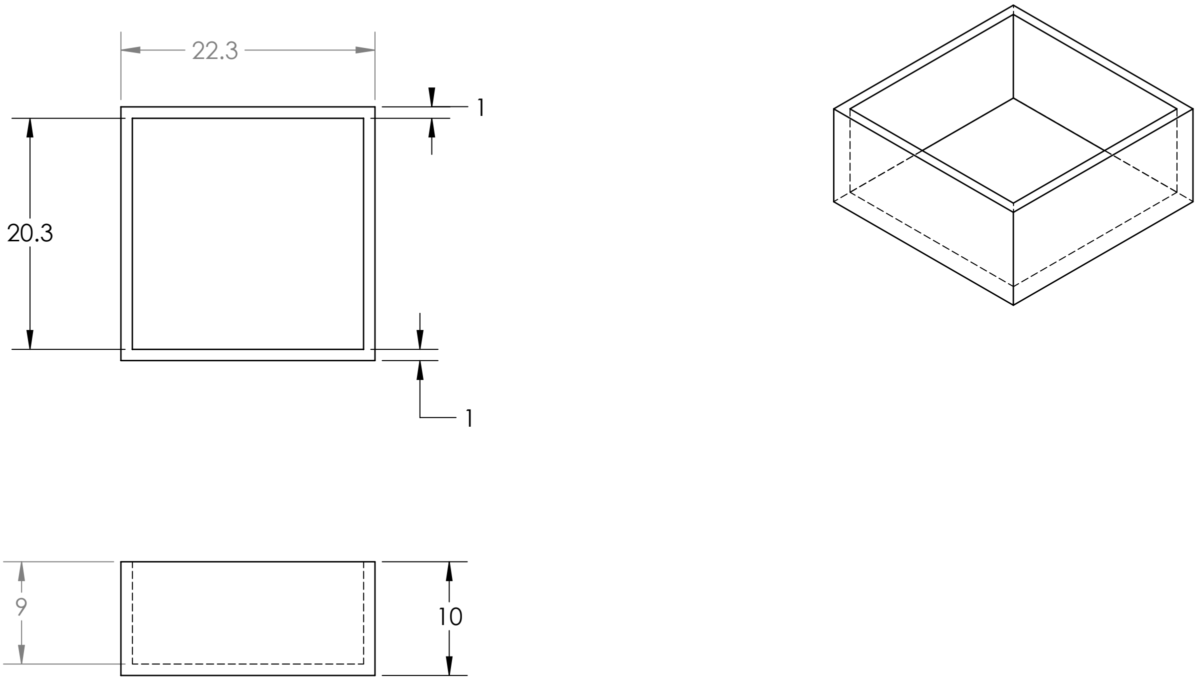


NOTES:
1. MATL: A36 STEEL
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE: shaker holder base plate		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	OLLIE GOODALL	
SIZE A	DWG. NO. EML4501-053	REV A
SCALE: 1:2		SHEET 1 OF 2

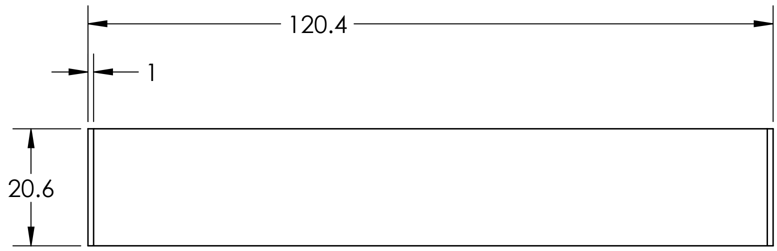


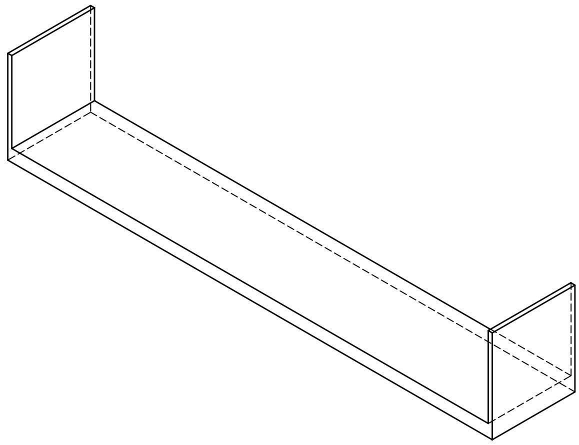
NOTES:
1. MATL: A36 STEEL
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

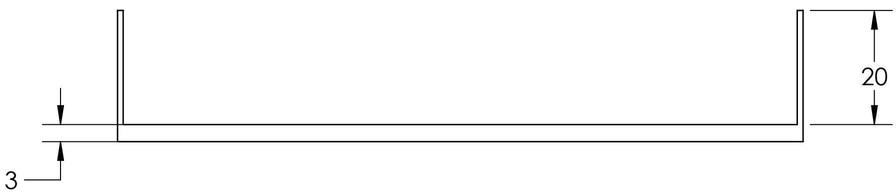
FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED				TITLE: large motor mount		
OPERATION	PLACES IN DIMENSION					
	0.0	0.00	0.000	DRAWN	WOJCIECH PRZEPIORA	
MACHINING				DESIGNED	OLLIE GOODALL	
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030	SIZE A	DWG. NO. EML4501-054	REV A
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2		SCALE: 2:1		SHEET 1 OF 2

5 4 3 2 1





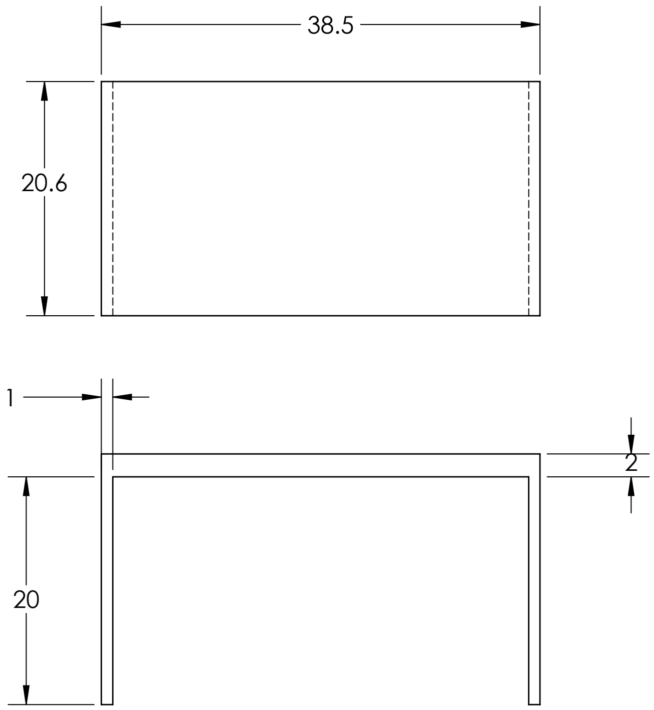


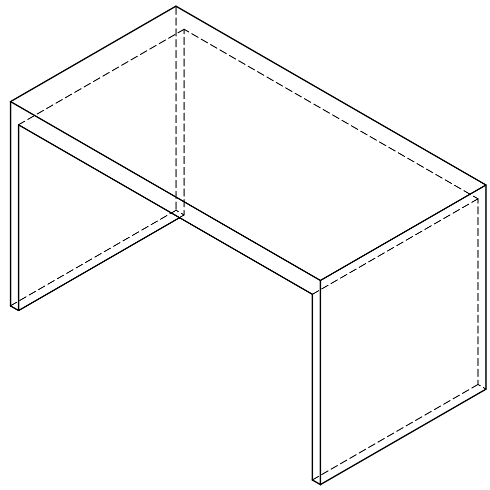
NOTES:
1. MATL: A36 STEEL
2. ALL DIMS IN MM
3. __________
4. __________
5. __________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED				TITLE: bottom layer spring plate		
OPERATION	PLACES IN DIMENSION					
	0.0	0.00	0.000	DRAWN	WOJCIECH PRZEPIORA	
MACHINING				DESIGNED	OLLIE GOODALL	
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030	SIZE A	DWG. NO. EML4501-055	REV A
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2		SCALE: 1:1		SHEET 1 OF 2

5 4 3 2 1





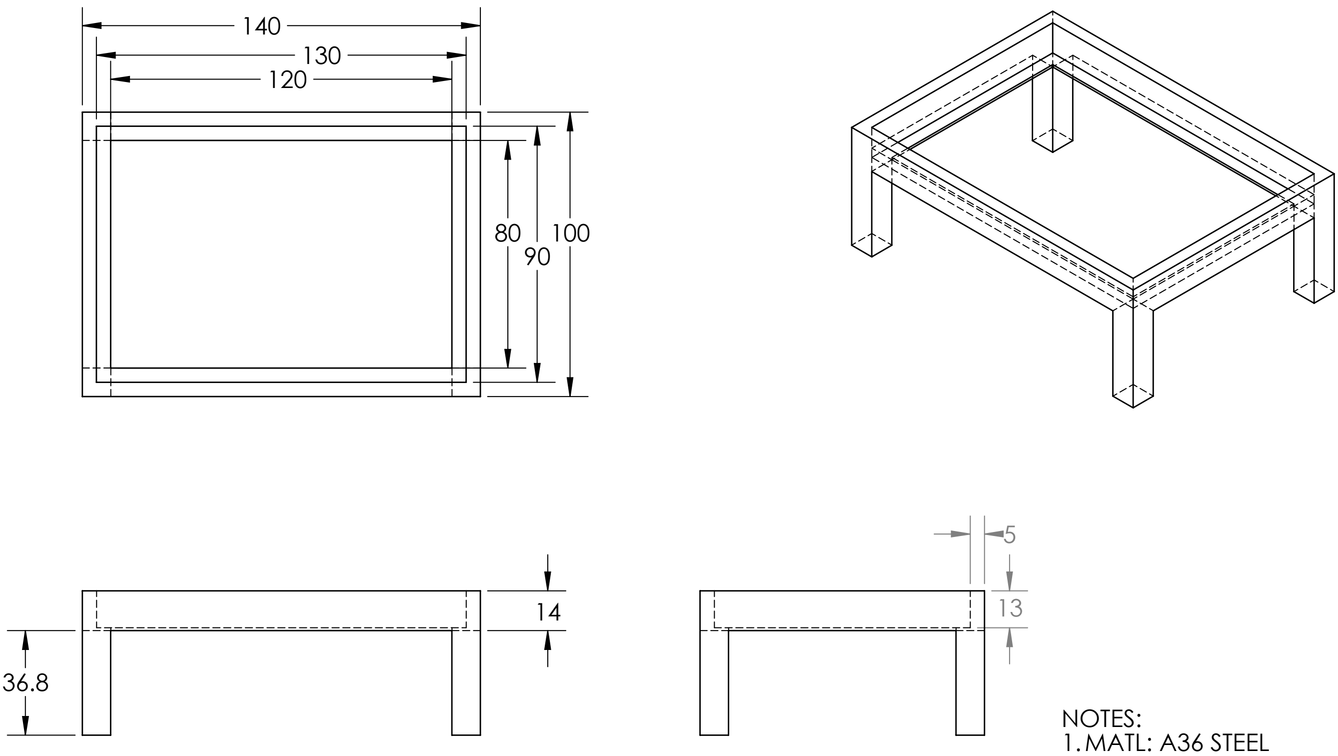
NOTES:
1. MATL: A36 STEEL
2. ALL DIMS IN MM
3. ___________
4. ___________
5. ___________

FOLDED VIEW
(IF APPLICABLE)

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING			
SHEETMETAL (SHEAR, BEND)	±0.1	±0.060	±0.030
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	

TITLE: top layer spring plate		
DRAWN	WOJCIECH PRZEPIORA	
DESIGNED	OLLIE GOODALL	
SIZE A	DWG. NO. EML4501-056	REV A
SCALE: 2:1		SHEET 1 OF 2

5 4 3 2 1

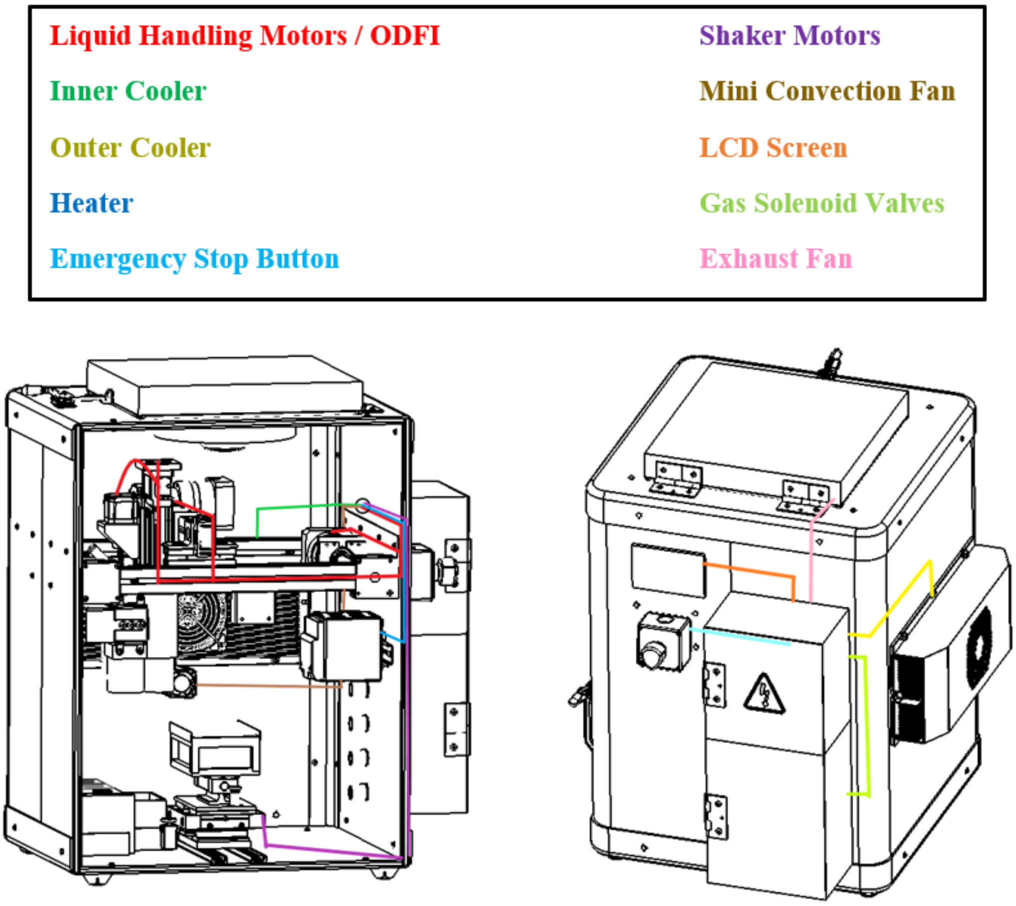


NOTES:
1. MATL: A36 STEEL
2. ALL DIMS IN MM
3.___________
4.___________
5.___________

TOLERANCE UNLESS NOTED				TITLE: well plate holder		
OPERATION	PLACES IN DIMENSION					
	0.0	0.00	0.000	DRAWN	WOJCIECH PRZEPIORA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	OLLIE GOODALL	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE A	DWG. NO. EML4501-057	REV A
WELDING	±0.1	±0.060				
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:2		SHEET 1 OF 1

5 4 3 2 1

A. Assembly Wiring Diagram



]

Figure 62: Wiring Diagram for the Full Assembly

H. Appendices: Handling/Insertion

Climate control				
Component handling/insertion	Count	Coordinates	time per part	total time
screws for inner/outer cooler to mount	4	0,9	2.98	11.92
screws for 40mm fan to mount	4	1,4	2.55	10.2
screws for din rail to mount	2	1,9	3.38	6.76
heater to din rail	1	0,0	1.13	1.13
cooler handling	1	9,1	3	3
heater handling	1	8,1	4.5	4.5
din rail handling	1	1,1	1.8	1.8
			total	**39.31**

Enclosure				
Component	Count	Coordinates	time per part	total time
screws for sheet metal back interior	12	8, 2	5.1	61.2
screws for sheet metal front interior	4	8,2	5.1	20.4
insulation handling	4	0,0	1.13	4.52
rivets for all 3 layers bottom insertion	12	8,2	5.1	61.2
rivets for all 3 layers top insertion	12	8,2	5.1	61.2
rubber legs (adhesive)	4	0,1	1.43	5.72
O-ring for electrical box to enclosure	4	1,4	2.55	10.2
screws for electrical box to enclosure	4	1,2	2.25	9
push in grommet insertion	1	0,1	1.43	1.43
fasteners for electrical box door	4	8,3	5.6	22.4
Rivets for gantry mount to enclosure	12	8,3	5.6	67.2
screws for gantry to enclosure mount	8	8,2	4.5	36
Screws for acrylic sheet support to m	4	3,8	3.34	13.36
Door seal around frame	4	0,1	1.43	5.72
Acrylic sheet handling and insertion	1	0,1	1.43	1.43
Screws for handle to mount	2	0,9	2.98	5.96
Screws for surface-mount hinge to m	2	0,9	2.98	5.96
Screws for door assembly to mount	4	2,5	2.57	10.28
Light blocker placement	1	1,0	1.5	1.5
Screws for door lock to mount	4	1,4	2.55	10.2
interior sheet metal pieces handling	8	8,3	5.6	44.8
exterior sheet metal pieces handling	4	6,3	5.6	22.4
			total	**482.08**

Gas control				
Component	Count	Coordinates	time per part	total time
Vinyl tube to valve handlii	5	0,0	1.13	5.65
tube fitting insertion	5	2,0	1.8	9
hose fitting insertion	5	2,0	1.8	9
push to connect fitting	5	8,0	4.1	20.5
sealing washer insertion	5	1,0	1.13	5.65
gas control to box handlin	5	2,0	1.8	9
O-ring on screw handling	4	1,4	2.55	10.2
screw for box to enclosure	4	1,2	2.25	9
pipe fitting on enclosure	5	0,1	1.43	7.15
screws for gas box door	4	8,2	5.1	20.4
wall exhaust fan handling	1	9,0	2	2
screws for wall exhaust fai	4	1,4	2.55	10.2
seal handling	4	1,0	1.5	6
fan cover handling	1	1,0	1.5	1.5
screws for cover insertion	4	1,4	2.55	10.2
screws for clamp end	2	1,4	2.55	5.1
screws for latch insertion	4	1,4	2.55	10.2
			total	**150.75**

Liquid handling				
Component handling/insertion	Count	Coordinates	time per part	total time
Motor to mount	1	1,1	1.43	1.43
screws for motor to mount	4	1,2	2.25	9
screws for mount to 80/20	2	1,4	2.55	5.1
coupler	1	1,1	1.8	1.8
Lead screw	1	0,1	1.13	1.13
lead screw bracket	1	3,1	2.25	2.25
plunger to handling	1	1,1	1.5	1.5
dowel pin insertion	1	0,4	2.18	2.18
seal/stopper insertion	1	0,2	1.88	1.88
syringe handling	1	1,1	1.13	1.13
pipette tips	1	0,2	1.88	1.88
pipette bracket handling	1	3,0	1.95	1.95
bracket bolt insertion	2	9,1	3	6
bracket nut insertion	2	9,1	3	6
bolts bracket to 80/20 insertion	2	9,1	3	6
nuts bracket to 80/20	2	9,1	3	6
Screws bracket to gantry insertion	4	9,3	3	12
Screws for container holder to mount	3	1,4	2.55	7.65
Containers placed on the holder	4	0,0	1.13	4.52
			total	**79.4**

OD/FI				
Component	Count	Coordinates	time per part	total time
OD/FI glass tube handling	1	0,1	1.43	1.43
Inside tube handling	1	0,1	1.43	1.43
DFM1 cube handling	1	9,1	3	3
screws for cube insertion	8	1,8	1	3
breadboard handling	1	1,1	1.8	1.8
light bracket handling	1	1,0	1.5	1.5
screws for light bracket insertion	3	1,1	1.8	5.4
screws for light bracket lid insertio	2	1,1	1.8	3.6
screws for ODFI to mount insertio	2	9,1	3	6
screws for mount to gantry insertio	4	9,3	3	12
mount to gantry handling	1	8,0	4.1	4.1
ODFI to mount handling	1	8,0	4.1	4.1
			total	**47.36**

Shakers				
Component	Count	Coordinates	time per part	total time
Al shafts to base handling	2	2,4	2.85	5.7
Ball BRNG to aluminum shafts	2	0,5	1.84	3.68
Compression springs to Al shafts	4	0,1	1.43	5.72
Al u-shapes to ball BRNG insertic	2	0,0	1.13	2.26
Middle base to ball BRNG inserti	1	1,0	1.5	1.5
Al shaft to middle base insertion	1	1,0	1.5	1.5
Ball BRNG to aluminum shaft	1	0,5	1.84	1.84
Compression springs to Al shaft	2	0,1	1.43	2.86
Al u-shapes to ball BRNG	2	0,0	1.13	2.26
Shaker table to ball BRNG	1	1,5	2.25	2.25
Led to shaker table	1	0,4	2.18	2.18
Well plate support to shaker table	1	0, 4	2.18	2.18
Well plate to support handling	1	0,4	2.18	2.18
Motor to the middle base handling	1	1,9	3.38	3.38
Motor to base insertion	1	1,9	3.38	3.38
			total	**42.87**

User Interface				
Component	Count	Coordinates	time per part	total time
LCD screen to enclosure handling	1	0,9	2.98	2.98
Emergency off to enclosure handling	1	1,6	2.57	2.57
LCD screen to enclosure insertion	1	0,9	2.98	2.57
Emergency off to enclosure insertion	1	1,6	2.57	2.57
			total	**10.69**

MANUAL HANDLING -- ESTIMATED TIMES (seconds)

ONE HAND

ONE HAND		parts are easy to grasp and manipulate					parts present handling difficulties (1)				
		thickness > 2 mm			thickness ≤ 2 mm		thickness > 2 mm			thickness ≤ 2 mm	
		size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm	size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm
		0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand without the aid of grasping tools: $(\alpha + \beta) < 360°$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
$360° \le (\alpha + \beta) < 540°$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
$540° \le (\alpha + \beta) < 720°$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
$(\alpha + \beta) \ge 720°$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

ONE HAND with GRASPING AIDS

ONE HAND with GRASPING AIDS		parts need tweezers for grasping and manipulation								parts need standard tools other than tweezers	parts need special tools for grasping and manipulation
		parts can be manipulated without optical magnification				parts require optical magnification for manipulation					
		parts are easy to grasp and manipulate		parts present other handling difficulties (1)		parts are easy to grasp and manipulate		parts present other handling difficulties (1)			
		thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm		
		0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand but only with the use of grasping tools: $\alpha \le 180°$, $0 \le \beta \le 180°$	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
$\alpha \le 180°$, $\beta = 360°$	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
$\alpha = 360°$, $0 \le \beta \le 180°$	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
$\alpha = 360°$, $\beta = 360°$	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

TWO HANDS for MANIPULATION

TWO HANDS for MANIPULATION		parts present no additional handling difficulties					parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)				
		$\alpha \le 180°$			$\alpha = 360°$		$\alpha \le 180°$			$\alpha = 360°$	
		size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm	size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm
		0	1	2	3	4	5	6	7	8	9
parts severly nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

TWO HANDS required for LARGE SIZE

TWO HANDS required for LARGE SIZE		parts can be handled by one person without mechanical assistance									two positions or mechanical assistance required for parts manipulation
		parts do not severly nest or tangle and are not flexible								parts severly nest or tangle or are flexible (2)	
		part weight < 10 lb				parts are heavy (> 10 lb)					
		parts are easy to grasp and manipulate		parts present other handling difficulties (1)		parts are easy to grasp and manipulate		parts present other handling difficulties (1)			
		$\alpha \le 180°$	$\alpha = 360°$	$\alpha \le 180°$	$\alpha = 360°$	$\alpha \le 180°$	$\alpha = 360°$	$\alpha \le 180°$	$\alpha = 360°$		
		0	1	2	3	4	5	6	7	8	9
two hands, two persons or mechanical assistance required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

MANUAL INSERTION -- ESTIMATED TIMES (seconds)

PART ADDED but NOT SECURED

			after assembly no holding down requried to maintain orientation and location (3)				holding down required during subsequent processes to maintain orientation or location (3)			
			easy to align and position during assembly (4)		not easy to align or position during assembly		easy to align and position during assembly (4)		not easy to align or position during assembly	
			no resistance to insertion	resistance to insertion	no resistance to insertion	resistance to insertion	no resistance to insertion	resistance to insertion	no resistance to insertion	resistance to insertion
			0	1	2	3	6	7	8	9
addition of any part (1) where neither the part itself nor any other part is finally secured immediately	part and associated tool (including hands) can easily reach the desired location		0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
	part and associated tool (including hands) cannot easily reach the desired location	due to obstructed-access or restricted vision (2)	1	4	5	5	6	8	9	9	10
		due to obstructed-access & restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

PART SECURED IMMEDIATELY

				no screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		plastic deformation immediately after insertion						screw tightening immediately after insertion	
						plastic bending or torsion			rivetting or similar operation				
							not easy to align or position during assembly and/or resistance to ins.			not easy to align or position during assembly and/or resistance to ins.			
				easy to align and position with no resistance to insertion	not easy to align or position during assembly and/or resistance to ins.	easy to align and position during assembly	no resistance to insertion	resistance to insertion	easy to align and position during assembly	no resistance to insertion	resistance to insertion	easy to align and position with no resistance to insertion	not easy to align or position during assembly and/or resistance to ins.
				0	1	2	3	4	5	6	7	8	9
addition of any part (1) where neither the part itself nor any other part is finally secured immediately	part and associated tool (including hands) can easily reach the desired location		3	2	5	4	5	6	7	8	9	6	8
	part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily	due to obstructed-access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
		due to obstructed-access & restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

SEPARATE OPERATION

		mechanical fastening processes (parts already in place but not secured immediately after insertion)				non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				non-fastening processes	
		none or localized plastic deformation				metallurgical processes					
							additional material required				
		bending or similar processes	riveting or similar processes	screw tightening (5) or other processes	bulk plastic deformation (large proportion of part is plastically deformed during fastening)	no additional material required (e.g. resistance, friction, welding, etc.)	soldering processes	welding/braze processes	chemical processes (e.g. adhesive bonding, etc.)	manipulation of parts or sub-assembly (e.g. orienting, timing, or adjustment of parts, etc.)	other processes (e.g. liquid insertion, etc.)
		0	1	2	3	4	5	6	7	8	9
assembly processes where all solid parts are in place	9	4	7	5	3.5	7	8	12	12	9	12

I. References

[1] Anne Helmenstine. What Is Room Temperature? https://sciencenotes.org/what-is-room-temperature/, 2020. Online; accessed 2, April 2021.

[2] Asco. Long life solenoid valves. https://www.emerson.com/documents/automation/catalog-long-life-valves-asco-en-584334.pdf, 2020. Online; accessed 2, April 2021.

[3] AutomationWorld. SCARA Robots Boost Speed, Versatility and Uptime. https://www.automationworld.com/factory/robotics/article/13320070/scara-robots-boost-speed-versatility-and-uptime#:~:text=The%20latest%20models%20feature%2045,speed%20at%201700%C2%B0%2Fs, 2019. Online; accessed 4 March 2021.

[4] Biocompare. BioProfile® FLEX2 Automated Cell Culture Analyzer. https://www.biocompare.com/10967-Cell-Analysis-Systems/1547277-BioProfile-FLEX2-Automated-Cell-Culture-Analyzer/., 2021. Online; accessed 4 March 2021.

[5] BMG LABTECH. Absorbance. https://www.bmglabtech.com/absorbance/, 2021. Online; accessed 4 March 2021.

[6] BMG LABTECH. Fluorescence intensity (incl. FRET). https://www.bmglabtech.com/fluorescence-intensity/, 2021. Online; accessed 4 March 2021.

[7] BMG LABTECH. Incubation and Shaking. https://www.bmglabtech.com/incubation-and-shaking, 2021. Online; accessed 4 March 2021.

[8] BMG LABTECH. Light Filters. https://www.bmglabtech.com/filters/, 2021. Online; accessed 4 March 2021.

[9] BMG LABTECH. Plate Reader. https://www.bmglabtech.com/fluostar-omega/, 2021. Online; accessed 4 March 2021.

[10] D. Dominguez, J. Scott, and B. Liu. ASSIST PLUS," INTEGRA. https://www.integra-biosciences.com/united-states/en/pipetting-robots/assist-plus, 2020. Online; accessed 4 March 2021.

[11] Divakar. Surface Temperatures of Electronics Products: Appliances vs. Wearables. https://www.electronics-cooling.com/2016/09/surface-temperatures-of-electronics-products-appliances-vs-wearables/#:~:text=ASTM%20C1055%20(the%20Standard%20Guide,without%20sustaining%20irreversible%20burn%20damage, 2016. Online; accessed 4 March 2021.

[12] Eitel L. Large-area travel XYZ gantry systems from IntelLiDrives. https://www.linearmotiontips.com/large-area-travel-xyz-gantry-systems-intellidrives-2/#:~:text=The%20XYZ%20gantry%20system%20carried,carrying%20light%20to%20medium%20payloads, 2021. Online; accessed 4 March 2021.

[13] Engineering toolbox. Thermoplastics - Physical Properties. https://www.engineeringtoolbox.com/physical-properties-thermoplastics-d_808.html, 2021. Online; accessed 31 March 2021.

[14] EngineeringToolbox. Physical properties of some thermoplastics like ABS, PVC, CPVC, PE, PEX, PB and PVDF. https://www.engineeringtoolbox.com/physical-properties-thermoplastics-d_808.html, 2020. Online; accessed 2, April 2021.

[15] Eppendorf Handling Solutions. From Rockers to Orbital Shakers – What Type to Use for Shaking Cultures? https://handling-solutions.eppendorf.com/sample-handling/mix-shake/principles/detailview-principles/news/from-rockers-to-orbital-shakers-what-type-to-use-for-shaking-cultures/, 2020. Online; accessed 4 March 2021.

[16] GRANTA DESIGN. Material property charts. https://www.grantadesign.com/education/students/charts/, 2020. Online; accessed 2, April 2021.

[17] GRU. Gainesville Energy Cost Rates. http://gru.com/Portals/0/Calculating%20Your%20Electric%20Bill%20FY19.pdf, 2020. Online; accessed 26, April 2021.

[18] Hans-Christian Luedemann. Interferometric Volume Measurement in Microplates. https://journals.sagepub.com/doi/pdf/10.1177/2211068216669689, 2017. Online; accessed 1 April 2021.

[19] Labcompare. Liquid Handling Equipment. https://www.labcompare.com/General-Laboratory-Equipment/312-Liquid-Handling-Equipment/#:~:text=Types%20of%20liquid%20handling%20equipment,variety%20of%20automated%20robotic%20systems, 2021. Online; accessed 4 March 2021.

[20] Lackey B. What's the Difference Between Servo and Stepper Motors? https://www.machinedesign.com/mechanical-motion-systems/article/21836868/whats-the-difference-between-servo-and-stepper-motors, 2018. Online; accessed 4 March 2021.

[21] MachineDesign. What's the Difference Between Industrial Robots? https://www.machinedesign.com/markets/robotics/article/21835000/whats-the-difference-between-industrial-robots, 2021. Online; accessed 4 March 2021.

[22] Marcela A., Joao S., Ashton G., Ollie G., Brenden M., Audrey M., Wojciech P., Pelayo U. Mechanical Design 2 Conceptual Design Report Group 14. https://ufl.instructure.com/courses/416646/assignments/4635541/submissions/1032152?download=57692054, 2020. Online; accessed 2, April 2021.

[23] Marcela A., Joao S., Ashton G., Ollie G., Brenden M., Audrey M., Wojciech P., Pelayo U. Mechanical Design 2 Preliminary Design Report Group 14. https://ufl.instructure.com/courses/416646/assignments/4588144/submissions/1032152?download=58463382, 2020. Online; accessed 26, April 2021.

[24] Matthew J. Traum. Tolerance Loop Template. https://ufl.instructure.com/files/56092083/download?download_frd=1, 2020. Online; accessed 26, April 2021.

[25] MechaniCalc. Fastener Size Tables. https://mechanicalc.com/reference/fastener-size-tables, 2020. Online; accessed 2, April 2021.

[26] Morgan and Carrier. Protective buttressing of the human fist and the evolution of hominin hands. https://jeb.biologists.org/content/216/2/236.figures-only, 2021. Online; accessed 31 March 2021.

[27] Nature News. Cell culture. https://www.nature.com/subjects/cell-culture#:~:text=Cell%20culture%20is%20a%20method,that%20can%20be%20cultured%20indefinitely, 2021. Online; accessed 4 March 2021.

[28] News Medical Life Sciences. Improving Bacterial Growth Assays. https://www.news-medical.net/whitepaper/20190828/Improving-Bacterial-Growth-Assays.aspx, 2019. Online; accessed 4 March 2021.

[29] Online Textbook of bacteriology. The Growth of Bacterial Populations. http://textbookofbacteriology.net/growth_3.html, 2020. Online; accessed 2, April 2021.

[30] OWENS CORNING FOAM INSULATION, LLC. Capturing the Thermal Performance of FOAMULAR® Extruded Polystyrene (XPS) . http://www.owenscorning.com/NetworkShare/EIS/10019949-FOAMULAR-XPS-vs-Polyiso-Tech-Bulletin.pdf, 2020. Online; accessed 2, April 2021.

[31] PerkinElmer. Microplate Dimensions, Working Volumes and Packaging. https://www.perkinelmer.com/lab-products-and-services/application-support-knowledgebase/microplates/plate-dimensions.html, 2021. Online; accessed 4 March 2021.

[32] Piyush G. Chapla. HOW MUCH WEIGHT IS TOO MUCH FOR MANUAL LIFTING: DETERMINING A WEIGHT LIMIT GUIDELINE FOR TEAM-EFFORT LIFTING TASKS. http://archives.njit.edu/vol01/etd/2000s/2004/njit-etd2004-111/njit-etd2004-111.pdf, 2020. Online; accessed 2, April 2021.

[33] Process Costing Table. Matthew J. Traum. https://ufl.instructure.com/files/56092345/download?download_frd=1, 2020. Online; accessed 26, April 2021.

[34] ScienceDirect Topics. Bioreactors - an overview. https://www.sciencedirect.com/topics/neuroscience/bioreactors, 2021. Online; accessed 4 March 2021.

[35] ST Robotics. R19E bench top 4-axis cylindrical format robot arm. https://strobotics.com/cylindrical-format-robot.htm, 2021. Online; accessed 4 March 2021.

[36] Stainless Structurals LLC. Comparing the Thermal Conductivity of Stainless Steel to other Metals. https://www.stainless-structurals.com/blog/comparing-the-thermal-conductivity-of-stainless-steel-to-other-metals/#:~:text=The%20thermal%20conductivity%20of%20carbon,choice%20for%20building%20structural%20components., 2020. Online; accessed 2, April 2021.

[37] theodore L. Bergman, adrienne S. Lavine. Fundamentals of Heat and Mass Transfer 8th Edition. https://www.wiley.com/en-us/Fundamentals+of+Heat+and+Mass+Transfer%2C+8th+Edition-p-ES81119320425, 2020. Online; accessed 2, April 2021.

[38] Thomas. All About 304 Steel (Properties, Strength, and Uses). https://www.thomasnet.com/articles/metals-metal-products/all-about-304-steel-properties-strength-and-uses/, 2020. Online; accessed 2, April 2021.

[39] ToyBuilder Labs. Material cost for printing. https://www.toybuilderlabs.com/blogs/news/13055597-material-cost-for-printing#:~:text=These%20are%20ball%2Dpark%20numbers,is%20%240.05%2Fcm%5E3., 2020. Online; accessed 2, April 2021.