



COMILLAS

UNIVERSIDAD PONTIFICIA

ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

AUTONOMOUS BIORREACTOR FOR THE NEW UF BIOFOUNDRY

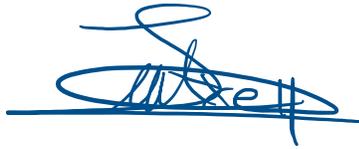
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Director: Matthew J. Traum

Madrid

Junio de 2021

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título
Autonomous Benchtop Bioreactor for the New UF Biofoundry
en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el
curso académico 2020-2-21 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.: Iratxe Astigarraga Pablogorran

Fecha: 08/06/2021

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Mathew J. Traum

Fecha: 08/11/2021





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BIORREACTOR DE MESA PARA LA NEW UF BIOFOUNDRY

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RESUMEN DEL PROYECTO:

I. Introducción

A. Planteamiento del problema

Los avances tecnológicos de los últimos años han permitido el desarrollo de sistemas biológicos con un alto ratio de reproductividad de bacterias. Sin embargo, el comportamiento dinámico de estos dificulta la réplica de experimentos, y además, la gestión de los residuos biológicos que se hace es en muchos casos incorrecta e insuficiente.

La complejidad de los organismos biológicos, la espontaneidad de las variaciones físicas que ocurren en los experimentos y la evolución, dificultan también la caracterización de organismos biológicos sintéticos en los laboratorios.

Las actuales opciones en el mercado son además mayormente manuales, ya que supone una importante reducción de costes. Esto implica que el usuario debe intervenir en distintas etapas del experimento para manipular las muestras, lo que tiene como consecuencia la alteración del resultado.

La manera de hacer frente a estos problemas es incorporando sensores y monitorización a los procesos, asegurar la repetibilidad y estandarización de los experimentos, y extender la producción a gran escala.

B. Estado de la técnica

Existen varios laboratorios competidores que han desarrollado aparatos que incluyen algunas de las funciones mencionadas anteriormente; Chi-Bio, Opentron, Klavin's lab entre otros.

Muchos de ellos han sacado al mercado turbisodatos, que se tratan de sistemas de cultivo continuo capaces de controlar la concentración celular en un medio determinado a través de la turbidez. Otros dispositivos como el Opentron Liquid Dispenser permiten llenar placas de cultivo 20 veces más rápido de lo que haría un técnico de laboratorio. Aunque existen alternativas, la mayoría de estos biorreactores son poco sofisticados y suponen un desembolso importante de dinero.

C. Objeto del proyecto

Para hacer frente al problema explicado, el laboratorio Synthetic Biology Consortium de la Universidad de Florida ha creado la Industry 4.0 UF Biofoundry, con la que busca crear un biorreactor autónomo con manipulación de líquidos y que pueda tratar muestras biológicas a gran escala a un precio menor que el que ofrecen las alternativas del mercado.

Entre otras funciones, el diseño deberá integrar al menos las siguientes cinco capacidades: (1) manipulación de fluidos en microplacas y tubos de ensayo; (2) agitador de muestras; (3) incubadora de células; (4) sensores ópticos metabólicos; y (5) herramientas adicionales como control medioambiental y tratamiento de residuos.

Siguiendo la estrategia 4.0, se introducirán en el biorreactor materias primas como bacterias o levaduras que han sido manipuladas por separado; sin intervención humana, el aparato deberá ser capaz de hacer crecer el cultivo de manera monitorizada. El objetivo a futuro del laboratorio es el desarrollo de biocombustibles, biopolímeros, productos farmacéuticos e incluso biomasa comestible.

II. Metodología

Tal y como se ha explicado anteriorente, la base de este proyecto son los requisitos impuestos por el cliente. A partir de estos, el proyecto se ha desarrollado mediante un proceso de diseño en el que se han ido descartando, revisando y perfeccionando bocetos hasta llegar al diseño final teniendo en cuenta las propuestas que fueron planteando los clientes.

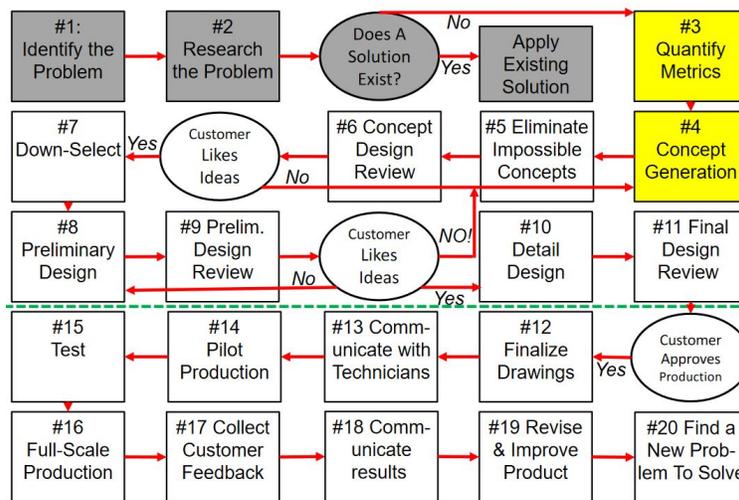


Fig. 1 Flow Chart Proceso de Diseño

El proceso de diseño esta dividido en tres partes principales:

En la primera, el Concept Design Report o CDR, se analizó el mercado, se indentificaron los objetivos del proyecto y se hicieron los primeros bocetos de los conceptos que formarían más adelante cada subsistema.

En la segunda parte, el Preliminary Design Report o PDR, se establecieron los parámetros de medida en base a los requisitos del cliente. Mediante matrices de selección se ponderaron cuáles tenían mayor importancia en el diseño de cada subsistema de cara a las funciones que debía desarrollar. En la mayoría de los casos el diseño elegido fue el que mayor puntuación obtuvo, aunque en algunos subsistemas, como el de manipulación de fluidos, se dio prioridad a la funcionalidad del aparato, lo que llevó a elegir otras características para el diseño. Los bocetos se perfeccionaron y se eligieron los materiales mediante tablas Ashby asegurando siempre que soportaban las cargas del sistema.

El proyecto culminó con el Final Design Report o FDR, parte en la que se realizó el estudio económico y estructural del biorreactor. Esta etapa del proceso de diseño también incluye una lista de materiales, el pedido de compra de las partes necesarias para construir el diseño y los análisis matemáticos pertinentes. Junto con ello se adjuntan planos detallados de cada una de las piezas que serán fabricadas e indicaciones de montaje.

Una vez acabado se analizó el proyecto para ver cómo se ajustaba a los objetivos Objetivos de Desarrollo Sostenible.

NOTA: Este trabajo se realizó poniendo el foco en el subsistema de dispensador de fluidos, aunque teniendo en cuenta su interrelación con el resto de los subsistemas del biorreactor.

III. Resultados

El biorreactor se construyó basándose en las necesidades del cliente. Para ello, se decidió dividir el biorreactor en los siguientes siete subsistemas: manipulador, agitador de muestras, manejo de fluidos, control ambiental, controles, saneamiento y estructura general.

El manipulador tiene como función principal transportar las placas y los tubos de ensayo de todos los tamaños dentro de la cámara del biorreactor gracias a su diseño con tres grados de libertad. El manipulador es necesario para acercar las placas a la válvula dispensadora de nutrientes, al agitador, al regulador de temperatura o para colocar los cultivos debajo del lector de densidad óptica. Adicionalmente, gracias a un pequeño mecanismo incorporado en su pinza, es capaz de retirar las tapas de los distintos tubos de ensayo.

Para poder airear bien los cultivos el agitador debe ser capaz de reproducir movimientos lineales, circulares y circulares dobles (forma de infinito). El sistema está formado por una carcasa que engloba los siguientes elementos: una bandeja donde poder sujetar tanto las placas como los tubos de cultivo, un yugo escocés, dos motores DC, un actuador lineal y dos ensamblajes con engranajes.

El dispensador de líquido es uno de los elementos más importantes del biorreactor ya que su función es proporcionar a los cultivos los nutrientes necesarios para su correcto desarrollo. El diseño implantado formado por tres depósitos, tres válvulas solenoides, una bomba y una válvula dispensadora, es capaz tanto de expulsar como de absorber materia e incorpora un mecanismo de autolimpieza para evitar contaminación cruzada. Los nutrientes se transportarán a través del sistema y se insertarán en la placa de cultivo con una precisión de más del 98%. Posteriormente, se bombeará lejía por los conductos para evitar neutralizar los restos y evitar una reacción química inesperada, y finalmente, el agua destilada tiene como función dejar el sistema libre de residuos para el siguiente experimento.

Dentro del mismo subsistema se encuentra también el sistema de inyección y evacuación de aire mediante el que se incorporan N₂, O₂, H₂, CO₂ y CH₄ para la realización de experimentos. El sistema de inyección se compone por cinco tanques presurizados, válvulas y reguladores de presión automatizados mediante los cuales el operador puede adaptar el flujo de gases por el sistema. Gracias a un sistema de vacío incorporado con filtros homologados, la mezcla gaseosa se limpia antes de ser expulsada al exterior.

El subsistema de control ambiental es responsable de mantener la temperatura y demás condiciones estables en la cámara de incubación para el correcto desarrollo de los experimentos. Mediante condensadores, ventiladores y otros elementos se transmite el calor a través de la conducción y convección.

Todas las acciones que se ejecutan en el biorreactor son controladas desde un mismo procesador, por lo que se trata de un elemento fundamental en el diseño. Sus funciones van desde la correcta lectura de variables como temperatura, presión o número de bacterias, hasta la emisión de resultados en el display. El diseño incorpora tres placas Arduino, desde donde se controlan los movimientos de los demás subsistemas además de luces especiales led para favorecer el crecimiento celular.

El sistema de saneamiento es responsable de desinfectar las placas y tubos de ensayo después de cada experimento. Incorpora una cámara principal con puertas accesibles, dos depósitos, un sistema de tuberías, una bomba, un motor y un desagüe. El manipulador introduce las placas y tubos de ensayo ya usados dentro del sistema y este se encarga de desinfectarlo empleando un mecanismo parecido al de un lavabajillas para que puedan ser reutilizadas en vez de deshecharlos. Esta característica tan singular es la que le da nombre al biorreactor Dr. Clean y lo que lo diferencia de otras alternativas del mercado.

La estructura del biorreactor engloba a los demás subsistemas. Su función principal es estar correctamente aislado para la correcta evolución de los cultivos, razón por la que está compuesto de materiales aislantes que previenen que los cultivos contaminen el exterior a la vez que mantiene la temperatura del interior. Como sistema de seguridad incorpora un botón de apagado de emergencia.

El ensamblaje final del biorreactor se puede ver en la siguiente imagen donde se indican las partes que forman el subsistema de inyección de fluidos.

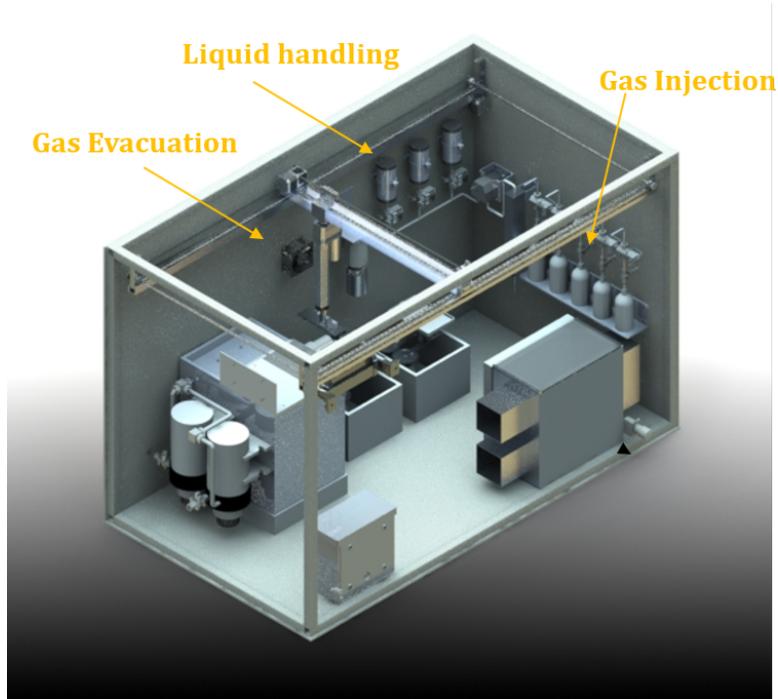


Fig. 2 Vista isométrica del diseño

En cuanto al análisis económico del biorreactor, los resultados fueron los siguientes: el coste de fabricación fue 834.78 USD, correspondiente a la impresión en 3D de las piezas personalizadas. Tomando como referencia el tiempo de ensamblaje del subsistema de saneamiento, el tiempo total para el biorreactor en su conjunto es de 1.5 horas. Con un coste medio de 56.74 USD la hora, la mano de obra suma un total de 85.11 USD. Sumando estos costes a los de la lista de compra donde se incluyen las piezas proporcionadas por proveedores, el coste total es de 10,565.36 USD.

IV. Conclusiones

El objetivo principal de este proyecto era crear un nuevo diseño de un micro biorreactor autónomo que cumpliera los requisitos impuestos por el cliente. Además, el proyecto de ingeniería no podía sobrepasar ciertos límites de presupuesto, debía ser lo suficientemente pequeño como para caber en la encimera de un laboratorio, y debía ser automatizado. Dr. Clean, no sólo cumplió con los requisitos sino que fue más allá ya que incluye un sistema de saneamiento revolucionario que lo hace destacar sobre otras alternativas del mercado. Gracias a este sistema el biorreactor realiza el experimento de principio a fin, limpiando integralmente el material de laboratorio para que esté listo para el siguiente experimento sin que el usuario tenga que intervenir.

En general los objetivos del proyecto se cumplieron satisfactoriamente gracias a haber seguido el proceso de diseño propuesto. Los clientes quedaron contentos y se dio luz verde al proyecto.

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BENCHTOP BIOREACTOR FOR THE NEW UF BIOFOUNDRY

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- **Collaborating institutions:** ICAI- Universidad Pontificia de Comillas, UF- University of Florida

ABSTRACT:

I. Introduction

A. Introduction to the problem

Biological advances throughout the years have been able to engineer systems of bacteria that increase at a large rate, however, the dynamic behavior of the system makes it difficult to replicate the experiment. In addition, current techniques are not reliable due to the environment caused by waste production.

Biological complexity of organisms, alongside with evolution and spontaneous physical variations that take place during experiments, make the characterization of synthetic biological systems tedious.

Most of the alternatives on the market are manual, since there is a substantial reduction in price. This means that the user has to take part in different phases of the process for manipulating the cultures. Consequently, most of the results obtained are contaminated.

The way to solve this problem is by introducing sensors and proper monitoring in experiments to enable repeatability and standardization in the lab processes as well as implementing large scale manufacturing.

B. State of Art

The idea of incorporating these functions into one single device is not novel, there are several laboratories who attempted these before. Among others can be found Chi-Bio, Opentron and Klavin's lab. Most of them have developed some devices called turbidostats, which are continuous microbiological devices that incorporate feedback of the cellular concentration in a given environment thanks to turbidity. Other devices such as the Opentron Liquid Dispenser, are able to dispense nutrients 20 times faster than any lab technician. Although there are some alternatives, most of these bioreactors are not so sophisticated and are very expensive.

C. Motivation

To solve these issues, the University of Florida Bio-foundry is seeking a conceptual design for a bioreactor capable of investigating properties at a cellular level while maintaining consistent conditions for experimental growth in addition to other customer needs. The goal of the design is that the reactor is capable of both culturing microbes in fully enclosed compartments and monitoring optical density (OD) and fluorescent intensity (FI).

The desired design will allow for the testing of hundreds of variants, control factors that impact growth and tune cultures to produce the desired outputs, mainly focused on gene cloning and cell growing of bacteria such as E-coli. Additionally, the bioreactor will not require human labor, will avoid cross-contamination between experiments and will interrogate cellular properties in larger volumes than other ones already available in the market.

Among other capabilities the autonomous unit should include: (1) well plate/ conical tube fluid handling; (2) sample shakers; (3) cell incubators; (4) optical metabolic sensor and diagnostics; and (5) operation support features such as environmental control and waste disposal.

Following an Industry 4.0 approach separately engineered raw materials like bacteria or yeast will go into the device, and with no human intervention, these will grow to produce substantial amounts of well-monitored microbial culture. Ultimate goals for the biofoundry include producing products like biofuels, biopolymers, pharmaceuticals, and even edible biomass.

II. Methodology

The methodology used in the development of this project is the Engineering Design Process explained throughout the Mechanical Engineering Design 2 class. Starting with the identification of the problem, followed by quantified metrics and then by the generation of concepts and the following down- selection, a new product will be designed.

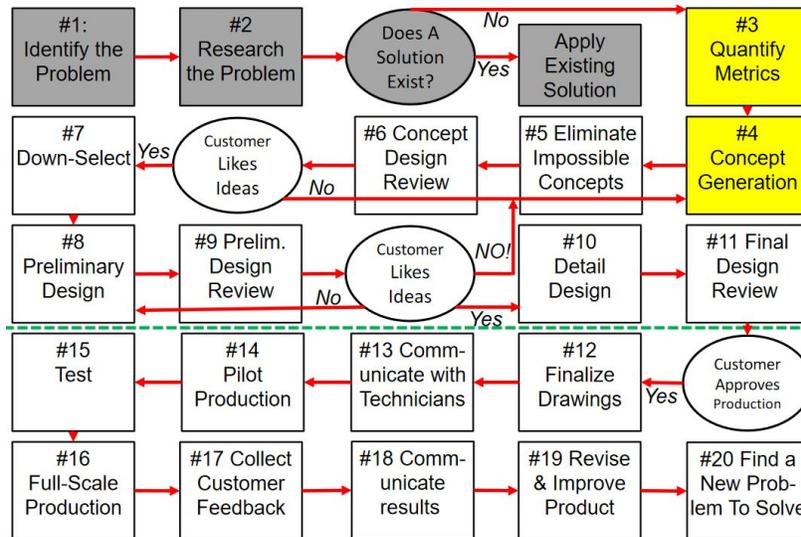


Fig. 1 Flow Chart Design Process

This design will be updated and improved taking into account the customer’s feedback, as well as limitations in cost and the ability to be manufactured. This process will consist in three different parts which are the CDR (Concept Design Report), PDR (Preliminary Design Report) and FDR (Final Design Report).

The first part, the Concept Design Report, culminates in generation of design concepts for the Autonomous Microbioreactor meeting all customer needs. This document will include background information supporting multiple concepts, hand drawings of concepts and their key mechanisms. In the second part, the Preliminary Design Report, the proposed concepts are evaluated and the most suitable one is selected according to previously established decision matrices.

For each selected design, calculations will be included to prove the limitations given by the customer on each subsystem are not exceeded. Following different Ashby plots, materials for each design are specified and included in a Bill of Materials alongside with the Purchase Order, including the OTS parts. In addition, in the PDR, a model of Dr. Clean was created in SolidWorks as part of the manufacturing process. In the final assignment, the Final design Report, necessary minor improvements are made to the model and drawings for each element are included. A detailed visual explanation is included on how to put together the different parts of the subsystems.

NOTE: This project focuses on the Fluid Handling subsystem, although it also takes into account its interrelation with other subsystems in the biorreactor.

III. Results

The manipulator system was primarily tasked with successfully transporting well plates and tubes of various sizes across the structure. It is used to fill up the each well plate or tube with its required nutrients, is able to place them onto any of the shakers, move them into the environmental management chamber, and position the testing vessels underneath the dual spectrometers so that optical density and fluorescent intensity information could be collected and reported through the controls system to the customer. The manipulator is also responsible for being able to take the lids off of the well plates that the user might be using, which requires high precision.

To properly aerate the cell cultures, the shaking mechanism needs to be capable of linear, orbital and double orbital movement. This system is comprised of a housing structure, a tray where well plates and conical tubes can be held, a scotch yoke mechanism, two DC motors, a linear actuator, motor mounts, and two gear-rod assemblies.

The liquid handling in the bioreactor is capable of automatically adding and subtracting fluid from each well plate or conical tube. It can satisfactorily move cultures suspended in liquid between compartments, and provide nutrients without creating aerosols. No cross contamination between individual wells or tubes takes place in the process thanks to a properly designed sanitation system. The fluid dispensing must be done with an accuracy >98%.

The air injection and evacuation system is also part of this subsystem. Some valves and pressure regulators enable to introduce N₂, O₂, H₂, CO₂ and CH₄ into the main chamber. Thanks to a vacuum-like system in addition to an homologated filter, the gaseous mix is evacuated out of the bioreactor without risk of contamination.

The environmental management subsystem is responsible for the maintenance of temperature and consistent atmospheric conditions within the chamber of incubation for the well plates and conical tubes. This subsystem is principally concerned with the interaction of heating and cooling elements in conjunction with the motor controllers and motion aspects of the assembly. Conduction and convection principles were investigated in accordance to the customer needs metrics outlined in an attempt to rank concepts by suitability to design standards.

The controller subsystem is principally concerned with regulating the outputs of a laboratory data acquisition in a controlled setting. Encoders that measure pressure, volume, temperature, and other notable values that a laboratory technician would seek access to must be located in a convenient location to be read, and inputs to the system depending on closed loop control should be easily modified. Without timely and accurate readings of the performance of the system, achievement of optimal results becomes much more cumbersome and exposed to the issue of confounding variables resulting from operating a biological system. Reliably and predictably being able to raise a bacterial culture requires extreme discipline towards all possible variables in growth.

The sanitation system sterilizes and disposes of the bacteria as well as the well plates and conical tubes where the bacteria is cultivated. The system is comprised o a housing structure to contain all the parts and the cultures with a retractable lid, a reservoir and pump system to flush the internal structure with bleach for sterilization and then distilled water is used to neutralize any residue, a fluid dispersal system using flat spray nozzles, and a drain and waste reservoir for fluid and solid waste collection that can be sterilized manually after several experiments.

The structure is the main subsystem that houses all of the other subsystems and encloses the cell cultures. The structure provides a base for the other subsystems and insulation inside. This is done by having a sealed container which can prevent the cultures that are being developed from escaping into the outside environment. This outer seal also serves

the purpose of preventing the environmental contaminants from coming into the culture generation area. Another aspect that is crucial to the function of the structure is the insulation that it holds. This is important because the customer requires the entire system to maintain an internal setpoint temperature within a certain tolerance. Overall, the structure is key to the generation of cell cultures.

The final assembly of the bioreactor can be seen in the picture below, where the parts that make up the fluid handling system have been pointed out.

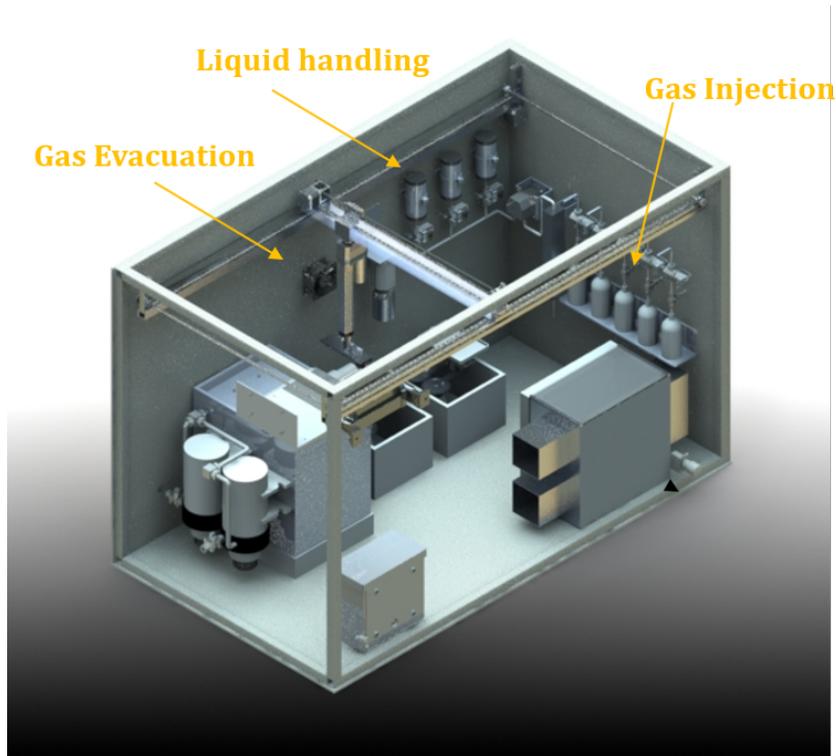


Fig. 2 Full Assembly

In terms of the economic analysis, the overall manufacturing cost of the system was found to be 834.78USD for all machining operations required for the custom parts in the system. If we take the assembly time of the sanitation system as a basis, the total assembly will take approximately 1.5 hrs to build. With a wage of 56.74 USD per hour, the assembly labor will cost 85.11 USD. Combining the purchase order, manufacturing costs, and labor costs, the total system will cost 10,565.36 USD

IV. Conclusions

The main objective of this project was to create a new design for an autonomous micro bioreactor that successfully satisfied the customers' needs. In addition, the whole engineering project could not exceed the given budget, had to fit into a lab benchtop and had to be automated. Dr. Clean not only stayed within the given limits but also went beyond and included some revolutionary characteristics that make it different from any other bioreactor in the market. This system will carry out an experiment from start to finish, being ready for the next experiment with little to no additional work to the user. The sanitation system incorporated in the bioreactor is able to safely dispose of culture materials and sanitize the equipment used, making the system ready for the next experiment.

Overall, the objectives of the project were successfully achieved by specifically following the design process, making the customers be happy with the result.

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I. Introduction

A bioreactor is a product that supports biologically active environments. It provides specific nutrients, pH levels, oxygenation levels, temperature levels, and a cell liquid culture that is needed for certain organisms to survive and grow into large-scale production.

The University of Florida Bio-foundry is seeking a conceptual design for a bioreactor capable of investigating properties at a cellular level while maintaining consistent conditions for experimental growth in addition to other customer needs. The goal of the design is that the reactor is capable of both culturing microbes in fully enclosed compartments and monitoring optical density (OD) and fluorescent intensity (FI). The desired design will allow for the testing of hundreds of variants, control factors that impact growth and tune cultures to produce the desired outputs, mainly focused on gene cloning and cell growing of bacteria such as E-coli. Additionally, the bioreactor will not require human labor, will avoid cross-contamination between experiments and will interrogate cellular properties in larger volumes than other ones already available in the market.

The project will be carried out in collaboration with some other Mechanical Engineer students from Group 10 within the subject EML4501 – Mechanical Engineering Design 2, whose director will be Matthew Traum. The final design, in this case the Dr. Clean Bioreactor, will meet the requirements that the UF Biofoundry establishes in the customer needs provided and will be designed so that it can be manufactured in the future.

The methodology used in the development of this project is the Engineering Design Process explained throughout the Mechanical Engineering Design 2 class. Starting with the identification of the problem, followed by quantified metrics and then by the generation of concepts and the following down-selection, a new product will be designed. This design will be updated and improved taking into account the customer's feedback, as well as limitations in cost and the ability to be manufactured. This process will consist in three different parts which are the CDR (Concept Design Report), PDR (Preliminary Design Report) and FDR (Final Design Report).

The first part, the Concept Design Report, culminates in generation of design concepts for the Autonomous Microbioreactor meeting all customer needs. This document will include background information supporting multiple concepts, hand drawings of concepts and their key mechanisms. In the second part, the Preliminary Design Report, the proposed concepts are evaluated and the most suitable one is selected according to previously established decision matrixes. For each selected design, calculations will be included to prove the limitations given by the customer on each subsystem are not exceeded. Following different Ashby plots, materials for each design are specified and included in a Bill of Materials alongside with the Purchase Order, including the OTS parts. In addition, in the PDR, a model of Dr. Clean was created in SolidWorks as part of the manufacturing process. In the final assignment, the Final design Report, necessary minor improvements are made to the model and drawings for each element are included. A detailed visual explanation is included on how to put together the different parts of the subsystems.

NOTE: A brief description of each subsystem will be provided in this document, although it will only go deep into the Fluid Handling Subsystem. It also includes parts that are common to all of the subsystems, which include the Bill of Materials, Purchase Order, CAD Model and overall results.

II. Nomenclature

C_{total}	=	Total Cost
$C_{\text{component},i}$	=	Cost of Component i
V_{total}	=	Total Required Voltage
$V_{\text{req},i}$	=	Voltage of Each Component
h	=	Free Body Height
ω	=	Rotational Velocity
r	=	Radius
h_0	=	Initial Height
V	=	Volume
R	=	Well Radius
H	=	Well Height
g	=	Force of Gravity
ω_{max}	=	Max Rotational Velocity
a_x	=	Acceleration in X direction
C	=	Clearance
Q	=	Volumetric Flow Rate
A	=	Cross-Sectional Area
Re	=	Reynolds Number
ρ	=	Density
D	=	Diameter
μ	=	Dynamic Viscosity
ΔP	=	Pressure Change
h_L	=	Height
R	=	Thermal Resistance
h_∞	=	Heat Coefficient of Surroundings
K	=	Thermal Conductivity Constant
T	=	Temperature
T_∞	=	Temperature of Surroundings
q	=	Heat Flux
Nu	=	Nusselt Number
H	=	Enthalpy
A	=	Area
L	=	Length
w	=	Width
P	=	Power
i	=	Current
KE	=	Kinetic Energy
q	=	Average Heat transfer Coefficient
λ_{max}	=	Maximum wavelength
T_{total}	=	Total Torque
T_{constant}	=	Constant Velocity Torque
$T_{\text{acceleration}}$	=	Acceleration Torque
η	=	Pulley System Efficiency
μ	=	Friction Coefficient
J	=	Moment of Inertia
α	=	Max Acceleration
n	=	Factor of Safety
C	=	Stiffness Constant
F_i	=	Preload
k_b	=	Bolt Stiffness
k_m	=	Member Stiffness
G	=	Gear Ratio

2. PDR. Preliminary Design Report

Preliminary System Design

UF MAE Mech Design 2
Group 10

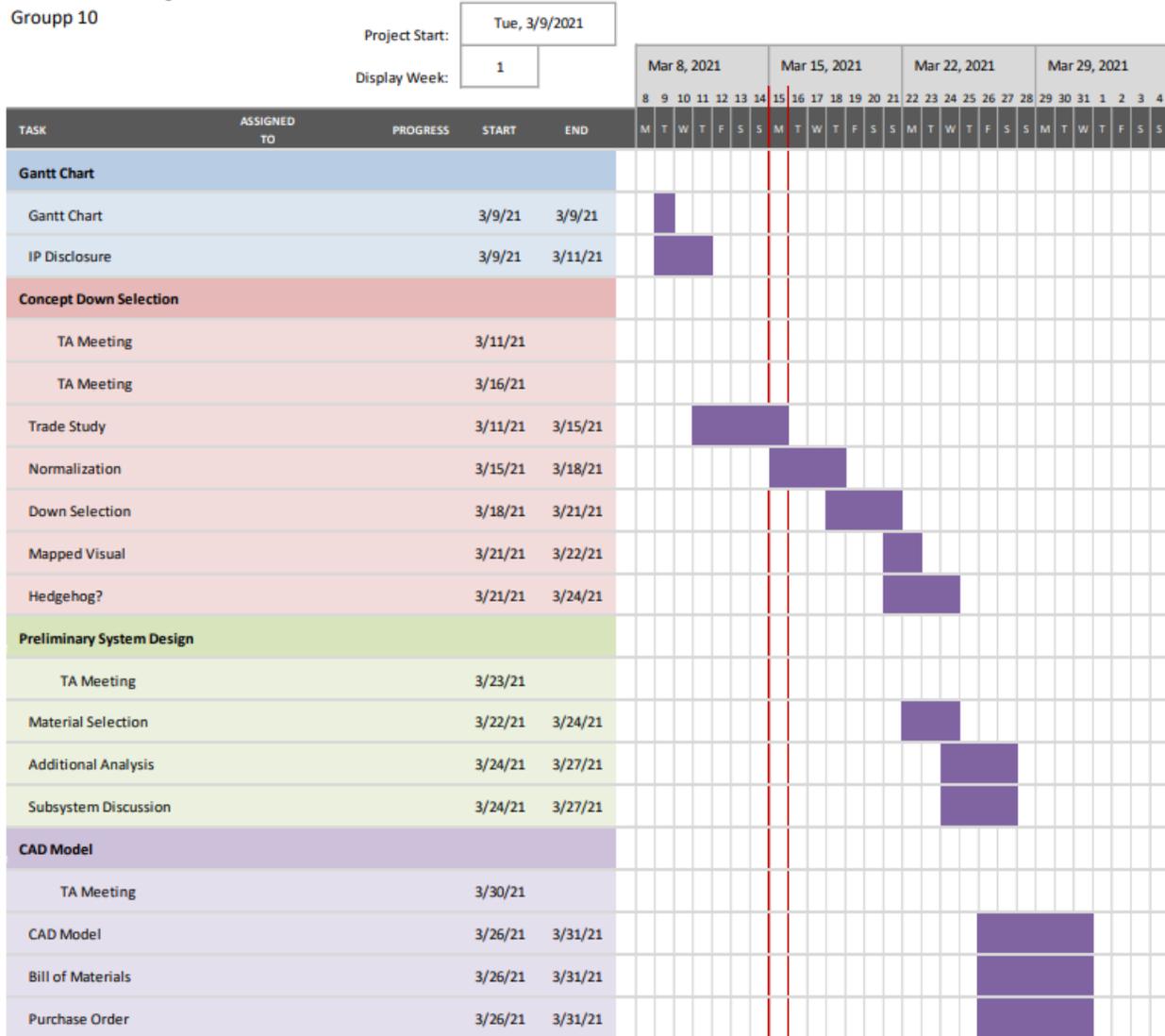


Fig. 2 Gantt Chart

This was probably the assignment in which the time was best managed. A lot of effort was put into evaluating each of the concepts developed in the Concept Design Report, and into the analysis. The Bill of Materials, Purchase Order and the CAD on Solid Works were left for the last minute since it needed all of the parts of the system to be complete. A lot of effort was done in the last two days but the work was finished on time. Meetings with the TA were crucial in this part of the project to get feedback and for setting up guidelines for the Final Design Report.

B. Background Information and Research

1. Problem Statement

The variable nature of growing bacterial cultures within an experimental environment creates a diverse challenge in obtaining data while avoiding biological complexities. Spontaneous physical variations and evolution take place continuously, making the characterization of synthetic biological systems tedious.

Minimizing the unreliability of bacteria species in propagation of their population even within a controlled space can allow for standardized experiments to observe phenomena within their growth such as culture conditions, control of factors pertaining to growth, and continuous improvement. This is done thanks to large scale manufacturing, sensors and monitoring the experiments, and repeatability and standardization of lab processes. The University of Florida Bio-foundry is seeking a conceptual design for a bioreactor capable of investigating properties at a cellular level while maintaining consistent conditions for experimental growth.

2. Literature Review

Biological advances throughout the years have been able to engineer systems of bacteria that increase at a large rate, however, the dynamic behavior of the system makes it difficult to replicate the experiment. In addition, current techniques are not reliable due to the environment caused by waste production.

The UF Bio-foundry detailed design is based upon principles of heating and cooling that have been attempted in consumer markets, namely with a device called a peltier. The assembly stores bacterial cultures or fluids in a bag with a heating mechanism to result in proper fermentation, which is also similar to existing designs from companies such as Thermo Fisher within industrial reactors [2]. These devices have the capability to heat and cool according to manipulation from a controller, seeking an acceptable temperature range in order to avoid a phenomenon called the Seebeck Effect. The applied temperature differential travels across a series of semiconductors in order to produce a voltage, which causes a temperature change within the structure. Cooling is done through electrical impulse sent in one direction across the wiring, while heating sends current across what are now modeled as resistors in the opposite direction. Both are necessary according to the customer needs and must be completed within tolerable temperature.

Measuring optical density in a bacterial culture can be done in various ways, from general purposes of visual identification to analysis by mass spectrometry. Measuring the optical density of a culture can tell the technician the number of cells present within a medium, which is the most typical answer sought after in media analysis. Light absorbance received by the medium can apply to how much is transmitted, where calculations will work backwards to understand how light scattered. This entirely depends on the thickness of the well plate or control medium, as well as the level of absorbance typically observed by the bacterial culture. A baseline measurement can be obtained by measuring a blank cuvette or test tube containing pure media in order to see light's transmission [3].

As cells are added, transmittance can be calculated through a ratio of transmitted to received light, applying a logarithmic scale to derive absorbance. This normally will depend on the pure number of bacterial cultures and not necessarily the coloring. As a reference, an E-coli culture with an optical density of 1 generally corresponds to about 10 billion cells[4]. A caveat is the reading of light is only accurate if light is able to travel through the tube, calibrating for each absorbance and not repeated. The resulting optical density should correlate on a linear scale with cell density.

Bacterial growth is known to happen according to a curve broken up into phases. The lag phase is initially when a bacterial culture is inserted with active cells that are active but not necessarily dividing yet. The exponential phase or growth period is a time of rapid division and number multiplication: E-coli is known to double about every 20 minutes within this phase.[5] The stationary phase can be observed when the overall number of cells is consistent to the maximum cell density within a liquid culture that can be achieved. Finally, the death phase is reached for a number of reasons which vary according to the particular culture, including malnutrition, pH changes, accumulation of toxic waste, or general cell maturation.

A typical bioreactor on the market will generally be comprised of continuous culture devices, either concerned with manipulating bacteria at pace until reaching steady state and then controlling future production or using a feedback control loop to keep density of desired cultures constant [5]. Controlling maximum growth of cells in this type of device, known as a turbidostat, has been attempted at Rice University in very similar conditions to present customer needs including control sensors, optical density measurement, and fluorescent identification. An issue with the commercially available turbidostats is their high cost.

In accordance with the customer's needs, our bioreactor must include the following features: liquid dispensing with incubation and measurement, adjustable working volumes, larger temperature range than other commercial bioreactor and added atmospheric conditions. Moreover, the bioreactor must be able to fit into a laboratory bench top space, be easy to use and to install, must be as fast as possible processing data.

C. Metric Quantification and Subsystem Identification

1. Customer Needs Overview

The UF Biofoundry is seeking to combine in a single device the following features that can be divided into four main groups: The bioreactor must have the ability to dispense liquid as well as being able to incubate cells and take measures of all kinds. Adjustable working volumes should be available to the user as well as added atmospheric conditions, to be able to integrate different experiments in the same device. The bioreactor should reach temperatures within a bigger range than others available in the market. While most bioreactor can usually only get up to 37°C, this new system must be able to maintain cultures in a well plate or tube at a constant temperature within a range from 4°C to 79°C.

Bacteria growth is largely dependent on the amount of dissolved oxygen available, which can be supplied by aerating the cultures via shaking/stirring the cultures. Without this dissolved oxygen supplementation, the cultures would expend the supply and switch to anaerobic growth, which would produce carbon dioxide gas, alcohols, and acids. To properly aerate the cultures, a shaking mechanism capable of linear and rotational motion is needed.

In addition to the health risks to humans *E. Coli* poses, for experimental accuracy it is necessary to ensure that there is no residual cells left alive in the well plates and test tubes being utilized in the next experiment. To ensure proper sanitation currently in the lab, researchers cull the cell culture with bleach and rinse the well plates in a sink to sanitize them [6]. This process needs to be replaced with an automated process to sanitize equipment used at the end of the experiment to minimize work for the researchers.

2. Subsystem Selection

The subsystems were selected on the repetition and relevance of the customer needs. Requirements such as operational lifetime, prototype, production, ability to transport, and using 120 VAC power were applied to all subsystems since they are cumulative. The same goes for requirements such as nonporous and nonreactive material as they depend on the materials selected for each system. The ability to incubate 1000 cultures for two weeks was applied to most if not all subsystems as that is the final use for the design.

Considering the requirements that dealt with the mobility of cultures and the desire to make the entire process autonomous with as little human interaction as possible, a subsystem for manipulation seemed fitting. There were two requirements that specifically called for shaking patterns, so a shaker system was created. We considered merging it with the manipulator, but the vibrations while moving could unbalance the manipulator and make it less accurate.

A controller system was created so control the system. The creation of the system also indirectly encourages making the system more autonomous. We briefly considered a subsystem just for sensors since there were four requirements for optical density (OD) and fluorescent intensity (FI), but the concepts generated were not very diverse so it was absorbed into the controller subsystem.

The customer emphasized the need for control in the injection of bacteria samples and nutrients. This includes the volume accuracy and precision during dispensing and the ability to alter the volume of each vessel whether it is a well plate or conical tube. Therefore, a fluid handling subsystem was created.

We know temperature control is important during biological testing, so we originally made a temperature control subsystem. After reviewing the requirements, it was decided that the temperature control system would be reconfigured to include the possibility of measuring and controlling pressure and humidity within the system. We see the requirement for sterilizing, and while it is only repeated one other time, we understand the important of sterilizing, neutralizing, and disposing of bacteria samples to reduce contamination within and outside of and experiment and therefore we dedicated a subsystem for sanitation.

All of these components still need to be housed into a structure. While the concept of a structure does not inspire a lot of diverse ideas, the requirements stated that the structure must be able to fit nicely on a standard laboratory benchtop and the benchtop must be able to withstand the weight of the entire subsystem so we assigned a subsystem to the structure itself.

3. Customer Needs and Preliminary Metric Mapping

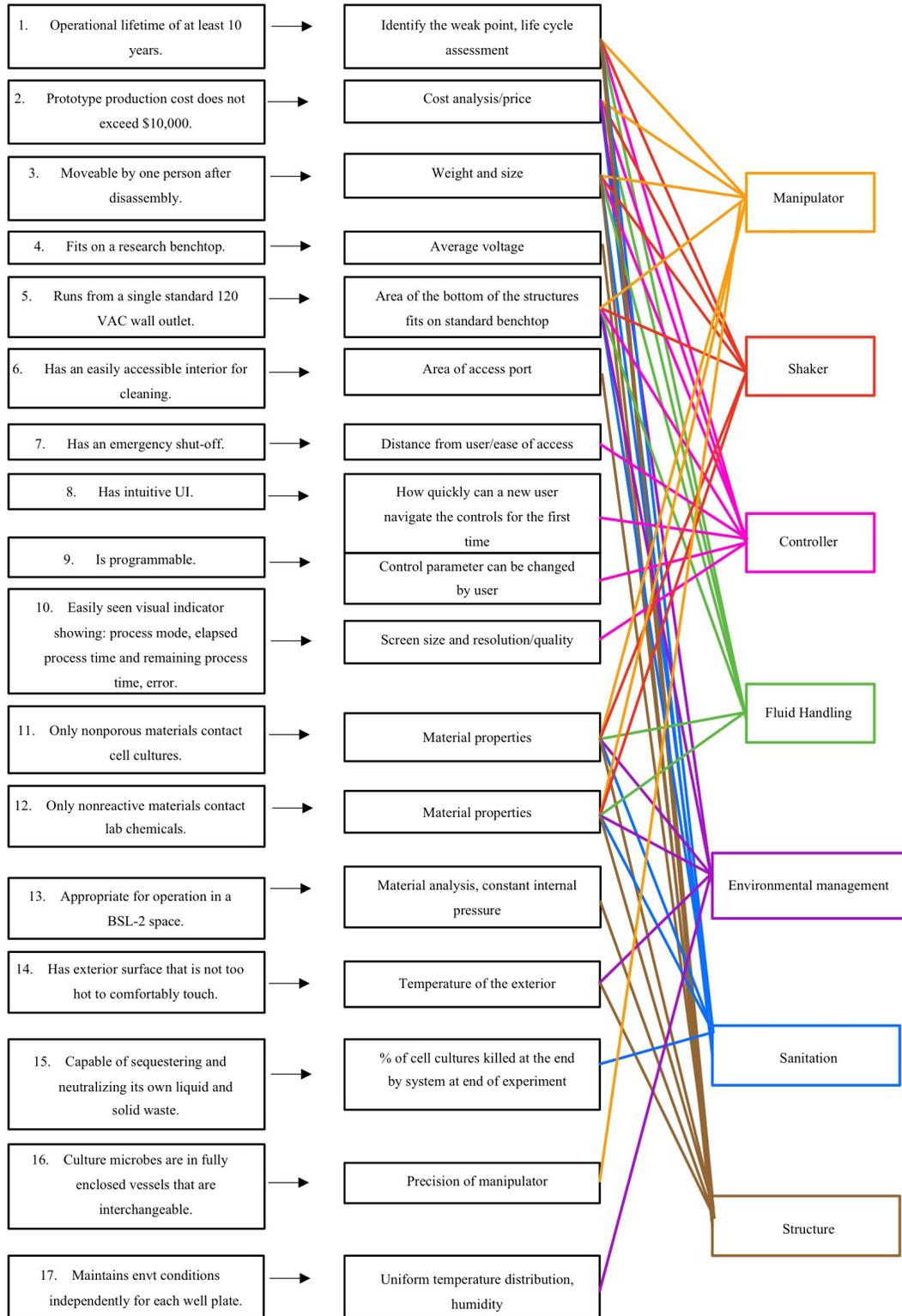


Fig. 4 Customer Needs Map 1-17

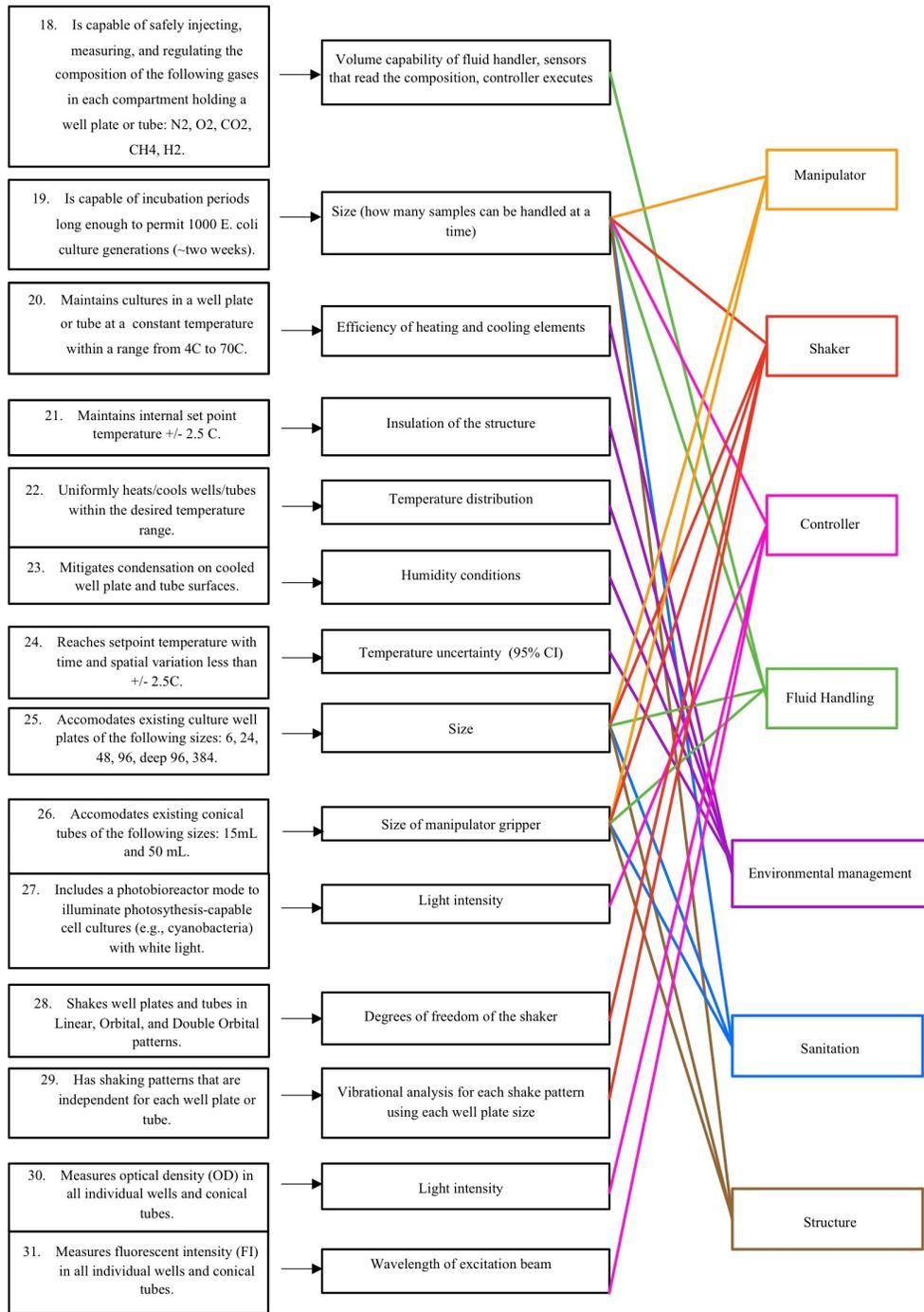


Fig. 5 Customer Needs Map 18-31

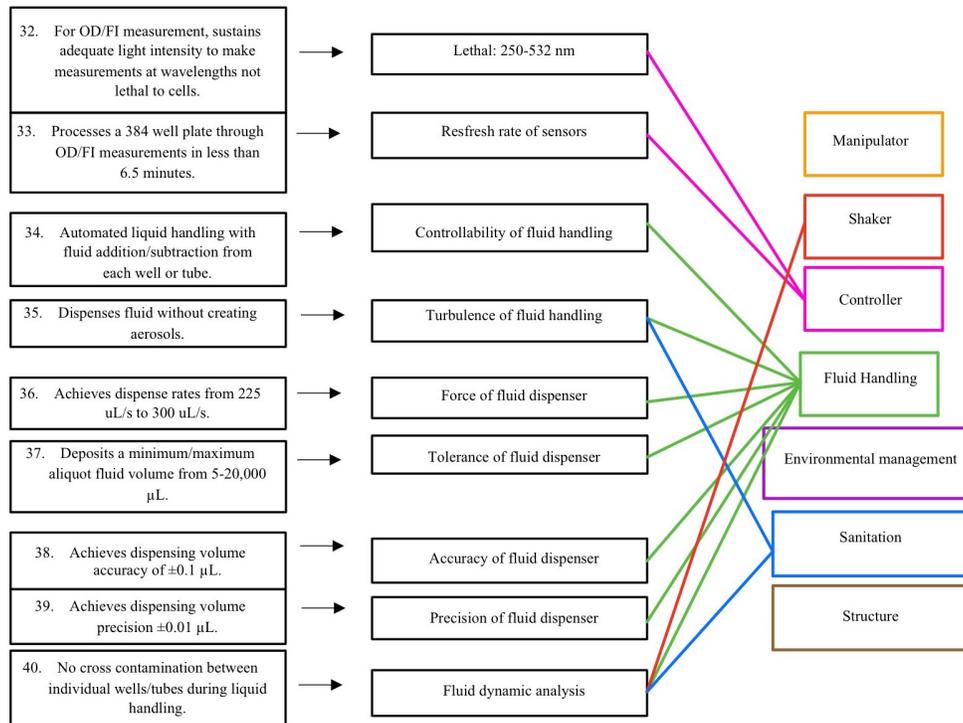


Fig. 6 Customer Needs Map 31-40

Figures 4, 5 and 6 link each of the customer needs with their calculated metrics inside each of the subsystems. These metrics related to each customer requirement have been used in the down-selection process for choosing the winning concept in each subsystem. Three figures show that every customer need is met by the selected design.

IV. Project Description

A. Hedgehog Concept

This system will carry out an experiment from start to finish, being ready for the next experiment with little to no additional work to the user. The sanitation system incorporated in the bioreactor will be able to safely dispose of culture materials and sanitize the equipment used, making the system ready for the next experiment. The well plates and conical tubes, still filled with cell culture media, are placed into a sanitation chamber that will cull the cell cultures and dispose of solid and liquid waste, leaving sanitized well plates and tubes for future use.

B. Concept Design Generation

1. Manipulator

The manipulator subsystem is responsible for being able to transport well plates and test tubes from storage areas to the shaker subsystem, and ideally anywhere else the user would like to move the cultures to. The manipulator is also responsible for being able to take the lids off of the well plates that the user might be using, which requires high precision. The manipulator ties into many of the sanitation concepts as they require the well plates and/or test tubes to be dumped before they are sanitized. These imposed requirements lead to the assumption that the manipulator must be placed in a very central position of the structure, where it is within range of storage locations, shaker plates, and sanitation areas. Since the well plates and test tubes may be incubating and filled with fluids when they are being transported, it is crucial that the manipulator transports them in as stable a manner as possible. Additionally, the freedom of motion of the manipulator is one aspect that would make for a more user-friendly experience.

2. Shaker

To properly aerate the cell cultures, the shaking mechanism needs to be capable of linear and orbital movement. For orbital shakers, a key variable is the diameter of the orbit. Many commercial shakers have an orbit diameter between 1.27 cm to 5.1 cm, with larger orbitals yielding better results. The other variable of importance is the agitation speed. [7] references using speeds of 150 to 300 revolutions per minute (RPM), so maximum RPM values must be calculated to avoid cross contamination from fluid rising past the top of the well or tube. Rigid body rotational analysis will be done to determine how quickly the well plates may be spun.

The orbital motion causes a fluid rise directly related to angular velocity and radius of rotation. The average radius of rotation for commercial systems has been described as 1.27 to 5.1 cm [7] To find the maximum angular velocity the cultures may be spun at, which will yield the best aeration results possible, the volume of the wells and test tubes that is filled must be determined. Best growth results have been cited to be when culture volume is 10 to 25% of the flask or well volume [7]. Without knowing the exact volume filled by researchers in the UF Biofoundry, a fill volume of 50% will be assumed to provide a conservative estimate to ensure avoidance of cross contamination between wells.

3. Environmental Management

The environmental management subsystem is principally concerned with the interaction of heating and cooling elements in conjunction with the motor controllers and motion aspects of the assembly. Conduction and convection principles will be investigated in accordance to the customer needs metrics outlined in an attempt to rank concepts by suitability to design standards. Elements included in approximated HVAC systems will be researched and will be off the shelf if possible while also considering requirements for power generation. Each heating element or compressive cooling element will be modeled with best regard to function and in order to most accurately target the customer needs metrics for the subsystem in question. Power and convective heat transfer coefficient values will differ when considering one dimensional flow versus a three dimensional enclosure where heating will cycle.

Temperature ranges are known as a target, but resistances, power to maintain a certain temperature, and average convective heat transfer coefficient must be derived in order to analyze possible approaches to concept generation. The stability of the system must be kept into consideration when looking into lifetime operation of the assembly, which will vary in temperature and pressure conditions depending on the needs of the cultures. A nodal matrix will be approximated for every conceptually generated design in order to investigate the temperature propagation against bordering materials. This will operate under the assumption that the enclosure to the testing or laboratory environment has two layers, one of a nonreactive metallic housing and one of a removable glass solid incubator. The provided governing equations will be concerned with heat, pressure, fluid flow, and variations according to philosophies of the assembled concepts.

4. Controls

The controller subsystem is principally concerned with regulating the outputs of a laboratory data acquisition in a controlled setting. Encoders that measure pressure, volume, temperature, and other notable values that a laboratory technician would seek access to must be located in a convenient location to be read, and inputs to the system depending on closed loop control should be easily modified. Without timely and accurate readings of the performance of the system, achievement of optimal results becomes much more cumbersome and exposed to the issue of confounding variables resulting from operating a biological system. Reliably and predictably being able to raise a bacterial culture requires extreme discipline towards all possible variables in growth.

5. Sanitation

The sanitation subsystem addresses the needs for the sterilization of cell cultures and their proper disposal. The cultures must be killed prior to disposal down a drain, and the well plates or test tubes they resided in must be sterilized for future experiments. This can be done a few different ways, including using UV light of a high enough intensity, rapidly heating to a high temperature and holding that temperature for a set amount of time, and using bleach as is already done by the customers [6].

To effectively cull *E. Coli* bacteria cultures with UV light, there is a particular range of wavelengths that have been found to be most effective in the UV spectrum. The optimal range is between 250 and 532 nanometers (nm), with the ideal wavelength being 265 nm. To ensure that the output of a light source achieves a wavelength in this ranges, and therefore is able to cull the bacteria cultures, a UVC Dosimeter may be used to indicate the amount of UV energy received, verifying the effectiveness of the system [8].

To effectively cull *E. Coli* bacteria cultures with heat, they must quickly heated to a temperature of 70°C and held at that temperature for an extended period of time (this varies per strain, sometimes being only as long as a few seconds, though a minimum of 10 minutes seems reasonable for a large number of strains to ensure the cultures are terminated [9]).

To effectively cull *E. Coli* bacteria cultures with bleach, as has been done in the labs at UF [6], researchers simply poured bleach into the well plates and tubes and then rinsed them in a sink. Automating this process will involve either having a reservoir filled with bleach to soak well plates and test tubes or a nozzle that can spray the cultures with bleach and then rinse with water.

6. Structure

The main purpose of the structure subsystem is to house all of the other subsystems in one cohesive unit. This is done by having a sealed container which can prevent the cultures that are being developed from escaping into the outside environment. This outer seal also serves the purpose of preventing the environmental contaminants from coming into the culture generation area. Another aspect that is crucial to the function of the structure is the insulation that it holds. This is important because the customer requires the entire system to maintain an internal setpoint temperature within a certain tolerance. Overall, the structure is key to the generation of cell cultures.

7. Fluid Handling

Subsystem description

The fluid handling subsystem consists of the liquid handling system and the air injection and evacuation system. The liquid handling addresses the needs for satisfactory moving cultures suspended in liquid between compartments and providing nutrients in media to cultures. The liquid handling in the bioreactor must be automated and must be capable of precisely adding and subtracting fluid from each well plate or conical tube. In this process no aerosols can be created and no cross contamination between individual wells or tubes can take place. Liquid dispensing must be done achieving certain dispensing rates and volume accuracy and precision that will be specified below.

Although not indicated in all the concept illustrations, the following elements always make up the liquid handling system: a liquid reservoir, a peristaltic pump, a upstream and a downstream switching valve and flexible tubes connecting these elements. Since multiple techniques for waste disposing and sterilization are available, a deeper study of it will be done in the sanitation subsystem, focusing this analysis only on the nutrient supply to cultures.

Since the flow rates required to sustain cell cultures are small and the system is operated accordingly, the velocity of the flow is so small that it can be considered to be essentially laminar and two-dimensional, considered to travel smoothly along a simple, well-defined path.

In order to satisfy requirement number 18, a system for injecting gas was required. Although the way to dispense liquid and gases are completely different, both were included in this subsystem for their nature. This part will consist of 5 different gas tanks (one for each type of gas), solenoid valves and pressure regulators. Although none of these gases are toxic, the bioreactor needed a system to filter and expel the mixture outside of the main chamber, so in the later versions of the design a gas evacuation system was added.

The customer need metrics evaluated for this subsystem are listed as follows:

- Requirement 1: Operation lifetime of at least 10 years.
- Requirement 2: Prototype production cost does not exceed \$10,000 .
- Requirement 3: Moveable by one person after disassembly.
- Requirement 5: Runs from a single standard 120 VAC wall outlet.
- Requirement 11: Only nonporous materials contact cell cultures.
- Requirement 12: Only nonreactive materials contact lab chemicals.
- Requirement 18: Is capable of safely injecting, measuring, and regulating the composition of the following gases in each compartment holding a well plate or tube: N_2 , O_2 , CO_2 , CH_4 , H_2 .
- Requirement 19: Is capable of incubation periods long enough to permit 1,000 *E. coli* culture generations (two weeks).
- Requirement 25: Accommodates existing culture well plates of the following sizes: 6, 24, 48, 96, deep 96, 394.
- Requirement 26: Accommodates existing conical tubes of the following sizes: 15mL and 50mL.
- Requirement 34: Is capable of automated liquid handling with fluid addition/subtraction from each well or tube.
- Requirement 35: Dispenses fluid without creating aerosols.
- Requirement 36: Achieves dispense rates from 225 $\mu\text{L/s}$ to 300 $\mu\text{L/s}$.

Governing Equations

$$Q = VA \quad (1)$$

$$Re = \frac{\rho VD}{\mu} \quad (2)$$

$$\Delta P = \frac{8\pi\mu Q}{A^2} \quad (3)$$

$$P_1 + \frac{\rho V_1^2}{2} + \rho gh_1 = P_2 + \frac{\rho V_2^2}{2} + \rho gh_2 + h_L \quad (4)$$

In order to apply the following equations, some assumptions must be made. The flow through the syringe or pipettes will assumed to be Newtonian, laminar, in-compressible and with negligible acceleration.

Equation (1) will be used to determine the flow rate through the tube during dispensing. V stands for the velocity of the fluid and A corresponds to the cross-sectional area of the conduct.

Equation (2) will determine the Reynolds number, which must be <2300 because the flow must not be turbulent to avoid the creation of aerosols during liquid dispensing. ρ refers to the density of the fluid, V is the velocity of the fluid, D is the diameter of the dispensing tube and μ coefficient of friction of the fluid.

Equation (3) corresponds to the Hagen-Poiseuille Law which will provide the pressure gradient across the fluid dispenser conduct which can be used to determine the target flow rate.

In order to be able to apply (4) which is Bernoulli's Equation the following assumptions must be made: steady flow, in-compressible flow and fully developed boundary layer. hL stands for the head loss in the conduct.

Below can be found the concepts that were developed for the down-selection corresponding to the Fluid Handling system.

Concept 1

Cartesian Syringe

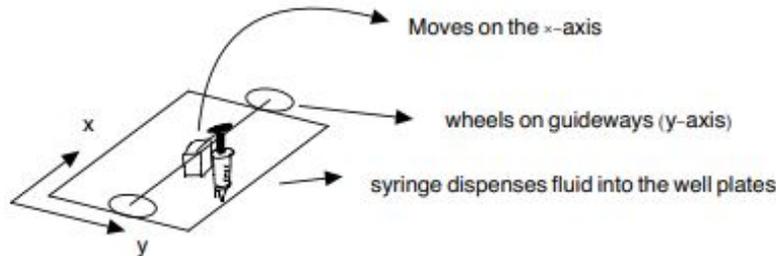


Fig. 7 Cartesian Syringe

This concept is composed of two main parts, the frame and the syringe dispenser. The frame borrows aspects from Concept 1 of the manipulator subsystem, namely the motorized wheels which are mounted on guide ways, allowing for movement in the Y-axis, and the 5V DC motor which allows the syringe itself to move on the shaft, which is in the direction of the X-axis. The syringe itself is powered by a miniature linear actuator, which is able to dispense fluid at very precise intervals. The advantages of this concept are the ability of the syringe to move virtually anywhere within the bounds of the structure, and the precision at which the syringe can dispense the needed fluids at.

- Requirement 1: The concept utilizes a 5V DC motor which has a typical life span under normal conditions of approximately 5000 hours [10], which equates to 2 and a half years of use at 8 hours per day for 5 days per week. Since with this kind of motor this requirement is not satisfied an AMP Step Motor will be used instead, which typically represents 10+ years of field use under same use conditions [[11]]. Therefore, this requirement would be satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids pipettes that cost less than \$100 to mid-range bench top units. Assuming that the raw stock material used for the shaft, the frame, the wheels, and the mechanism will be some type of nonreactive alloy, the raw material price should not exceed \$50. The approximate cost of a 5V DC motor is \$15 . The concept has an estimated total cost of \$285. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: The power requirement of this concept includes a 5 V DC which falls well below the max required 120 VAC.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: his concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.

- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen syringe diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: Since a single syringe is used for fluid handling sanitation plays an important role in this concept in order to avoid cross contamination.

Concept 2

384 Well plate filler

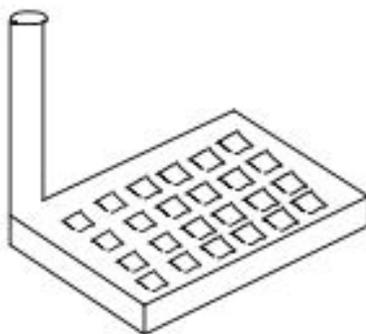


Fig. 8 384 Well Plate Filler

This concept is unique in that it is meant to fill an entire 384 well plate at once, which is very time efficient when compared to a single syringe. The concept is made of a hollow nonreactive plastic vessel, with an fluid entry point at one corner. The fluid would be fed to the system from a reservoir, with a pneumatic regulator controlling how much fluid enters the system at a given instant. The plastic structure contains 384 precision drilled holes which are organized in 16 rows and 24 columns, to match that of a 384 well plate. The main disadvantage to this concept is that it is not able to fill any of the other well plate sizes, such as 96, 96 deep, 48, 24, 6, and neither of the two sizes of tubes required, such as 15 mL and 50 mL.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. A pneumatic regulator may last 25 years without replacing any major components, so the 10+ years requirement would be satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids pipettes that cost less than \$100 to mid-range benchtop units. For the fluid regulator, cost should not exceed \$20. The total sum would go up to \$240. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: For this fluid handling system no additional power supply is needed.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.

- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen syringe diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which s
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: The specific shape of the dispenser and its way of filling well plates does not allow the correct waste removal from well plates.

Concept 3
Modified Syringe

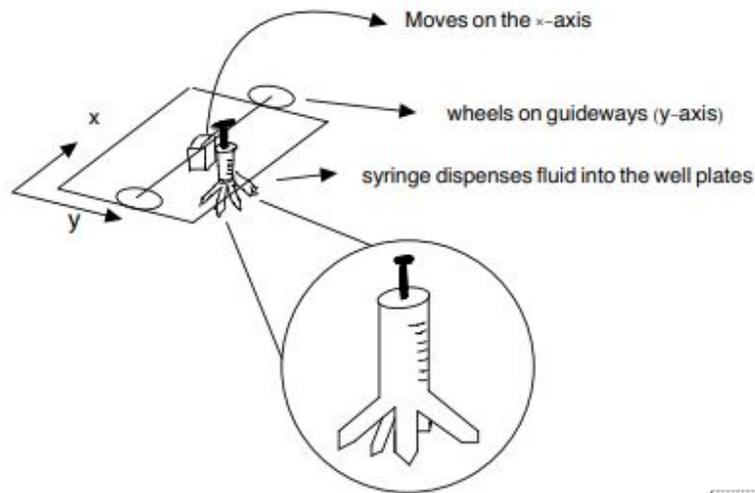


Fig. 9 Modified Syringe

This concept is very similar to Concept 1 for the fluid handling. Similarly, it is composed of a frame section, and the syringe itself. The frame part is composed of two grooved wheels that sit on guide ways, and one of the wheels is equipped with a 5 VDC motor, which allows it to move along the X-axis. The rod on which the wheels are mounted is also equipped with a 5 VDC motor, which allows the syringe mechanism to translate in the Y-axis. The syringe is a custom built piece, which can alternate between a single fluid dispensing point, such as in a standard syringe, to a four point dispensing mechanism. This alternating is done by capping off the 4 other exits when the single syringe effect is desired, and capping the single center point when the four point dispenser is needed. The advantage of having the single dispenser is that it makes it easier to fill up test tubes and do precise work when feeding nutrients to a single well. On the other hand, the advantage to having a four point dispensing mechanism is that it can make filling an entire 384 well plate a lot more time efficient than if the single point mode was used. The dispensing of the fluid is done by the controls system via a miniature linear actuator.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. The concept also utilizes a 5V DC motor which has a typical life span under normal conditions of approximately 5000 hours[], which equates to 2 and a half years of use at 8 hours per day for 5 days per week. Since with this kind of motor this requirement is not satisfied an AMP Step Motor will be used instead, which typically represents 10+ years of field use under same use conditions []. Therefore, this requirement would be satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids cost less than \$100 to mid-range benchtop units. Assuming that the raw stock material used for the shaft, the frame, the wheels, and the mechanism will be some type of nonreactive alloy, the raw material price should not exceed \$50. The approximate cost of a 5V DC motor is \$15 . The concept has an estimated total cost of \$285. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: The power requirement of this concept includes a 5 V DC which falls well below the max required 120 VAC.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: Syringes are usually disposed because they are difficult to sterilize. In this case, since it is a custom built piece, removable parts could be added to the system to avoid cross contamination.

Concept 4

Motorized Syringe

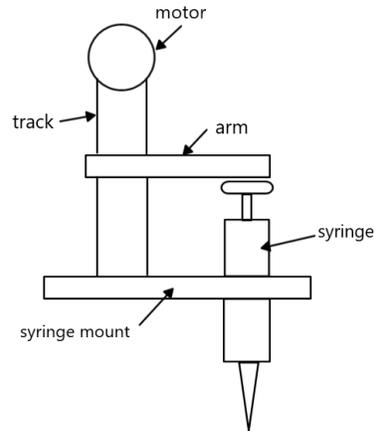


Fig. 10 Motorized Syringe

A single syringe is used to dispense fluid into the well plates or test tubes. The syringe is mounted by its barrel onto a manipulator arm that has two axes of movement. To dispense the fluid, a rectangular piece slides on a track that is belt driven by a motor. The rectangular piece applies pressure onto the plunger of the syringe, dispensing the fluid. The motor that applies pressure onto the syringe is connected to the system controller.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. If an AMP Step Motor is used which typically represents 10+ years of field assuming 8 hours of daily use 5 days a week[.]. Therefore, this requirement would be the \$10,000 budget, the requirement is satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids cost less than \$100 to mid-range benchtop units. Assuming that the raw stock material used for the arm, track and mount will be some type of nonreactive alloy, the raw material price should not exceed \$70. The approximate cost of an AMP Step motor is around \$100. The concept has an estimated total cost of \$390. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied. Cost could be reduced by placing other type of motors like a 5V DC.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: The power requirement of this concept includes a 5 V DC which falls well below the max required 120 VAC.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar

flow.

- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: Syringes are usually disposed because they are difficult to sterilize. Other options such as introducing bleach into the syringe for sterilizing could be studied in order to avoid cross contamination between experiments.

Concept 5

Closed-Loop fluid distribution

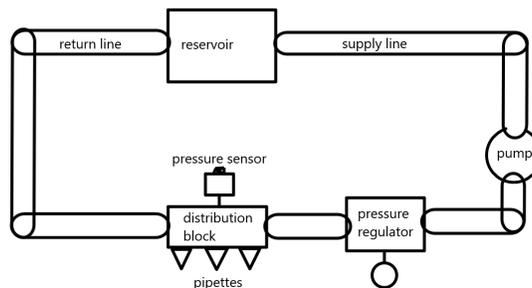


Fig. 11 Closed-Loop Fluid Distribution

In this closed-loop fluid distribution system, the nutrients for the samples are in a reservoir and are supplied to the pipettes using a pump and distribution block before returning to the nutrient reservoir. The supply and return lines are of a rubber material that is resistant to chemicals. The pressure regulator allows the fluid into the inlet if its pressure exceeds the set value. The pressure sensor can be communicated with a controller and the distribution block allows for more than one pipette to function at a time.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. Pressure sensors have an approximate life expectancy of 10 to 15 years [] so this requirement would be satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids cost less than \$100 to mid-range benchtop units. For the fluid regulator, cost should not exceed \$20. For a regular pressure sensor an approximate cost of \$50 will be assumed. Then, the concept has an estimated total cost of \$290. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: For this fluid handling system no additional power supply is needed.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safely injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.

- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: The closed-loop fluid distribution of this concept where all parts are connected favours cross contamination between experiments. It is a robust system which makes it harder to isolate elements when contamination takes place.

Concept 6

Burette/Stopcock assembly dispensing

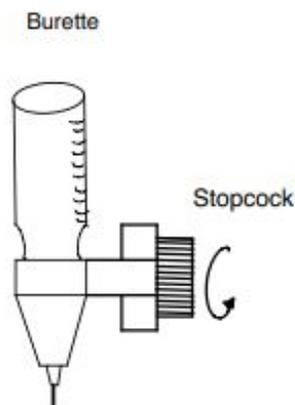


Fig. 12 Burette/stopcock assembly dispensing

This concept for fluid handling consists of a burette/stopcock system for allowing automatic dispensing. This concept would be extended to multiple vessels for a full well tray. The stopcock should provide proportional control over dispensing of fluid for experimentation manually, without a gauge from motor controls to determine when to stop manipulation of the turning mechanism.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life so this requirement would be satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids cost less than \$100 to mid-range benchtop units. An automatic stopcock costs around \$400. Then, the concept has an estimated total cost of \$620. Although this system only makes up one of the several subsystems, we can assume the requirement is satisfied (total cost $< \$10,000$).
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: For this fluid handling system no additional power supply is needed.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of $N_2, O_2, CO_2, CH_4, H_2$. This will be done by adjusting the capability of the fluid handler and via different

sensors. All the gas dispensing process will be executed by the controller.

- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: Syringes are usually disposed because they are difficult to sterilize. Other options such as introducing bleach into the syringe for sterilizing could be studied in order to avoid cross contamination between experiments.

Concept 7

Piston/cylinder assembly pressure differential

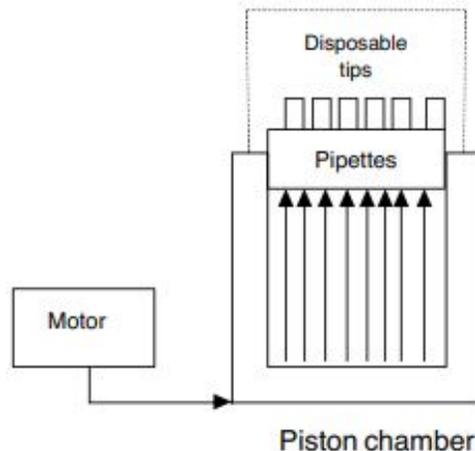


Fig. 13 Piston/cylinder assembly pressure differential

This concept consists of a motor, a piston and pipettes. The motor makes the piston move creating a pressure gradient that will let the fluid fill the pipettes. The tip actuating mediums for experimentation is removable for replacement in each new trial. A motor controller will set a speed and desired pressure within the chamber.

- Requirement 1: In this case no pump would be necessary since the fluid would get into the pipettes by the pressure difference inside the piston chamber. If an AMP Step Motor is used for this concept which has a 10+ years lifespan, this requirement would be satisfied.
- Requirement 2: A piston that has the size we need costs around \$25. An AMP step motor's price is \$100 approximately. Assuming pipettes will be less than \$50, the concept has an estimated total cost of \$175. Since it is a small fraction of the required budget of \$10,000, the requirement is met.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: For this fluid handling system no additional power supply is needed.

- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: The shape of pistons do not allow for proper cleaning or sterilization, so although disposable tips are used in this concept, cross contamination is possible.

Concept 8

Well Plate Industrial Filler

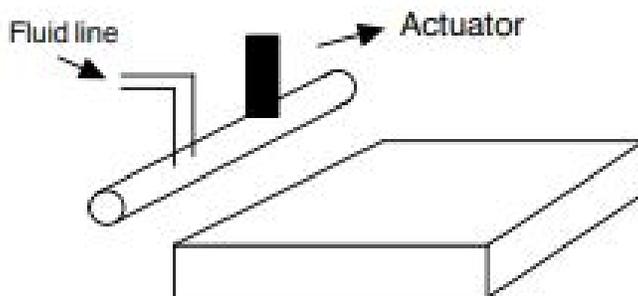


Fig. 14 Well Plate Industrial Filler

To rapidly fill 384 well plates, this concept uses multiple nozzles connected to a central tube that can distribute fluid to entire rows on the well plate at a time. To achieve this, the unit will move in two axes via linear actuators, one directly attached to the unit and one attached to the structure, allowing precisely controlled motion to fill the wells accurately with minimal cross contamination between wells.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. Linear actuators have a very long lifespan usually 10+ years. Therefore, this requirement is satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids cost less than \$100 to mid-range benchtop units. The selected linear actuator costs \$20, although more expensive ones can be chosen. Then, the concept has an estimated total cost of \$240. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.

- Requirement 5: The power requirement for this concept includes a 5V micro linear actuator, which falls well below the max 120VAC requirement.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: The shape of the fluid handler allows cross contamination to take place if no proper sanitation is done between experiments.

Concept 9

Well PLate Irrigation

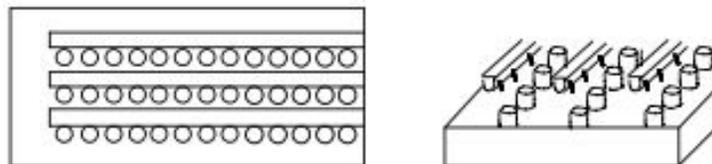


Fig. 15 Well Plate Irrigation

This design concept deploys an irrigation system in order to deliver fluids to all 384 well plates included in the system. The irrigation extends above the well plates and uses gravity to drip into each subsequently. A pump is used to begin delivery of the fluids through the irrigation system.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. Therefore, this requirement is satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Assuming the irrigation system conducts are made from plastic they should not exceed \$20. Then, the concept has an estimated total cost of \$140. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: For this fluid handling system no additional power supply is needed.

- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: The shape of the fluid handler makes it harder to clean irrigation conducts allowing cross contamination to take place if no proper sanitation is done between experiments.

Concept 10

384 Well Plate Dispenser with Conveyor

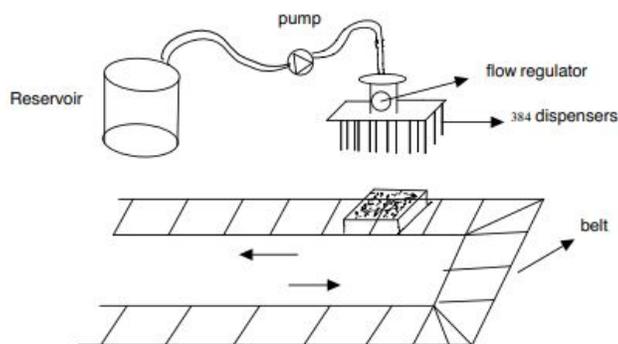


Fig. 16 384 Dispenser with conveyor

This concept includes the nutrient reservoir, a pump, an automatic flow regulator and 384 dispensers. The pump will allow the flow to move to the flow regulator and then into the 384 dispensers. The system will be static while well plates will move along a conveyor making the process faster and allowing cell culturing in a larger scale.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. Regular flow regulators have an approximate life expectancy of 25 years. Therefore, this requirement is satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids cost less than \$100 to mid-range benchtop units. The flow regulator should not exceed \$20. For as the conveyor, it might take up a cost of \$150 depending on how sophisticated it is. Then, the concept has an estimated total cost of \$390. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied.

- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: This concept includes a fixed speed conveyors belt which needs a 120VAC power supply.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: The fact there are 384 dispensers instead of one makes it more difficult to sterilize them. The conveyor transporting well plates can also be a source of cross contamination.

Concept 11

Two degrees of freedom Micro Pipette

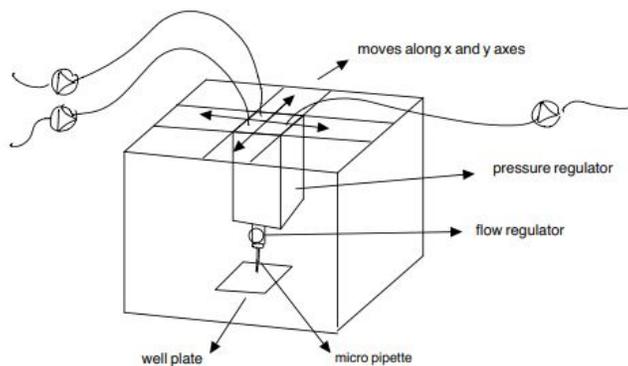


Fig. 17 Two degrees of freedom micro pipette

This concept includes a flow regulator that will move along the x and y axis in order to be able to fill the well plate. A pressure regulator and a flow regulator will set the flow rate going through the micro pipette which will be previously monitored from the controller.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. Regular flow regulators have an approximate life expectancy of 25 years. If an AMP Step Motor is used to move the micro pipette along the x and y axes, which typically represents 10+ years of field assuming 8 hours of daily use 5 days a week[] this requirement would be satisfied.

- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids cost less than \$100 to mid-range benchtop units. The flow regulator should not exceed \$20. Micro pipettes can be found from \$15. Then, the concept has an estimated total cost of \$255. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: For this fluid handling system no additional power supply is needed.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: The fact that there is a single liquid dispenser makes it easier to avoid cross contamination. The micro pipette is a small and easily interchangeable part of the concept.

Concept 12

Enclosed multi-pipette styled tubes

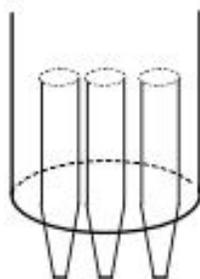


Fig. 18 Enclosed Multi-pipette Styled Tubes

This concept is comprised of multiple pipette-styled tubes that are able to both release and absorb fluids. These pumps are attached to one main central tube that holds and encloses each pipette pump. Each pump can suck in a certain amount of fluid and hold it or suck in all of the liquid and transport it.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. Therefore, this requirement is satisfied.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids cost less than \$100 to mid-range benchtop units. Then, the concept has an estimated total cost of \$220. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: For this fluid handling system no additional power supply is needed.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safety injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96,384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: Since pipettes are sunk in a single tube, proper sterilization is not that easy, but sanitation methods for cleaning E-coli can be applied such as bleach dispensing.

Concept 13

Linear multi-pipette with separated nozzles

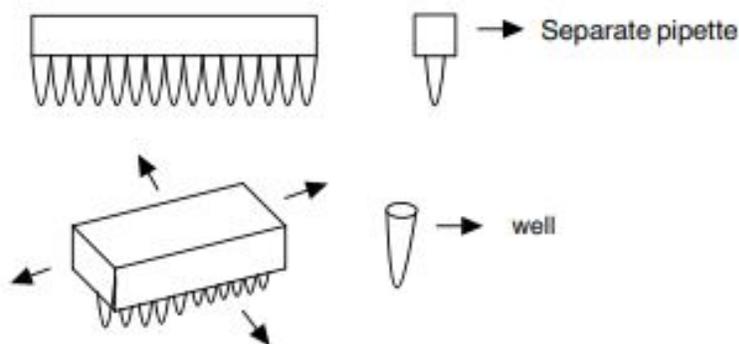


Fig. 19 Linear Multi-pipette with Separate Pipette

This concept uses 2 pipettes at once to intake and release liquids. There is a linear portion that holds multiple pipettes and this portion can translate on the x-y plane to reach different wells. Additionally, there is a separate pipette on the side that is able to move independently of the main system in order to handle wells that may need specific adjustments.

- Requirement 1: A correctly specified pump should last for 10-15 years and other components are expected for infinite life. Regular flow regulators have an approximate life expectancy of 25 years. Micro pipette units are still in operation 15 to 20 years after purchase, so this requirement is satisfied by all components.
- Requirement 2: Since volumes are small, a 3D printed peristaltic pump could be used which presents an estimated cost of \$120. Equipment for dispensing and aspirating liquids cost less than \$100 to mid-range benchtop units. Multi-channel micro pipettes can be achieved from \$300. Then, the concept has an estimated total cost of \$520. Since this is a small fraction of the \$10,000 budget, the requirement is satisfied, although this option would probably not be the best one because of its higher price.
- Requirement 3: Since almost all elements in the fluid handling system plastic and their volume is very small, all components should be easily carried by a human.
- Requirement 5: For this fluid handling system no additional power supply is needed.
- Requirement 11: All materials used in the concepts, which are mainly PVC, aluminum and silicone are nonporous. This satisfies the requirement of using only nonporous materials making contact with the cell culture.
- Requirement 12: None of the materials in this concept are reactive with chemicals and processes that will be present in the system. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 18: The fluid handling system is capable of safely injecting, measuring and regulating compositions of N_2 , O_2 , CO_2 , CH_4 , H_2 . This will be done by adjusting the capability of the fluid handler and via different sensors. All the gas dispensing process will be executed by the controller.
- Requirement 19: This concept can service 1,000 *E. Coli* cultures over a two week period.
- Requirement 25: This concept can support existing culture well plates of sizes 6, 24, 48, 96, deep 96, 384.
- Requirement 26: This concept can support existing conical tubes of sizes 15 mL and 50 mL.
- Requirement 34: The fluid handling system will be able to add/subtract liquid from the system by means of pressure and flow sensors, automated valves and pumps that will be adjusted from the controller.
- Requirement 35: Bernoulli's equation (4) will be applied to get the fluid velocity. The chosen dispenser diameter should be smaller than 3.7mm (which is the diameter of the well plates holes). With equation (1) and equation (2) the actual flow rate and Bernoulli's Number will be calculated which should be <2300 in order for it to be laminar flow.
- Requirement 36: This fluid handling concept achieves minimum and maximum dispense rates of $225\mu\text{L/s}$ to $300\mu\text{L/s}$.
- Requirement 38: This fluid handling concept achieves a dispensing volume accuracy of $\pm 0.1\mu\text{L}$.
- Requirement 39: This fluid handling concept achieves a dispensing volume precision of $\pm 0.1\mu\text{L}$.
- Requirement 40: This concept includes a separate pipette in order to handle pipettes that might need a specific adjustment. This system favours no contamination.

C. Concept Design Down-Selection to Preliminary Design

1. Fluid Handling

Binary Trade Study

This section will present a trade study made among the members of this team for the fluid handling subsystem. There were 8 metrics used to compare each concept design in a decision matrix. The binary trade study will determine the unique weightings for each metric relevant to the subsystem in the decision matrix. After each concept has been evaluated, the trade study matrix will be used to in the down-selection process to identify the best concept to use in the final design out of the 13 concepts presented in the Conceptual Design Report (CDR). Some requirements were eliminated from the previous submission and others were integrated in the same metric.

- **Cost**

The total cost of each concept was determined by using (18). The total costs could not exceed \$10,000 as per requirement 2, and the concepts with the lowest cost were scored the highest using (5). The unit for this metric is USD.

- **Size**

The size of the concept was considered as a relevant metric since it affects the ability of the system to be easily moveable by a person after disassembly, which is requirement number 3. The concept with lower weight were scored the highest using (5). The unit of this metric is kg.

- **Power**

Power was chosen as a relevant metric given requirement number 5 which states that the systems need to run from 120 VAC. Pumps and motors which require power electronics are used in these concepts; they cannot exceed this requirement. The concepts which consume less power were scored the highest.

- **Risk of aerosol creation**

Requirement 35 states that liquid must be dispensed without creating aerosols. In order to measure this Reynolds number (8) will be used, which must be lower than 2100. If the Reynolds number is greater than 2100 the flow will be considered turbulent and therefore aerosol creation will be assumed. The lower the non-dimensional number the higher the score.

Risk of Aerosol Creation	
Level	Score
Low	1
Medium	5
High	10

Table 1 Risk of Aerosol Creation

- **Force of fluid dispenser**

Force of fluid dispenser is the metric corresponding to requirement 36 which states the liquid handling system must achieve dispensing rates from 225 $\mu\text{L/s}$ to 300 $\mu\text{L/s}$. This metric measures the flow rate of each concept, receiving a higher score those with a higher flow rate capacity.

- **Available volume of fluid dispenser**

This metric corresponds to requirement 37 in which it is specified the fluid handling concepts need to achieve an aliquot fluid volume from 5-20,000 μL . All concepts that do not meet this volume will fail to meet the requirement. Larger volumes will score higher since the concept needs to at least meet the specified range but may also exceed it.

- **Tolerance of fluid dispenser**

Tolerance of the fluid dispenser was chosen as a relevant metric given. Requirements 38 and 39 specify that the dispenser must achieve a dispensing volume accuracy of $\pm 0.1 \mu\text{L}$ and a dispensing volume precision of $\pm 0.01 \mu\text{L}$. Those values will be given in %, which corresponds to the average between accuracy and precision. The lower the value the higher the score since higher accuracy and precision are sought.

- **Risk of Cross Contamination**

According to requirement number 40, no cross-contamination between wells and tubes should take place during liquid handling. The risk of contamination was determined qualitatively. The more pipettes /syringes the concept has the higher the risk of cross contamination and the lower the score. Some concepts included systems for avoiding cross contamination, which received the highest score (2).

Risk of Contamination	
Level	Score
Low	1
Medium	5
High	10

Table 2 Risk of Contamination Qualification

My group mates contributed in this following tables

Fluid Handling											
Iratxe Astigarraga	Cost	Size	Power	Risk of Aerosol Creation	Force of Fluid Disp.	Avail. Vol. of Dispenser	Tol. of Fluid Dispenser	Risk of Cross Cont.		Count	%
	A	A	C	D	E	F	G	H	A	1	3.6
		B	C	D	E	F	G	H	B	0	0
			C	C	C	C	C	C	C	7	25.0
				D	E	F	G	H	D	2	7.1
					E	F	G	E	E	4	14.3
						F	G	F	F	5	17.9
							G	G	G	6	21.4
								H	H	3	10.7

Table 3 Binary Trade Study and Tally Matrix by Iratxe Astigarraga

Fluid Handling											
Vidal Cruz Ramos	Cost	Size	Power	Risk of Aerosol Creation	Force of Fluid Disp.	Avail. Vol. of Dispenser	Tol. of Fluid Dispenser	Risk of Cross Cont.		Count	%
	A	B	A	D	E	F	G	H	A	1	3.6
		B	B	D	E	F	G	H	B	2	7.1
			C	D	E	F	G	H	C	0	0
				D	E	F	G	H	D	3	10.7
					E	F	G	H	E	4	14.3
						F	F	H	F	6	21.4
							G	H	G	5	17.9
								H	H	7	25.0

Table 4 Binary Trade Study and Tally Matrix by Vidal Cruz Ramos

Fluid Handling										Count	%
Garrett Doty	Cost	Size	Power	Risk of Aerosol Creation	Force of Fluid Disp.	Avail. Vol. of Dispenser	Tol. of Fluid Dispenser	Risk of Cross Cont.			
	A	A	A	D	E	F	G	H	A	2	7.1
		B	B	D	E	F	G	H	B	1	3.6
			C	D	E	F	G	H	C	0	0
				D	D	D	G	H	D	5	17.9
					E	F	G	H	E	3	10.7
						F	F	H	F	5	17.9
							G	H	G	5	17.9
								H	H	7	25.0

Table 5 Binary Trade Study and Tally Matrix by Garrett Doty

Fluid Handling										Count	%
Jack Drohan	Cost	Size	Power	Risk of Aerosol Creation	Force of Fluid Disp.	Avail. Vol. of Dispenser	Tol. of Fluid Dispenser	Risk of Cross Cont.			
	A	A	A	A	E	F	G	H	A	3	10.7
		B	B	D	E	F	G	H	B	1	3.6
			C	D	E	F	G	H	C	0	0
				D	E	D	D	D	D	5	17.9
					E	F	E	H	E	5	17.9
						F	F	F	F	6	21.4
							G	H	G	3	10.7
								H	H	5	17.9

Table 6 Binary Trade Study and Tally Matrix by Jack Drohan

Fluid Handling										Count	%
Vitan Georgievski	Cost	Size	Power	Risk of Aerosol Creation	Force of Fluid Disp.	Avail. Vol. of Dispenser	Tol. of Fluid Dispenser	Risk of Cross Cont.			
	A	B	A	C	E	F	G	H	A	1	3.6
		B	B	D	E	F	G	H	B	4	14.3
			C	D	E	F	G	B	C	1	3.6
				D	D	F	F	D	D	4	14.3
					E	F	G	H	E	3	10.7
						F	F	H	F	7	25.0
							G	H	G	4	14.3
								H	H	4	14.3

Table 7 Binary Trade Study and Tally Matrix by Vitan Georgievski

Fluid Handling								
Salomon Molko	Cost	Size	Power	Risk of Aerosol Creation	Force of Fluid Disp.	Avail. Vol. of Dispenser	Tol. of Fluid Dispenser	Risk of Cross Cont.
	A	B	A	D	E	F	G	H
		B	B	D	E	F	G	H
			C	D	C	F	G	H
				D	D	F	G	H
					E	F	G	H
						F	F	H
							G	G
								H

	Count	%
A	1	3.6
B	2	7.1
C	1	3.6
D	4	14.3
E	2	7.1
F	6	21.4
G	6	21.4
H	6	21.4

Table 8 Binary Trade Study and Tally Matrix by Salomon Molko

Fluid Handling								
Denisse Pena-Valerio	Cost	Size	Power	Risk of Aerosol Creation	Force of Fluid Disp.	Avail. Vol. of Dispenser	Tol. of Fluid Dispenser	Risk of Cross Cont.
	A	B	A	D	E	F	G	H
		B	B	D	B	F	G	H
			C	D	E	F	G	H
				D	E	D	D	H
					E	F	G	E
						F	G	E
							G	G
								H

	Count	%
A	1	3.6
B	3	10.7
C	0	0
D	5	17.9
E	5	17.9
F	4	14.3
G	6	21.4
H	4	14.3

Table 9 Binary Trade Study and Tally Matrix by Denisse Pena-Valerio

Weight Factors			
	Category	Count	%
A	Cost	10	5.1
B	Size/Weight	13	6.6
C	Power	9	4.6
D	Risk of Aerosol Creation	28	47.6
E	Force of Fluid Dispenser	26	13.3
F	Available Volume of Fluid Dispenser	39	19.9
G	Tolerance of Fluid dispenser	35	17.9
H	Risk of Cross Contamination	36	18.4

Table 10 Binary Trade Result for the Fluid Handling Subsystem

Normalization and Down-Selection

$$y_i = \frac{(y_{\max} - y_{\min})}{(x_{\max} - x_{\min})} (x_i - x_{\min}) + y_{\min} \quad (5)$$

Concept	Values	Metric								Total
		Cost (USD)	Weight (kg)	Power (VDC)	Risk of aerosol creation	Flow rate of fluid dispenser (μL/s)	Available volume of fluid dispenser (μL)	Tolerance of fluid dispenser (%)	Risk of cross contamination	
1	Score	285.00	1.00	17.00	10.00	300.00	500.00	1.00	5.00	
	Normalized	7.28	9.03	1.00	10.00	10.00	1.00	8.35	5.00	
	Weighted	0.37	0.60	0.05	1.43	1.33	0.20	1.49	0.92	5.46
2	Score	240.00	0.40	5.00	5.00	300.00	1000.00	2.00	1.00	
	Normalized	8.13	9.40	7.35	5.00	10.00	1.04	6.51	1.00	
	Weighted	0.41	0.62	0.34	0.71	1.33	0.21	1.16	0.18	4.79
3	Score	285.00	1.00	10.00	10.00	300.00	2000.00	1.00	5.00	
	Normalized	7.28	9.03	4.71	10.00	10.00	1.12	8.35	5.00	
	Weighted	0.37	0.60	0.22	1.43	1.33	0.22	1.49	0.92	5.66
4	Score	390.00	4.50	5.00	10.00	300.00	500.00	1.00	5.00	
	Normalized	5.31	6.87	7.35	10.00	10.00	1.00	8.35	5.00	
	Weighted	0.27	0.46	0.34	1.43	1.33	0.20	1.49	0.92	5.51
5	Score	290.00	3.50	0.00	10.00	300.00	900.00	1.65	1.00	
	Normalized	7.19	7.49	10.00	10.00	10.00	1.03	7.15	1.00	
	Weighted	0.37	0.50	0.46	1.43	1.33	0.21	1.28	0.18	5.56
6	Score	620.00	1.00	0.00	5.00	300.00	500.00	0.10	5.00	
	Normalized	1.00	9.03	10.00	5.00	10.00	1.00	10.00	5.00	
	Weighted	0.05	0.60	0.46	0.71	1.33	0.20	1.79	0.92	5.14
7	Score	175.00	10.00	2.80	1.00	300.00	1800.00	5.00	10.00	
	Normalized	9.34	3.48	8.35	1.00	10.00	1.10	1.00	10.00	
	Weighted	0.48	0.23	0.38	0.14	1.33	0.22	0.18	1.84	2.96
8	Score	240.00	3.00	12.00	10.00	300.00	7200.00	1.65	5.00	
	Normalized	8.13	7.80	3.65	10.00	10.00	1.53	7.15	5.00	
	Weighted	0.41	0.52	0.17	1.43	1.33	0.30	1.28	0.92	5.44
9	Score	140.00	3.00	0.00	10.00	300.00	76800.00	2.00	1.00	
	Normalized	10.00	7.80	10.00	10.00	10.00	6.99	6.51	1.00	
	Weighted	0.51	0.52	0.46	1.43	1.33	1.39	1.16	0.18	6.80
10	Score	550.00	10.00	0.00	10.00	300.00	115200.00	1.65	1.00	
	Normalized	2.31	3.48	10.00	10.00	10.00	10.00	7.15	1.00	
	Weighted	0.12	0.23	0.46	1.43	1.33	1.99	1.28	0.18	6.83
11	Score	255.00	15.00	10.00	10.00	300.00	500.00	1.00	10.00	
	Normalized	7.84	0.40	4.71	10.00	10.00	1.00	8.35	10.00	
	Weighted	0.40	0.03	0.22	1.43	1.33	0.20	1.49	1.84	5.09
12	Score	220.00	2.00	0.00	5.00	300.00	900.00	0.70	5.00	
	Normalized	8.50	8.41	10.00	5.00	10.00	1.03	8.90	5.00	
	Weighted	0.43	0.56	0.46	0.71	1.33	0.21	1.59	0.92	5.29
13	Score	520.00	2.50	5.00	10.00	300.00	8200.00	1.65	10.00	
	Normalized	2.88	8.11	7.35	10.00	10.00	1.60	7.15	10.00	
	Weighted	0.15	0.54	0.34	1.43	1.33	0.32	1.28	1.84	5.37

Fig. 20 Fluid Handling Subsystem Decision Matrix

Since most of the concepts for fluid handling were very inaccurate and gave little detail about their components and specifications, some assumptions had to be made.

- Although many of the concepts did not include any kind of mechanism for pumping the fluid, a standard pump was included in calculating the cost of each concept.
- Concepts that did not include any kind of motor and only explained how fluid was being dispensed have been considered not to consume any kind of power.
- Aerosols are created when the flow is not laminar, with a Reynolds number below 2100. Since concepts had no dimensions, the risk of creating aerosols was determined qualitatively depending on their way to dispense the fluid and the overall dimensions of the dispensing tube.
- An specific syringe model and an specific type of pipette were selected in order to be able to compare the concepts in terms of available volume and tolerance of fluid dispenser.
- Since both accuracy and precision were qualified under the same metric, the value in percentage corresponds to the average of both values for each concept.
- Risk of contamination was determined qualitatively, being 10 the highest score. Those concepts with more dispensing points were considered of a higher risk of contamination since it was assumed they were more difficult to correctly clean and sanitize.

The highest scoring concept for the liquid handling system was concept 10 but it was mainly because of its low risk of aerosol creation and high dispensing volume due to its 384 nozzles. The concept that got the second highest score was concept number 9 which had the same characteristics as the previous one in metrics that were weighted higher. In the end, a single nozzle was chosen instead of 384 for the fluid handling system but overall small changes were made to the winning concept. Although a conveyor belt was the original idea the last concept will have the well plates and tubes moved by a manipulator.

D. System Design Synergy and Discord Discussion

The combination of subsystems in overall assembly design can lead to unforeseen design challenges. For this reason, even if the winning concept from the down-selection process possessed a higher weighted score by a large margin, it was still necessary to examine all aspects of design integration. Interactions between subsystems sometimes required integration of other concepts to best optimize overall performance of the assembly.

The fluid handling concept selected, Concept 10, used a conveyor belt to position well plates and tubes below a fixed fluid distributor similar to a burette. This conveyor system caused discord between other subsystems located on the floor of the structure and with the structure itself. There was not enough room on the floor of the structure without expanding it beyond the size constraints given to accommodate for the conveyor system. Therefore, this concept was modified to use the manipulator alone to locate well plates and conical tubes below the fluid handler. This could allow for more precise well location and reduce risk of spilling conical tubes, so this modification may have increased the synergy between the manipulator and fluid handling system while also reducing the discord with the sanitation, shaker, and environmental management systems.

E. Preliminary System Design Analysis

1. Fluid Handling

Description

The liquid handling in the bioreactor is capable of automatically adding and subtracting fluid from each well plate or conical tube. It can satisfactorily move cultures suspended in liquid between compartments, and provide nutrients without creating aerosols. No cross contamination between individual wells or tubes takes place in the process thanks to a properly designed sanitation system.

This fluid handling system will be static and well plates will be transported by the manipulator, accommodating all sizes of well plates and tubes. The main controller will make sure the moves of the manipulator are small, fast and precise enough for the fluid dispensing.

Fluids will be stored in three different deposits. One will be for nutrients necessary for the cell culturing and the other two will have bleach and sterilized water as part of the sanitation process.

Solenoid valves will be used to open and close the way from the deposits to a peristaltic pump. The pump will then move the fluid to the high accuracy K8MDC dispensing valve, which will adjust its inner nozzle diameter from 0.5mm to 1.8 mm to achieve the specified flow rate.

Once the experiment is over bleach will be pumped along the fluid handling system to kill any remaining E-coli. Additionally, the system will be cleaned with sterilized water for neutralizing the reacting components that might still be found in the tubes and fluid dispenser, making sure no cross contamination takes place.

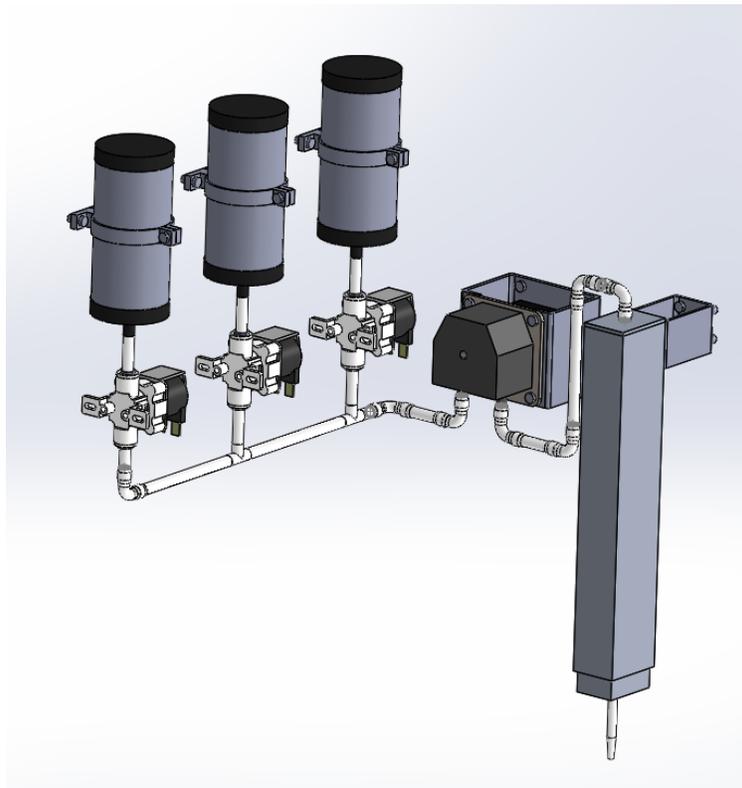


Fig. 21 Fluid Handling Subassembly

As stated above, the concept chosen through down selection for the fluid handling subsystem is comprised of 3 deposits, 3 solenoid valves, a peristaltic pump, tubes and a high precision dispensing valve. Additionally, mounts for the pump and dispenser were included to be able to attach them to the structure walls. The fluid dispenser was also covered in a case, to protect the dispensing valve from the outer conditions.

MATERIAL SELECTION

All materials involved need to be nonporous and non reactive to the fluids used in the system in order to prevent leaks or contamination and reaction with sterilizing and neutralizing agents. Moreover, we want the system to be light enough to carry to meet customer need 3 and cost will also be a determining factor. This specific subsystem does not experience significant loads. Thus, the fluid handling system provides an opportunity to use materials that a weaker but more cost effective.

Fluid dispenser case

For the housing of the fluid dispenser we are looking for a material that is light weighted and non reactive. An Ashby plot for strength vs cost will be used for this material selection.

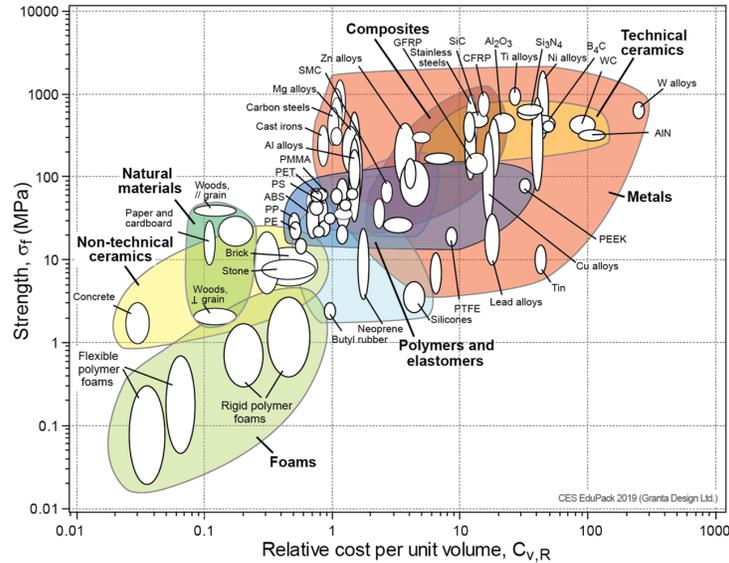


Fig. 22 Strength vs. Cost Ashby Plot

The possible materials for the fluid dispensing case are:

- Polymers and elastomers: acceptable strength and density.
- Composites: they have a high strength and an acceptable density
- Metals: higher strength and higher density but better thermal properties as well.

Polymers and elastomers were considered as the best option for this purpose and out of many of them hard PVC and ABS were selected for the analysis. Rigid PVC has a yield strength between 37.9 - 54.8 MPa, whereas ABS of 29.6 - 48 MPa. Therefore, rigid PVC was chosen for the fluid dispenser case. PVC is also cheaper and can be easily 3D printed.

Fluid deposits

The deposits in the fluid handling system will also be self made. The requirements for the materials for it will be the same but an additional feature is needed for the cylinder in the deposits: it has to be see-through. PMMA was chosen for this purpose which is a transparent thermoplastic polymer with a yield strength between 64.8 - 83.4 MPa.

Pump mount

The part in this subsystem that experiences the most load is the pump mount which weights approximately 5N including the pump and the 42 stepper motor attached.

Although its geometry is slightly different the mount will be modelled as a cantilever beam under a single point loading in order to determine the internal bending stress induced by the pump's weight. The maximum bending moment of a cantilever beam is found at the support point and it is given by $M = FL$. In this case the maximum bending moment is 0.215Nm. In order to calculate the bending stress the following equation (38) is needed.

The total cost of the amount of material required to make the mount can be computed by multiplying the mount's volume V , by the density of the material ρ , and by its cost.

$$C = C_m \rho V \quad (6)$$

In selecting a material for these purposes, one with a higher strength and low cost is preferable. Creating a ratio between these two parameters, the value index line will give us which of materials are ideal for this application in the Strength vs. Relative cost per unit volume Ashby plot.

- Polymers and Elastomers: ABS and Epoxies
- Metals: Aluminum, Zink and Magnesium Alloys

Out of these two types of materials polymers and elastomers were selected because of their lower price. The least expensive material happens to be ABS which is also a material that is commonly used in additive manufacturing. Since this material has a strength that exceeds by far the one required, ABS was used for manufacturing the pump mount. Since the pump is the heaviest element in the subsystem, ABS was also chosen as a material for the mounts for the deposits.

The remaining parts of the subsystem are all OTS, so materials are decided by each manufacturer. They will be listed under "OTS" in the BOM.

The flexible tubes are also OTS parts although several materials can be selected. PVC plastic was chosen for the tubing because it is rated for ultra-chemical resistivity, having an "A" rating for chemical resistivity to bleach among many other chemical solutions.

F. Final System Design Analysis

1. Engineering Analyses for Critical Components

Fluid Handling Nozzle selection

For this concept the main governing equations will involve the flow rate, pressure differential, and size of the injector inlets and outlets. Poiseuille's Law will be used to determine the pressure differential required for the system, which will decide the pump used.

The following assumptions were made over the fluid as seen in the following equation, this law is dependent on the flow rate Q , the pressure differential ΔP , the radius of the outlet r , the viscosity of the fluid μ and the length of the nozzle l .

Assumptions:

- Steady flow
- In-compressible flow
- Fully developed flow

$$Q = \frac{\pi \Delta P r^4}{8 \mu l} \quad (7)$$

In order to determine the cross-sectional area of the nozzle the Reynold number will be used. Requirement 35 specifies no aerosols can be created during dispensing, which means the Reynold number must be <2300 for the flow to be laminar, although to ensure the nozzle does not atomize the fluid the Reynolds number should be <1680 . The Reynold number is dependent on the fluid density ρ , the fluid velocity v , the length of the nozzle l and the fluid viscosity μ .

$$Re = \frac{\rho v D}{\mu} = \frac{\rho v D}{\pi \mu r^2} = \frac{4 \rho Q}{\pi \mu D} \quad (8)$$

As an approximation water was used for performing the analysis:

- $\rho = 997 \text{ kg/m}^3$
- $\mu = 1.002 * 10^{-3} \text{ Pa} \cdot \text{s} = 1.002 * 10^{-3} \text{ kg/m} \cdot \text{s}$

Assuming $Re=1680$ to avoid atomization:

$$D_{min} = \frac{4 \rho Q}{\pi Re \mu} = \frac{4(997 \frac{\text{kg}}{\text{m}^3})(300 * 10^{-9} \frac{\text{m}^3}{\text{s}})}{\pi(1680)(1.002 * 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}})} = 2.2 * 10^{-4} \text{ m} = 0.226 \text{ mm} \quad (9)$$

Assuming $Re=2300$ to avoid atomization:

$$D_{min} = \frac{4 \rho Q}{\pi Re \mu} = \frac{4(997 \frac{\text{kg}}{\text{m}^3})(300 * 10^{-9} \frac{\text{m}^3}{\text{s}})}{\pi(2300)(1.002 * 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}})} = 1.6 * 10^{-4} \text{ m} = 0.16 \text{ mm} \quad (10)$$

Fluid dispenser and pump selection

$$\Delta P = \frac{8 l \mu Q}{\pi r^4} = \frac{8(0.03 \text{ m})(300 * 10^{-9} \frac{\text{m}^3}{\text{s}})(1.002 * 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}})}{\pi(0.0025 \text{ m})^4} = 0.58788 \text{ Pa} \quad (11)$$

Where l is the length of the nozzle (30 mm in our case). The dosing valve, for a 0.5 mm diameter, at the established pressure, with fluids of a viscosity close to $0.001 \text{ Pa} \cdot \text{s}$ has a volumetric flow rate of $350 \mu\text{L/s}$ which fits in the customer requirements.

The pump selected is a OEM B01 peristaltic pump with a flow rate between $0.0024\text{-}190 \text{ mL/s}$, which also fits the requirements by far.

Further analysis on atomization

Considering the analysis performed in the breakup of liquid jets, for zero relative velocity between the jet and the air, the optimum wavelength for breakup is:

Rayleigh method:

$$\lambda_{opt} = 4.51 d = 2.255 \text{ mm} \quad (12)$$

Weber method:

$$\lambda_{opt} = 4.44d = 2.22mm \quad (13)$$

where d is the initial jet diameter.

When it comes to the diameter of the drops in the primary atomization is:

$$D = 1.89d = 0.944mm \quad (14)$$

Since the velocity is 0, there is no secondary atomization.

Weber also examined the effect of liquid viscosity on jet disintegration. He showed that the effect of an increase in viscosity is to increase the optimum wavelength for jet breakup.

$$\lambda_{opt} = 4.44d\sqrt{(1 + 3Oh)} \quad (15)$$

where

$$Oh = \frac{\mu_L}{(\rho_L \sigma D)^{0.5}} \quad (16)$$

With the actual diameter of the liquid dispenser the velocity is:

$$v_1 = \frac{Q}{A} = \frac{300 * 10^{-9} m^3/s}{\pi(0.5 * 10^{-3} m)^2/4} = 1.528m/s \quad (17)$$

which is not very high. In this case the optimum wavelength will not change because the relative velocity between the jet and the air is not significant.

G. Contributions to other subsystems

1. Concept Design Generation Additional Equations

$$C_{\text{total}} = \sum_{i=1}^N C_{\text{Component},i} \quad (18)$$

$$V_{\text{total}} = \sum_{i=1}^N V_{\text{req},i} \quad (19)$$

$$C = H - (h_0 + h_0 \sin(30)) \quad (20)$$

$$Re = \frac{VH}{v} \quad (21)$$

$$A_{\text{foot print}} = L_{\text{inner}} \cdot W_{\text{inner}} \quad (22)$$

Manipulator Concept 10

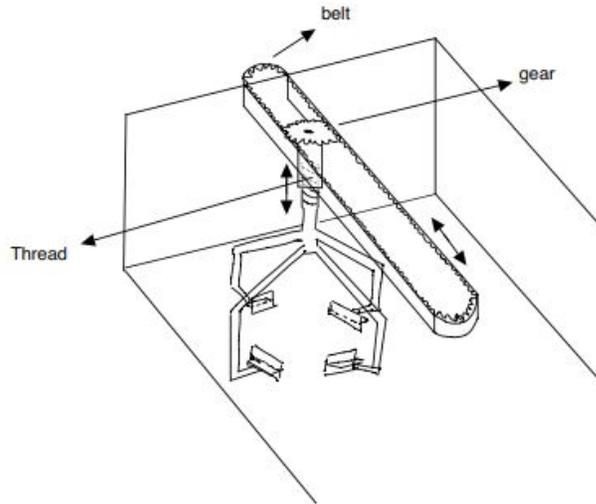


Fig. 28 Belt/thread manipulator

This concept includes a belt-gear system, a motor and a hook. The motor will move the belt allowing the hook to translate along the x-axis. The hook will be able to go up and down thanks to its threaded body. This movement will be monitored from the controller. In the whole process it is crucial well plates are stably transported, therefore the adherence between the manipulator and the well plate must be firm. In order to attain to this need, the manipulator will have some tabs at the end of each arm.

- Requirement 1: The 5 VDC motors used in this concept are expected to last several tens of thousands of hours[10], which is several years of continuous use. Because the materials used in this concept are not exposed to extreme fatigue and load bearing operations, the limiting factor is the motors. This satisfies the customer need of the minimum operational lifetime of 10 years.
- Requirement 2: Assuming that the raw stock material used for the gripper mechanism, the gear, and the belt drive system, is some non reactive alloy, such as stainless steel, the raw material price was calculated using (18) and should not exceed \$75. Factoring the cost of the 5 VDC motor, the cost of the motors comes in to \$8.95. The total cost of this concept should not exceed \$83.95, which is a small fraction of the required budget of \$10,000.
- Requirement 3: Assuming that the volume of the raw stainless steel stock used is equal to 100 cm^3 , and that the density of aluminum is 7.9 g/cm^3 , the material weight comes in at 790 grams. When factoring in the weight of the motor, the total weight of the system comes out to 521.75 grams, which can easily be carried by a human.
- Requirement 5: The power requirements of this concept include one 5 VDC motor, using 19 the total power need is found to be just 5 VAC. This falls well below the max required 120 VAC.
- Requirement 11: None of the materials used in this concept are porous, the gripper specifically is to be constructed of a non reactive alloy, and covered in a higher friction material such as rubber, both of which are not porous. This satisfies the requirement of only nonporous materials making contact with the cell cultures.
- Requirement 12: None of the materials used in this concept are reactive with the chemicals and processes that will be present in the system. This is assuming that the manipulator will be constructed of non-reactive metal and rubber. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 16: This design is capable of moving well plates and test tubes of all sizes. The precision of the power screw system which allows Z-axis motion, when combined with the abilities of the gripper, allow the concept to interchange well plates, and even remove and place the well plate lids. This satisfies the requirement that culture microbes are in interchangeable fully enclosed vessels.
- Requirement 19: Assuming that the space is allotted in the structure and that there are enough shakers present, the manipulator is not a limiting factor in the capability of the system to produce 1000 culture generations in two weeks. This is because the manipulator can move as many well plates and test tubes as necessary within a short

time interval.

- Requirement 25: For this concept, the gripper has a large range of expansion, allowing it to handle all the possible sizes of well plates. The size of the expanded gripper footprint was compared to the dimensions of the 384 well plate, which was 127.76 mm by 85.48 mm. The gripper size surpasses the size of the 384 well plate, the requirement was met.
- Requirement 26: For this concept, the gripper has a large range of expansion, allowing it to handle all the possible sizes of conical test tubes. The size of the expanded gripper footprint was compared to the dimensions of the 50 mL test tube, which had a diameter of 29.2 mm and a height of 119.6 mm. The gripper size surpassed the size of the largest conical tube, so the requirement was met.

Manipulator Concept 11

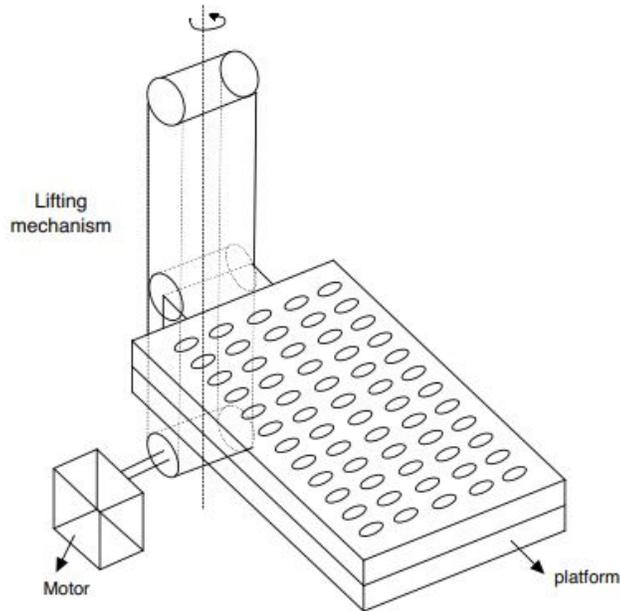


Fig. 29 Well plate lifting platform

This concept includes a motor, some pulleys and a platform. The mechanism regular elevators have will be used for lifting and getting down the well plates. The platforms where well plates lay will be extensible to allow transportation of various well plates simultaneously. An additional degree of freedom could be added to this concept allowing the pulleys to turn over their own axis.

- Requirement 1: The 2 VDC motors used in this concept are expected to last several tens of thousands of hours[10], which is several years of continuous use. Because the materials used in this concept are not exposed to extreme fatigue and load bearing operations, the limiting factor is the motors. This satisfies the customer need of the minimum operational lifetime of 10 years.
- Requirement 2: Assuming that the parts for the pulley system are purchased off of the shelf, the cost of this pulley system is calculated using 18 and should not exceed \$40. Factoring the cost of the 5 VDC motor [11], and 10 VDC motor [12], the cost of the motors comes in to \$38.25. The total cost of this concept should not exceed \$78.25, which is a small fraction of the required budget of \$10,000.
- Requirement 3: Assuming that the weight of the pulley system itself is about 680.389, the weight of the two motors brings the total weight of the concept to 786.34 grams, which can easily be carried by a human.
- Requirement 5: The power requirements of this concept include 5 VDC motor and the 10 VDC motor, using 19 the total power need is found to be 15 VAC. This falls well below the max required 120 VAC.
- Requirement 11: The materials used in this concept are nonporous, as the pulley is made of nylon. This satisfies the requirement of only nonporous materials making contact with the cell cultures.

- Requirement 12: None of the materials used in this concept are reactive with the chemicals and processes that will be present in the system. This is assuming that the manipulator will be constructed of nylon and two motors. This satisfies the need of only using nonreactive materials to contact lab chemicals.
- Requirement 16: This design is capable of moving well plates and test tubes of all sizes. The range of the machine in two directions is limited, however the motion in the third direction is quite good. Besides being limited in translational motion, the manipulator is not capable of taking the lids off of the well plates, preventing the concept from meeting this requirement.
- Requirement 19: The mechanism is not able to transport well plates to storage areas as well as sanitation areas and shaker stations, making it a limiting factor in the systems capability of producing 1000 culture generations in two weeks. This prevents it from fulfilling this requirement.
- Requirement 25: For this concept, the gripper has a large surface area, allowing it to handle all the possible sizes of well plates. The size of the expanded gripper footprint was compared to the dimensions of the 384 well plate, which was 127.76 mm by 85.48 mm. Because the gripper size surpassed this, the requirement was met.
- Requirement 26: For this concept, the gripper has a large surface area, allowing it to handle all the possible sizes of conical test tubes. The size of the expanded gripper footprint was compared to the dimensions of the 50 mL test tube, which had a diameter of 29.2 mm and a height of 119.6 mm. Because the gripper size surpassed this, the requirement was met.

Shaker Concept 7

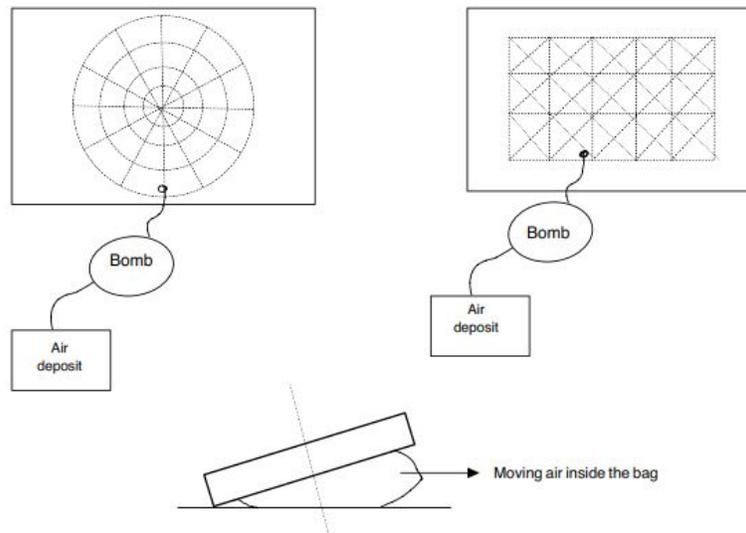


Fig. 30 Air bag shaker

This concept includes an air bag, an air deposit, a bomb and a plate where well plates will be placed. The shaking will be done by letting air move through different air circuits. As shown in the picture, when having more air pressure in one side of the air bag the plate on top will move one way or the other allowing well plates to describe a linear, orbital and double orbital patterns. The platform on top of the air bag will have some blocks to prevent well plates from falling during shaking.

This concept utilizes a tilt to aerate the cultures. Using a tilt angle of 30° [13], equation (20) can be used to show that there is roughly 3 mm of clearance from the free surface of the fluid to the top of the well [14].

- Requirement 1: The system is dependent on the air compressor, which is easily replaced if needed, so this system should perform for the desired lifetime.
- Requirement 2: The air compressor is inexpensive and plastic tubing is also widely available and inexpensive, so this system should be attainable for less than \$50 [15].
- Requirement 3: The system may be a little cumbersome with the air inlets, but should still be moved by one person.

- Requirement 5: The subsystem power requirements will be within the system requirements.
- Requirement 11: Only nonporous materials will be in contact with cell cultures.
- Requirement 12: Only nonreactive materials will be in contact with lab chemicals.
- Requirement 19: The concept will be capable of handling 1,000 *E. Coli* cultures in two weeks.
- Requirement 25: The concept will be capable of accommodating all sizes of well plates.
- Requirement 26: The concept will be capable of accommodating conical tubes on their own.
- Requirement 28: This concept can be programmed for single and double orbitals, and a linear approximation can be made.
- Requirement 29: This concept can shake independent well plates and conical tubes in trays, so it cannot handle individual tubes well.
- Requirement 40: From the calculation done above, no cross contamination will occur under the current assumptions.

Environmental Management Concept 6

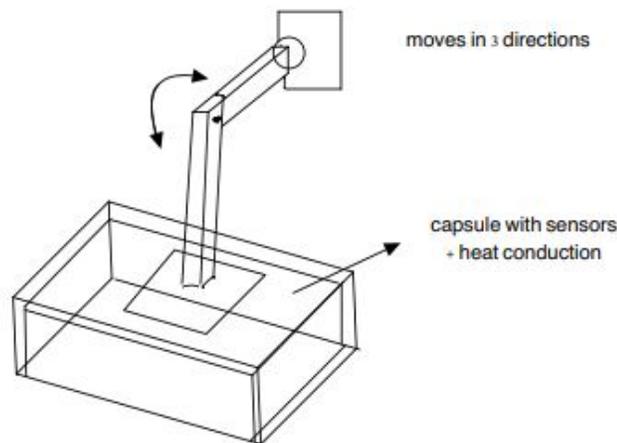


Fig. 31 Conveyor Arm to Heat Conduction Chamber

The concept's generation depends on another manipulator arm with three degrees of freedom which manipulates objects within the enclosure undergoing heat conduction. Within the enclosed space, an electric water heater can adjust and maintain the temperature of culture samples while utilizing heated water or another medium to flow around the wells of each well plate. The manipulator arm can be powered within a closed loop controller responsible for all aspects of operation, such as time powered, temperature of the water, and three dimensional position of the arm.

- Requirement 2: A high level 3 degree of freedom arm's opening to the enclosure will require a more robust design, but a set of previously stated heating elements and heatsink fan will collectively cost less than \$10,000.
- Requirement 5: A standard set of heating elements can be approximated as a set of miniature HP05 elements, in conjunction with a standard non-reactive metal cooler heatsink fan which combined should not reach a power usage of over 20W.
- Requirement 11: A completely enclosed case with a movable manipulated gap will not be based on a porous or nonmetal material and thus will not leak fluid or gas.
- Requirement 12: Metal heating or cooling elements will be nonreactive to bacterial cultures, as well as glass enclosures or well plates; no reaction will take place.
- Requirement 14: The heated water acting as a vehicle for heat transfer will have an impact on heating on the bottom of the enclosure at a metric of about 10°C due to less distance between structural walls and resulting heat transfer to outer surfaces. Approximating the Reynolds number from (21) can determine laminar or turbulent flow status for analysis, with H representing the distance from well plates to bottom of enclosure.
- Requirement 17: The requirement of independent conditions for well plates cannot reasonably be met in temperature reset, given the lack of pressure release or separate storage for testing equipment, as temperature increase cannot be met with a return to 20°C steadily.

- Requirement 20: A set of miniature heating elements rated at 20W can get to a 300°C upper limit, albeit at a slower pace than a higher power draw heater.
- Requirement 21: With less power distributed to heat an enclosed space, the set point temperature will vary by less than a degree with closed loop control, following the metric.
- Requirement 22: To meet uniform heating requirements, a heatsink fan is necessary to distribute conduction throughout the interior between 20 and 300°C, but no cooling element will inhibit uniform heat transfer.
- Requirement 24: Set point temperature without consideration to the life of heating elements can be reached through consistent running within 5 minutes to the 70°C limit.

Sanitation Concept 11

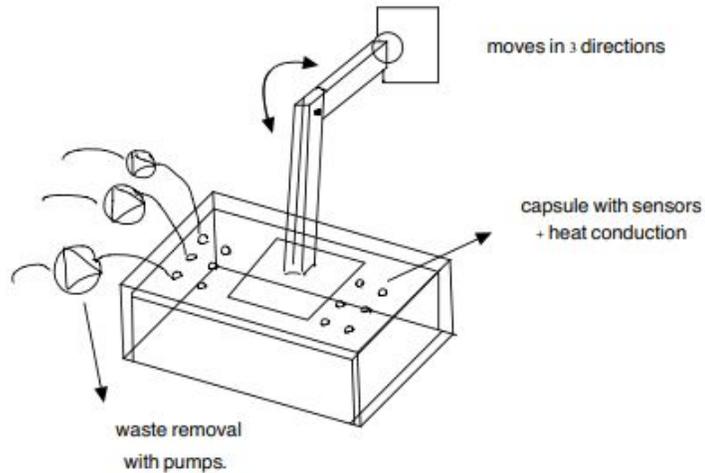


Fig. 32 3-degree of freedom arm attached to chamber with waste removal

This concept includes a monitored capsule or chamber that will kill *E. Coli* by heating above 70°C. It will also have some pumps connected to them that will be able to remove waste out of the well plate. The chamber will be monitored from the controller and will have the ability to move in all directions.

To determine the power required to pump the contents of the well plates out, the density and volume are used to find the mass of the fluid.

- Requirement 1: The lifetime of heating rods is around 20 years, and the lifetime of a bleach pump depends on the manufacturer [16].
- Requirement 2: We will use two bleach pumps because bleach is present in the waste. If the heating element inside are some form of heating rods, we can estimate the cost of prototyping to be \$1100.
- Requirement 3: The bulk of the weight comes from the pump and the insulated capsule. The ability for this system to be moved by a single person depends on the insulated metal used.
- Requirement 5: Each pump runs from 120 VAC, and the heating element also requires voltage. Since the max that can be used is 120 VAC, this concept does not meet this requirement using such a pump.
- Requirement 12: We assume the materials of the components are nonreactive.
- Requirement 15: The concept behaves like an oven so it is preheated. We know that the temperature 70°C can reliably kill most bacteria. So, with the pumps removing the waste generated during culling, this concept sterilizes, neutralizes, and disposes of all waster generated by the bacteria and on the well plates.
- Requirement 19: The volume of 1000 cultures in a well plate is 126 mL [14]. At the end of the incubation, they all must be disposed of, so if the volume inside the capsule is larger than 130 mL, it can properly dispose of the waste.
- Requirement 25: The volume of the 384 well plate housing is 138 μ L [14], so if the volume inside the capsule is larger than 150 μ L, it can accommodate for all well plate sizes.
- Requirement 26: As long as the volume of the capsule is larger than 50 mL, the capsule can accommodate for both 15 mL and 50 mL tube sizes.

- Requirement 35: The creation of bacteria laden aerosols is not a concern for this concept.
- Requirement 40: The heat will kill all the bacteria house within the capsule so the chances of cross contamination after this sterilization are low.

Sanitation Concept 12

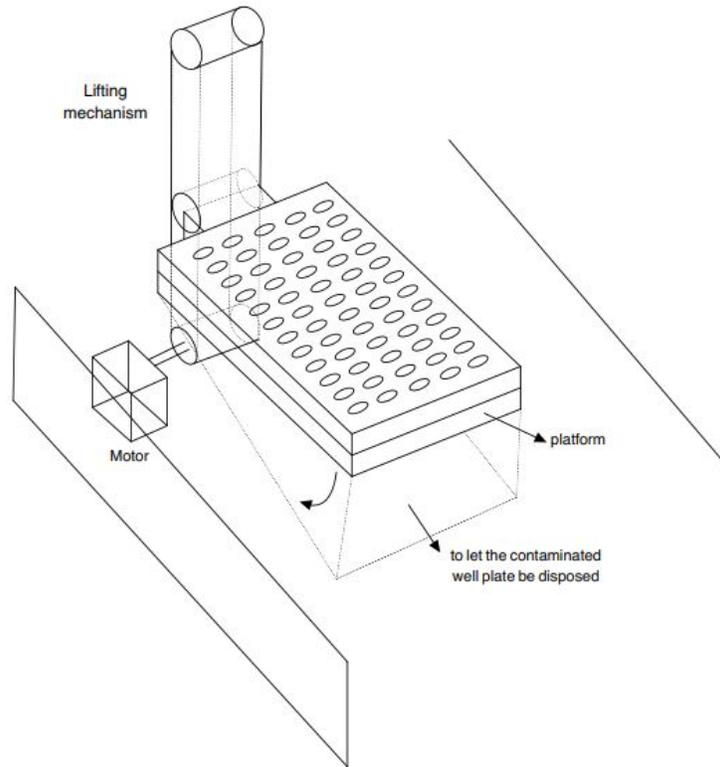


Fig. 33 Lifting platform and deposit for contaminated well plates and tubes

This concept includes a lifting mechanism, a platform and a deposit. This mechanism will turn the platform allowing contaminated well plates and tubes fall into a deposit. In this case no further treatment is done to them, instead they will be disposed and replaced by new ones.

i To find the power requirements of the motor used to lift the well plates for disposal, the gravitational force from the weight of the full well plate is multiplied by the distance traveled to determine the work done by the motor. For now, the weight of the platform will be assumed to be small relative to the weight of the full well plate and will not be taken into consideration. However, without knowing the mass of the filled well plate or the platform as materials have yet to be selected, this calculation cannot be done at this time. As this concept does not address the sterilization of the cultures either, this concept will not be considered further.

- Requirement 1: The lifetime of this system is dependent on the motor. As the motor requirements are not known, this is difficult to determine at this time.
- Requirement 2: Motors for other concept designs have not been expensive, and it is plausible to assume that it will not be for this one either.
- Requirement 3: This will be movable by one person.
- Requirement 5: Motors for other concepts fell within the power parameters of this system, and it is plausible that this one would as well.
- Requirement 12: No materials needed will be reactive with lab chemicals.
- Requirement 15: This concept is not capable of neutralizing waste, only moving it, making it not suitable for the needs of this system.

- Requirement 19: This concept is capable of handling 1,000 cultures in two weeks.
- Requirement 25: This concept can accommodate all well plate sizes.
- Requirement 26: This concept cannot accommodate lone conical tubes, but could accommodate a tray of them.
- Requirement 35: As this concept dumps the contents of trays without sterilization, microbial aerosols could be created.
- Requirement 40: Due to the possible generation of microbial aerosols, cross contamination within the system is possible.

Structure Concept 7

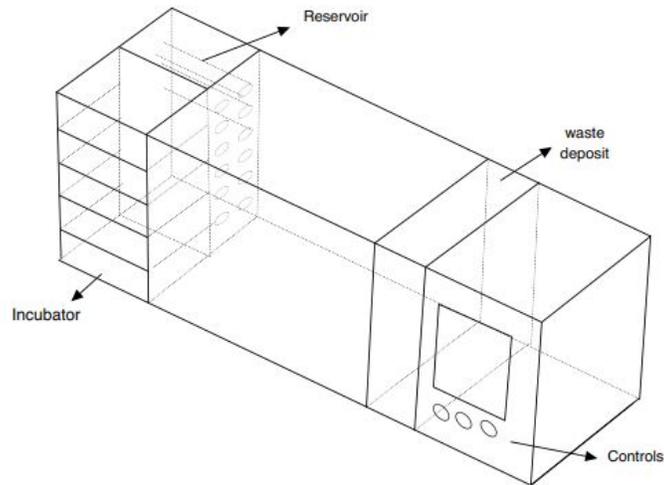


Fig. 34 Structure Concept 7

This concept includes five separated parts which include the reservoir, culture chamber, waste deposit, the system controls and a deposit for well plates and tubes. All parts except for the controls will be transparent and independent from one another, allowing the customer to place them in different ways and facilitating their cleaning.

- Requirement 1: Assuming that the metal material selected for the structure is of sound quality, there is no fatigue or extreme loads being placed on the structure, which causes this concept to meet the 10 year minimum lifespan requirement.
- Requirement 2: The average material costs of electrical wiring, the glass pane, and the metal used to create the housing were summed using (180 and should not exceed \$500.
- Requirement 3: After disassembly, the dimensions of the structure and the estimated weight of the structure are deemed to be under the carrying limit of a human being.
- Requirement 4: The max width and length of this concept were designed around being able to fit within a research benchtop, and the area is computed in (22). Additionally, when assembled the assembly should not surpass the load limit of a benchtop, therefore this requirement is met.
- Requirement 6: Because the concept does not have a door or a detachable glass pane, it is not accessible and does not meet this requirement.
- Requirement 11: In general, the structure will not be making contact with the cell cultures themselves, however if it were to, the metal chosen was nonporous, meeting this requirement.
- Requirement 12: In general, the structure will not be making contact with the cell cultures themselves, however if it were to, the metal chosen was nonreactive, meeting this requirement.
- Requirement 13: Because this concept is fully sealed and enclosed, there is no possibility for the cell cultures to escape into the environment, making it safe for use in a BSL-2 lab space.
- Requirement 14: The insulation of this concept prevent the outside surface from becoming too hot, meeting this requirement.

- Requirement 19: The structure is capable of housing several 384 well plates, allowing the other subsystems to generate over 1,000 *E. Coli* culture generations in 2 weeks, therefore this requirement is met.
- Requirement 21: The insulation of this concept was thick enough to maintain an internal set point temperature within a $\pm 2.5^{\circ}\text{C}$ tolerance, so this requirement is met.
- Requirement 25: The structure was found to be large enough to house several 384 well plates using 22, meeting this requirement.
- Requirement 26: The structure is large enough to house several 50 mL conical tube racks using 22, meeting this requirement.

Structure Concept 10

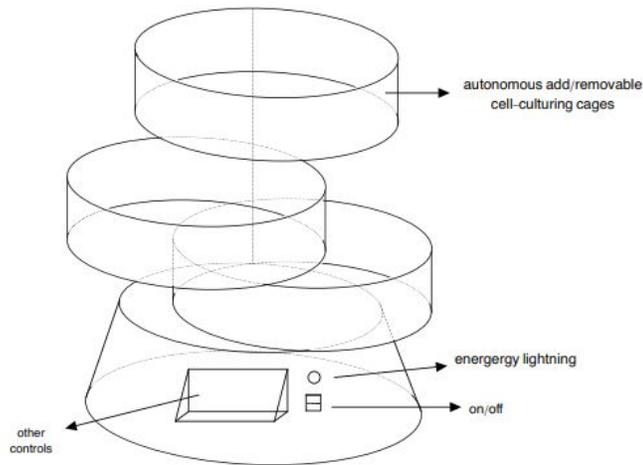


Fig. 35 Structure Concept 10

This concept includes easily interchangeable cages (can be round or can have any other shape) which will be assembled together using magnets. On the base the control system will be placed. Each cage will have each own environmental management and control systems allowing different experiments at the same time.

- Requirement 1: Assuming that the metal material selected for the structure is of sound quality, there is no fatigue or extreme loads being placed on the structure, which causes this concept to meet the 10 year minimum lifespan requirement.
- Requirement 2: The average material costs of electrical wiring, the glass pane, and the metal used to create the housing were summed using (18) and should not exceed \$500.
- Requirement 3: After disassembly, the dimensions of the structure and the estimated weight of the structure are deemed to be under the carrying limit of a human being.
- Requirement 4: The max width and length of this concept were designed around being able to fit within a research benchtop, and the area is computed in (22). Additionally, when assembled the assembly should not surpass the load limit of a benchtop, therefore this requirement is met.
- Requirement 6: Because the concept has detachable towers, it is accessible and does meet this requirement.
- Requirement 11: In general, the structure will not be making contact with the cell cultures themselves, however if it were to, the metal chosen was nonporous, meeting this requirement.
- Requirement 12: In general, the structure will not be making contact with the cell cultures themselves, however if it were to, the metal chosen was nonreactive, meeting this requirement.
- Requirement 13: Because this concept is fully sealed and enclosed, there is no possibility for the cell cultures to escape into the environment, making it safe for use in a BSL-2 lab space.
- Requirement 14: The insulation of this concept does not prevent the outside surface from becoming too hot, making this requirement incomplete.

- Requirement 19: The structure is capable of housing several 384 well plates, allowing the other subsystems to generate over 1,000 *E. Coliculture* generations in 2 weeks, therefore this requirement is met.
- Requirement 21: The insulation of this concept was not thick enough to maintain an internal set point temperature within a $\pm 2.5^{\circ}\text{C}$ tolerance, so this requirement is not met.
- Requirement 25: The structure was found to be large enough to house several 384 well plates using 22, meeting this requirement.
- Requirement 26: The structure is large enough to house several 50 mL conical tube racks using 22, meeting this requirement.

2. Final Design System Analysis

MANIPULATOR

A **bending moment analysis** was done on the X drive beam, as this beam is carrying a concentrated load in the center, and the most likely way that it would fail is due to tension under bending. The four point loading is shown in Fig . 36, with R1 and R2 being the reaction forces at each end, F1 being the load due to the linear actuator assembly, and F2 being the load due to the Nema17 motor and its mount.

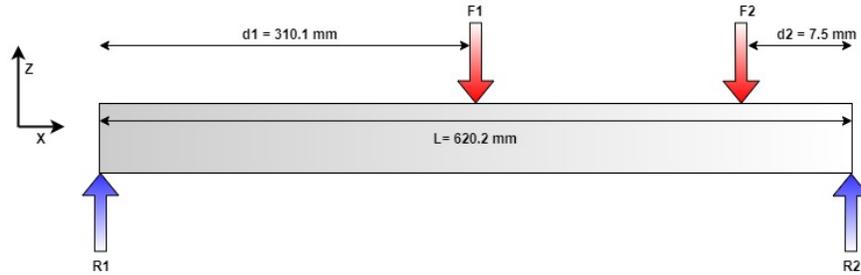


Fig. 36 Four point loading of the X drive.

To solve for the reaction forces R1 and R2, first a sum of moments (23) was taken about the X axis, starting at the point where R1 is applied. The knowns in this equation are the distances of all the forces, as well as F1 being equal to 1.99495 kg and F2 being equal to 0.2634 kg.

$$\sum M_x = 0 = -F_1 d_1 - F_2 (L - d_2) + R_2 L \quad (23)$$

The equation is solved to find the reaction force R2, which is 1.25769 kg. Then, a sum of forces (24) is taken to solve for the remaining unknown, R1.

$$\sum F_x = 0 = R_1 - F_1 - F_2 + R_2 \quad (24)$$

The value of R1 is determined to be 1.0007 kg, and now all the forces in the system are known. With these values, the shear and bending moment diagrams are calculated and plotted as shown in Fig . 37.

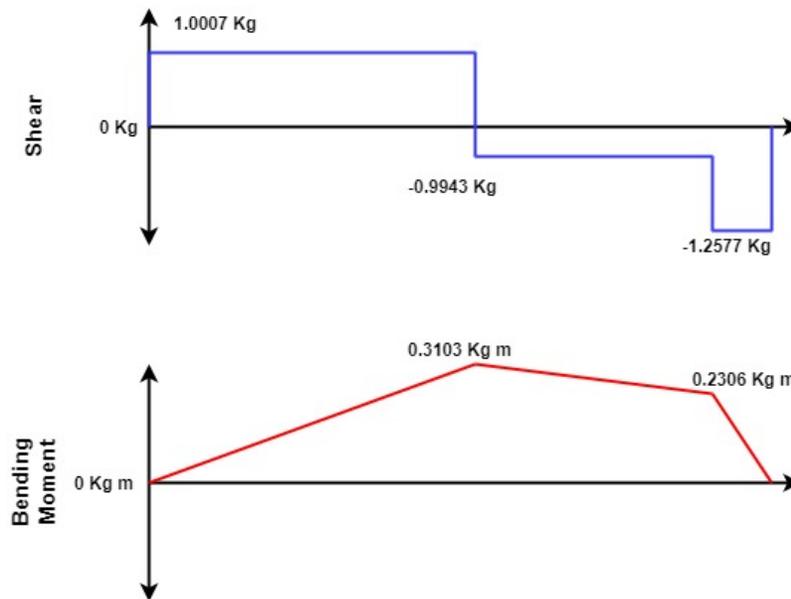


Fig. 37 Shear and bending moment diagrams.

The maximum bending moment M is used to find the max bending stress in (25), along with the distance from the center line, y , which was measured to be 0.0254 meters, and the second moment of area I_x . The second moment of area for a rectangular tube is calculated using (26), where B and H are the outer base and height of the tube, and b and h are the inner base and height. these values were measured as 0.0508 m, 0.0254 m, 0.04455 m, and 0.01905 m respectively.

$$\sigma_{\max, \text{ bending}} = \frac{My}{I} \quad (25)$$

$$I_x = \frac{BH^3 - bh^3}{12} \quad (26)$$

Once all the values were substituted into these equations, the maximum bending stress was calculated to be 180331.417 kg/m², which when converted to pascals, yields a value of 1.768447 MPa. This value is compared to the ultimate yielding stress (90 MPa) of 1060 aluminum alloy, using (27) to find the factor of safety.

$$n = \frac{S_y}{\sigma_{\max, \text{ bending}}} \quad (27)$$

The resulting factor of safety is 50.892, meaning that the beam could sustain loads of up to 50 times as much as the current one before it fails due to bending.

Finally, a screw stress analysis was completed to ensure that the manipulator could be securely mounted onto the roof of the structure without the possibility of the screws failing. The calculation begins by determining the formula for the factor of safety of the screws (28), which will be solved once all the values are known. In this equation, S_p is the proof load, which was found to be 830.986 MPa for M5 class 10.9 screws [17], A_t is the tensile area of the screw, which was found to be 14.2 mm², C is the stiffness constant, P is the load applied on each screw, and F_i is the preload force.

$$n = \frac{S_p A_t}{CP + F_i} \quad (28)$$

The load on each screw is computed by using (29), where P_{total} is the total load, and N is the number of screws. In this case, the total load was calculated with Solidworks to be 6.74665 kg, and since 8 screws are being used, the load for each screw comes out to 0.84333 kg.

$$P = \frac{P_{\text{total}}}{N} \quad (29)$$

The preload force F_i is calculated by using (30), and the final value comes out to 8850.00 MPa.

$$F_i = 0.75S_p A_t \quad (30)$$

The stiffness constant C is determined by using values k_b and k_m , the bolt and member stiffness respectively, in (31).

$$C = \frac{k_b}{k_b + k_m} \quad (31)$$

The bolt stiffness is found by using the tensile stress area, which is 14.2 mm², the Young's modulus, which is 180 GPa [18] and l_t , which is the length of the bolt that is in contact with the member, found to be 3.175 mm. These are used in (32) to find the final value of 805.04.

$$k_b = \frac{A_t E}{l_t} \quad (32)$$

The member stiffness is found by using the Young's modulus, d the inner diameter of the member, which is 5 mm in this case, D , the outer diameter of the member, which is 8mm, t , or the thickness of the member, which is 3.175, and the screw angle α which is assumed to be 30°. These values are plugged into (33), and a resulting number of 227.526 is derived for the member stiffness.

$$k_m = \frac{P}{\delta} = \frac{\pi E d \tan(\alpha)}{\ln \left[\frac{(2t \tan(\alpha) + D - d)(D + d)}{(2t \tan(\alpha) + D + d)(D - d)} \right]} \quad (33)$$

Now that all of the preliminary values have been derived, they are substituted into (28), and the factor of safety is found to be 1.241125. Since the value is over 1, the application of these bolts to hold up the manipulator is safe.

SHAKER

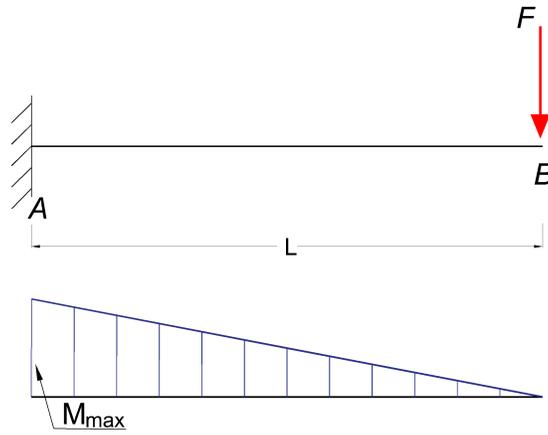


Fig. 38 Cantilever Beam Loading Schematic [1]

A stress analysis for the rods was conducted to ensure the material selected was strong enough to support the applied load. The rod was modeled as a cantilever beam under single point loading. The weight of the portion of the system supported by the beam was obtained from SolidWorks to be 106.44 grams, and the weight of the cell cultures was estimated to be 24.6 grams by taking the volume of a 384 well plate and a 50 mL conical tube filled to 50% of their total volume and assuming density to be the same as water (1 mL = 1 g). The gravitational force from this mass was calculated to be 1.29 Newtons.

As depicted in Fig . 39, the maximum bending moment of a cantilever beam is found at the support point. With the bending moment $M = FL$, and using equations (38) and (39), $y = b/2 = 0.005$ m, $L = 0.07$ m, $b = 0.01$ m, and $t = 0.015$ m, a stress value of 4778.67 Pa was found to be the applied stress on the rod. Note that the force is assumed to be entirely on one rod to account for when the second gear is disengaged.

$$\sigma = \frac{My}{I} \quad (34)$$

$$I = \frac{bt^2}{12} \quad (35)$$

A factor of safety of 1.2 was applied to this calculated applied stress, yielding a result of 5734.4 Pa. This means the beam material must be selected with a minimum strength requirement of 5.7 kPa.

Motor torque and power requirement calculations were done for both DC motors. The DC motor responsible for linear motion via the scotch yoke mechanism has to move the mass of the shaker tray, the scotch yoke mechanism, and the weight of the cell cultures. The torque was calculated using (40). The mass of the shaker components was obtained from SolidWorks, equaling 90.83 g. The fluid mass was estimated to be 24.6 g, from assuming the wells/tubes would be half full and the weight was the same as water. The radius was the distance from the motor shaft to the pin in the scotch yoke mechanism, which is 7.6 mm or 0.0076 m, which was obtained from SolidWorks as well.

$$M = FR = mgR \quad (36)$$

Plugging in the above values into (40), a value of 0.008606 Nm or J is obtained. Next the power requirement is obtained assuming 100 RPM in (41).

$$P = M\omega \quad (37)$$

Using (41), a value of 0.0901 W was obtained for the DC motor responsible for actuating the scotch yoke mechanism.

Using (40) and (41) again for the main drive motor for single and double orbital motions, and using the mass of the system obtained from SolidWorks equaling 191.12 g, and the radius equal to the length of the rod connecting the gear to the shaker area equaling 7 cm or 0.07 m, torque is found to be 0.1312 Nm and power is found to be 4.123 W.

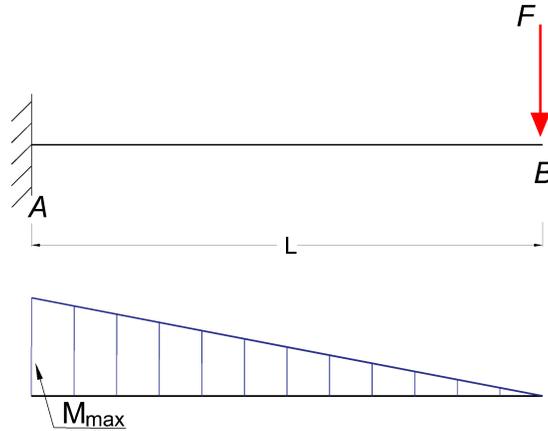


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$$T = FR = mgR \quad (40)$$

Plugging in the above values into (40), a value of 0.008606 Nm or J is obtained. Next the power requirement is obtained assuming 100 RPM in (41).

$$P = T\omega \quad (41)$$

Using (41), a value of 0.0901 W was obtained for the DC motor responsible for actuating the scotch yoke mechanism.

Using (40) and (41) again for the main drive motor for single and double orbital motions, and using the mass of the system obtained from Solid Works equaling 191.12 g, and the radius equal to the length of the rod connecting the gear to the shaker area equaling 7 cm or 0.07 m, torque is found to be 0.1312 Nm and power is found to be 4.123 W.

ENVIRONMENTAL MANAGEMENT

The heat loss should be calculated with an approximation of a thermal circuit, including a layer of insulation, the aluminum enclosure wall, and the heat transfer coefficient of the ambient air. The range of temperature is set between 4 and 70 degrees Celsius, applying the thermal circuit to the desired enclosure area and referencing material properties for the thermal conductivity. The thermal conductivity of aluminum alloy is 205 W/m-K and 0.03 W/m-K for the insulation, which is approximated from the overall enclosure assembly insulation. The convection coefficient is approximated as a function of velocity of air from intake. [19]

$$R = \frac{L}{K_{insu}A} + \frac{L}{K_{alum}A} + \frac{1}{hA} \quad (42)$$

The heat loss is calculated as a function of the thermal resistance. The temperature desired inside will be the maximum upper threshold and the outside temperature will be of the ambient air.

$$Q = \frac{T_{in} - T_{out}}{R} \quad (43)$$

The maximum heat loss is calculated at 90 W.

SANITATION

The top of the sanitation structure is comprised of two lids, one is fixed by welds to the tops of the top left of the sanitation structure while the other can be moved to create an opening for the manipulator to place and remove the vessels where the cultures are cultivated. Linear motion is possible through a rack and pinion system, where the rack is mounted to the retractable lid and gear motor mounted to the sanitation structure turns the spur gear, converting the angular motion of the gear to linear motion.

Using polypropylene, the retractable panel at the top of the structure has a mass of 0.430 kg for a weight of 4.21N. The torque required from a motor to carry the weight of the object was determined using (44).

$$T_{total} = F \cdot r \quad (44)$$

The length of the panel is 0.152 m, so the torque required by the motor is 0.64 Nm. The 7 rpm mini gear motor has torque of 140 in-oz. [20] which is 0.98 Nm.

The system is moved by a rack and pinion pairing, with a spur gear that has a pitch of 24 and 24 teeth with pitch diameter of 38.1mm. Using the speed gear ratio and the angular speed of the motor (45), the panel is moved at 0.67 m/s.

$$G = \frac{\omega_{in}}{\omega_{out}} \quad (45)$$

V. Results

A. Executive Summary with Hedgehog Concept

This system will carry out an experiment from start to finish, being ready for the next experiment with little to no additional work to the user. The sanitation system incorporated in the bioreactor will be able to safely dispose of culture materials and sanitize the equipment used, making the system ready for the next experiment. The well plates and conical tubes, still filled with cell culture media, are placed into a sanitation chamber that will cull the cell cultures and dispose of solid and liquid waste, leaving sanitized well plates and tubes for future use.

The manipulator subsystem is the backbone of the entire system, interacting with every other subsystem in some way by transporting well plates and conical tubes to each other subsystem so they may execute their tasks accordingly. All other subsystems are fixed in place in the overall system. The manipulator system is capable of removing the lids of well plates, and there is an opener for the conical tubes by the fluid handling system associated with the manipulator as well. Drive belts create motion in two directions, and a linear actuator raises and lowers the manipulator grabber in the third direction to allow the manipulator to access all areas of the system.

The shaker system is responsible for aerating cell cultures by disturbing the culture media with three different shaking patterns: linear, orbital, and double orbital. These shaking patterns are all possible with a single shaker unit, and two are included in the system. The tray area is large enough to support a 384 well plate, with a raised lip around the edge of the tray to ensure the well plate does not fall off the tray. There is a hole on the side of the shaker tray to support the 50 mL conical tubes, and a tube plug that can be inserted with a smaller inner diameter for the 15 mL tubes.

The fluid handling subsystem has fluid and gas reservoirs fixed to the side of the system structure. The liquid handler is comprised of three reservoirs, one containing the nutrients desired for the cell cultures, one of distilled water to flush the fluid line, and one of bleach in case the lines or possibly the wells need to be sterilized. The gas canisters are controlled with electronically actuated solenoids, allowing for different gas compositions to be added to the system as needed. The manipulator will move well plates and tubes to the burette responsible for dispensing liquid or to the gas canisters depending on the desired operation. There is a vent on the back of the overall system associated with the fluid handling system to vent out any gases so that gas composition in the system can be regulated. A filter is on the vent to ensure nothing harmful is being vented to the lab environment.

The environmental management subsystem is responsible for the consistent heating and cooling capabilities exhibited to the bacterial cultures. This includes a controllable heat exchanger which is rated for the temperatures outlined in the customer metrics, with control parameters being delivered from user inputted commands. The environment insulates temperature variation from affecting electrical components of the overall assembly while achieving necessary bacterial culture growth during experimentation. There will be readings to lab technicians for tracking the progression of growth and characteristics of the enclosure.

The sanitation subsystem is a unique aspect of the Dr. Clean Bioreactor and the inspiration for the system's name. As mentioned earlier, the subsystem is capable of culling cell cultures used in an experiment and disposing of their waste in a safe and effective manner. This means an otherwise unfortunate lab technician does not have to spend their afternoon cleaning out objectively gross well plates and conical tubes filled with old E. Coli cultures and can instead spend their time analyzing the results of the experiment. The system opens at the top and is sealed with a rubber strip to prevent contamination. A gear track opens and closes the lid and is driven by a small motor. Attached to the fixed section of the lid, a shower system is in place to shower bleach and distilled water over the contents of the system. There is a drain at the bottom of the system to empty it. Fixed to the side of the system, two tanks are fixed, one for bleach and one for water. Tubes connect these tanks to a fluid pump, with valves that can be opened or closed to determine which fluid will be pumped through to the shower system.

The overall structure subsystem that houses all the subsystems of the Dr. Clean Bioreactor is comprised of a hollow aluminum frame, ABS side panels, and fiberglass tape for insulation. The front face of the structure has a door with a glass panel for viewing purposes. An emergency stop button is located by the door. The door is held shut by small magnets, ensuring the door will close and seal while still being easy to open. The overall structure fits easily on a lab table per customer requirement.

B. CAD Model

These following images were taken from the group's CAD Model

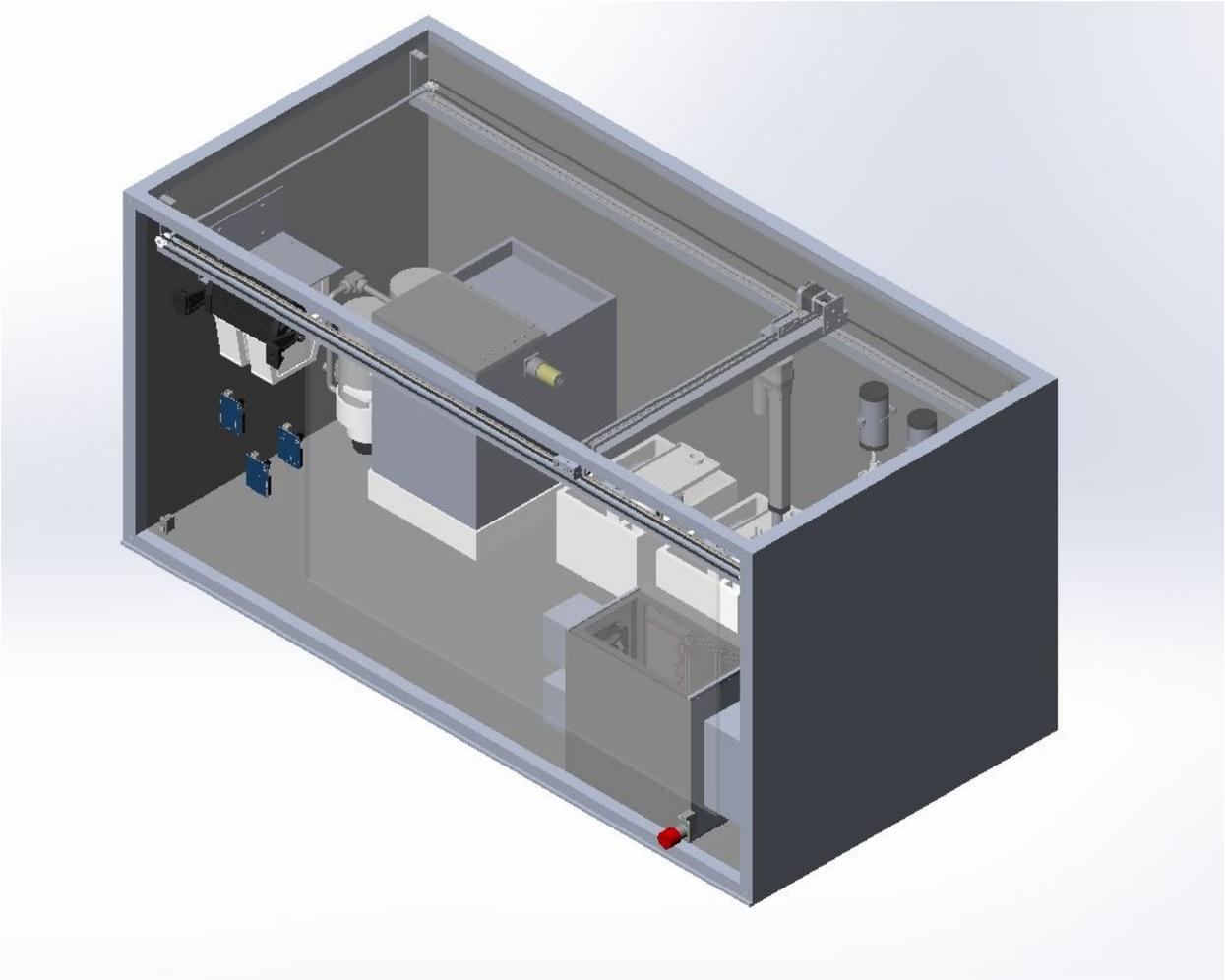


Fig. 40 Bioreactor ISO View

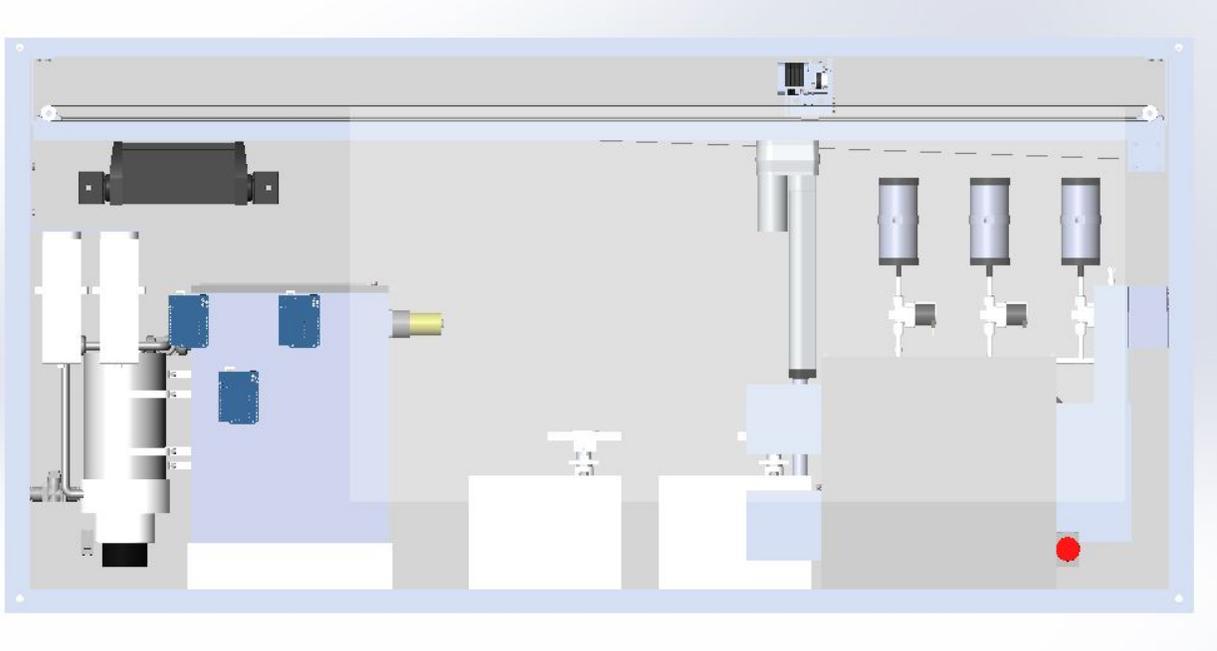


Fig. 41 Bioreactor Front View

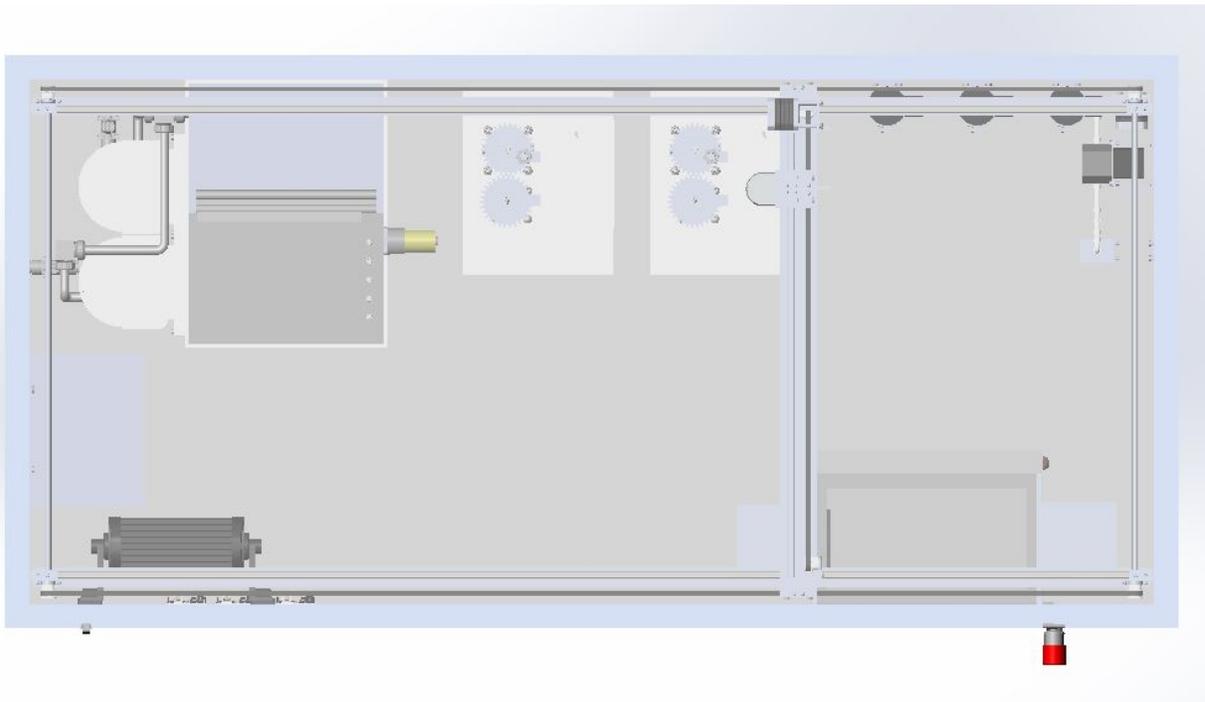


Fig. 42 Bioreactor Top View

C. Bill Of Materials, Purchase Order, and Manufacturing and Assembly Costs
 Bill of Materials

Item No.	DWG Number	Part Description	Qty.	Material
1	EML4501-A-100	Manipulator System Assembly	1	-
2	EML4501-A-101	X Drive Assembly	1	-
3	EML4501-A-102	Belt Clamp Assembly	1	-
4	EML4501-A-103	Far Pulley Holder Assembly	1	-
5	EML4501-A-104	Y Drive Assembly	1	-
6	EML4501-A-105	Y Beam Near	1	-
7	EML4501-A-106	Y Beam Far	1	-
8	EML4501-A-107	Actuator Bracket Assembly	1	-
9	EML4501-A-108	Gripper Assembly	1	-
10	EML4501-A-200	Shaker Assembly	2	-
11	EML4501-A-201	Shaker Plate Assembly	2	ABS
12	EML4501-A-202	Scotch Yoke Assembly	2	-
13	EML4501-A-203	Drive Gear Assembly	2	-
14	EML4501-A-204	Gear Shifter Assembly	2	-
15	EML4501-A-300	Fluid Handling System Assembly	1	-
16	EML4501-A-301	Peristaltic Pump Assembly	1	-
17	EML4501-A-302	Dispensing Mechanism single Assembly	1	-
18	EML4501-A-303	Deposit Assembly	1	-
19	EML4501-A-304	Air injection Assembly	1	-
20	EML4501-A-305	Air Evacuation Assembly	1	-
21	EML4501-A-400	Environmental Management System Assembly	1	-
22	EML4501-A-401	PC Fan Assembly	1	-
23	EML4501-A-402	Condenser Assembly	1	-
24	EML4501-A-500	Spectormeter System Assembly	1	-
25	EML4501-A-600	Sanitation System Assembly	1	-
26	EML4501-A-601	Sanitation Structure	1	-
27	EML4501-A-602	Rack and Pinion Assembly	1	-
28	EML4501-A-603	Drain and Waste System	1	-
29	EML4501-A-604	Assembled Drain	1	-
30	EML4501-A-605	Sanitation Fluid Spray System	1	-
31	EML4501-A-606	Spray Pipe Mounts	5	-
32	EML4501-A-607	Reservoir System	1	-
33	EML4501-A-608	Reservoir Assembly	2	-
34	EML4501-A-609	Pump Mounted Assembly	2	-
35	EML4501-A-610	Reservoir Clamp	4	ABS
36	EML4501-A-700	Structure Assembly	1	-
37	EML4501-A-701	Frame Assembly	2	-

38	EML4501-OTS1	Nema 17	2	OTS
39	EML4501-OTS2	M5x0.8 mm 20 mm Hex Head Screw	6	OTS
40	EML4501-OTS3	M3 x 0.50 mm 18 mm Button Head Cap Screw	11	OTS
41	EML4501-OTS4	Aluminum Sleeve Bearing Carriage	3	OTS
42	EML4501-OTS5	13 mm OD timing belt pulley	2	OTS
43	EML4501-OTS6	M5 x 0.8 mm 10 mm Hex Head	6	OTS
44	EML4501-OTS7	Low Profile Mounted Ball Bearing 8 mm ID	5	OTS
45	EML4501-OTS8	8 mm dia. Shaft	1	OTS
46	EML4501-OTS9	21 mm OD timing belt pulley	5	OTS
47	EML4501-OTS10	M2x0.4 22mm Button Head Cap Screw	4	OTS
48	EML4501-OTS11	7mm Wide Guide Rail 815mm	2	OTS
49	EML4501-OTS12	7 mm Wide Guide Rail Short 412.58	2	Modified OTS
50	EML4501-OTS13	7mm Wide Guide Rail 447.85mm	1	OTS
51	EML4501-OTS14	7mm Wide Guide Rail 145mm	1	Modified OTS
52	EML4501-OTS15	M2x0.4 8mm Socket Head Screw	201	OTS
53	EML4501-OTS16	M2x0.4 6mm Button Head Cap Screw	8	OTS
54	EML4501-OTS17	12 V Linear Actuator 6 inch	1	OTS
55	EML4501-OTS18	0.25"-20 1.25" Hex Head	1	OTS
56	EML4501-OTS19	0.25"-20 Nut	1	OTS
57	EML4501-OTS20	Nema 8	1	OTS
58	EML4501-OTS21	M4 x 0.7 300 mm Threaded Rod	1	OTS
59	EML4501-OTS22	Low Profile Mounted Ball Bearing 4 mm ID	1	OTS
60	EML4501-OTS23	0.125" Stainless Steel Washer	2	OTS
61	EML4501-OTS24	M3x0.5 10 mm Button Head Cap Screw	14	OTS
62	EML4501-OTS25	0.25"-28 0.5" Button Head Cap Screw	2	OTS
63	EML4501-OTS26	6mm Wide Timing Belt 1164 mm	1	OTS
64	EML4501-OTS27	6mm Wide Timing Belt 3000 mm	2	OTS
65	EML4501-OTS28	DC Drive Motor	2	OTS
66	EML4501-OTS29	Actuonix Linear Actuator	2	OTS
67	EML4501-OTS30	Scotch Yoke Motor	2	OTS
68	EML4501-OTS31	Drive Motor Shaft Clamp	2	OTS
69	EML4501-OTS32	Linear Actuator Shaft Clamp	2	OTS
70	EML4501-OTS33	Scotch Yoke Motor Shaft Clamp	2	OTS
71	EML4501-OTS34	36 Tooth 14" Pitch Steel Gears	4	Modified OTS
72	EML4501-OTS35	M12x1.75mm Steel Hex Nut	2	OTS
73	EML4501-OTS36	M7x1.0mm Steel Hex Nut	2	OTS
74	EML4501-OTS37	M6x1mm 10mm Polycarbonate Screw	16	OTS

75	EML4501-OTS38	OEM B01 Peristaltic pump	1	OTS
76	EML4501-OTS39	Nema 17 Step Motor	1	OTS
77	EML4501-OTS40	M5 x 0.8 mm 10 mm Hex Head	25	OTS
78	EML4501-OTS41	M5 x 0.8 mm Thread Steel Hex Nut	17	OTS
79	EML4501-OTS42	1/4" Soft PVC tube	1	OTS
80	EML4501-OTS43	KM8DC Dispensing valve	1	OTS
81	EML4501-OTS44	Solenoid valve	3	OTS
82	EML4501-OTS45	Automatic Gas Solenoid Valve	5	OTS
83	EML4501-OTS46	Compressed Air Regulator	5	OTS
84	EML4501-OTS47	1/4" rigid PVC tube	1	OTS
85	EML4501-OTS48	Mildew-Resistant Reusable Air Filter	1	Modified OTS
86	EML4501-OTS49	M4x16mm Hex Screw	4	OTS
87	EML4501-OTS50	Low Voltage Equipment Cooling Fan, 1.5" Deep	1	OTS
88	EML4501-OTS51	Low Voltage Equipment Cooling Fan, 1" Deep	2	OTS
89	EML4501-OTS52	Button Head Torx Screw, 18-8, M4.5x0.75mm, 8mm	8	OTS
90	EML4501-OTS53	Heat sink and condenser heat exchanger with 2 fans	1	OTS
91	EML4501-OTS54	Compact Spectrometer	1	OTS
92	EML4501-OTS55	Fiber Optic Probes	1	OTS
93	EML4501-OTS56	Spectrometer Mount	1	-
94	EML4501-OTS57	Arduino Uno Rev3	3	OTS
95	EML4501-OTS58	Nilight LED Light Bar	1	Modified OTS
96	EML4501-OTS59	LED RGB	12	OTS
97	EML4501-OTS60	Jumper Wires	3	OTS
98	EML4501-OTS61	Epoxy	1	OTS
99	EML4501-OTS62	Nema Wall Mount Enclosure	1	OTS
100	EML4501-OTS63	#10-24 Thread Size 1-1/4" Long Sealing Socket Head Screws	5	OTS
101	EML4501-OTS64	M4x0.7 35 mm Sealing Socket Head Screws	8	OTS
102	EML4501-OTS65	#6-40 Thread Size 1/2" Long Socket Head Screw	5	OTS
103	EML4501-OTS66	Rubber Push-on Seal	1	OTS
104	EML4501-OTS67	Rubber Adhesive Seal	1	OTS
105	EML4501-OTS68	7 RPM Mini Gear Motor	1	OTS
106	EML4501-OTS69	24 Tooth Spur Gear, 24 Pitch with Set Screw	1	OTS
107	EML4501-OTS70	15 cm Rack, 24 Pitch	1	Modified OTS
108	EML4501-OTS71	#10-32 Thread Size 3/4" Long Phillips Screws	2	OTS
109	EML4501-OTS72	PVC ID 8mm Tubing, 20 cm Length	3	OTS
110	EML4501-OTS73	90 degree elbow PVC adapters	4	OTS
111	EML4501-OTS74	Tube Tee Connectors	3	OTS
112	EML4501-OTS75	PVC ID 8mm Tubing, 6 cm Length	2	OTS

113	EML4501-OTS76	PVC ID 8mm Tubing, 4.5 cm Length	1	OTS
114	EML4501-OTS77	0.5" PVC Rod, 4.5 cm Length	2	OTS
115	EML4501-OTS78	1/8 NPT Flat Spray Nozzle	9	OTS
116	EML4501-OTS79	O-Rings	19	OTS
117	EML4501-OTS80	Routing Clamps	5	OTS
118	EML4501-OTS81	Spacers	5	OTS
119	EML4501-OTS82	#10-24 Hex Nut	5	OTS
120	EML4501-OTS83	Soft Tubing, 28 cm Length	2	Modified OTS
121	EML4501-OTS84	Soft Tubing, 21 cm Length	1	Modified OTS
122	EML4501-OTS85	D5 Pump	2	OTS
123	EML4501-OTS86	M4x0.7 Hex Nut	8	OTS
124	EML4501-OTS87	M4x0.7 50 cm Flat Head Screw	4	OTS
125	EML4501-OTS88	1"x1" 2024 Aluminum Bar Stock 155 cm length	4	OTS
126	EML4501-OTS89	1"x1" 2024 Aluminum Bar Stock, 70 cm length	8	OTS
127	EML4501-OTS90	M5 x 0.8 mm 40 mm Flat Head Screw	8	OTS
128	EML4501-OTS91	102x52 cm Glass Panel	1	Modified OTS
129	EML4501-OTS92	Rocker Switch	1	OTS
130	EML4501-OTS93	Emergency Stop	1	OTS
131	EML4501-OTS94	Magnets	2	OTS
132	EML4501-OTS95	#8-32 Thread Size 3/16" Long Hex Drive Flat Head Screw	1	OTS
133	EML4501-OTS96	Surface Mount Hinge with Holes 2" x 3/4" Door Leaf	3	OTS
134	EML4501-OTS97	#8-32 Thread Size 1" Long Flat Head Phillips Screw	12	OTS
135	EML4501-001	X Drive Extrusion	1	1060 Aluminum Alloy
136	EML4501-002	Nema 17 Motor Mount	2	1060 Aluminum Alloy
137	EML4501-003	Extrusion Tube Ends	2	1060 Aluminum Alloy
138	EML4501-004	Belt Clamp	3	1060 Aluminum Alloy
139	EML4501-005	Nema 17 Spacers	4	1060 Aluminum Alloy
140	EML4501-006	X Tensioning Block	1	1060 Aluminum Alloy
141	EML4501-007	Far Pulley Holder	1	1060 Aluminum Alloy
142	EML4501-008	Near Side Y Extrusion	1	1060 Aluminum Alloy
143	EML4501-009	Far Side Y Extrusion	1	1060 Aluminum Alloy
144	EML4501-010	Mounting Bracket	4	1060 Aluminum Alloy
145	EML4501-011	Actuator Bracket	1	1060 Aluminum Alloy
146	EML4501-012	Actuator Screw Mount	1	1060 Aluminum Alloy

147	EML4501-013	Gripper Base	1	1060 Aluminum Alloy
148	EML4501-014	Gripper Jaw (Moving)	1	1060 Aluminum Alloy
149	EML4501-015	Gripper Jaw (Fixed)	1	1060 Aluminum Alloy
150	EML4501-016	Nema 8 Motor Mount	1	1060 Aluminum Alloy
151	EML4501-017	Y Tensioning Block	2	1060 Aluminum Alloy
152	EML4501-018	Y Tensioning Cap	2	1060 Aluminum Alloy
153	EML4501-019	Gripper Pad	2	Neoprene
154	EML4501-020	Shaker Housing	2	ABS
155	EML4501-021	Shaker Plate	2	ABS
156	EML4501-022	Tube Plug	2	ABS
157	EML4501-023	Scotch Yoke Slot and Plate Mount	2	ABS
158	EML4501-024	Scotch Yoke Motor Hub	2	Aluminum Alloy
159	EML4501-025	Scotch Yoke Base Plate	2	ABS
160	EML4501-026	Scotch Yoke Rod	4	Aluminum Alloy
161	EML4501-027	Scotch Yoke Motor Mount	2	ABS
162	EML4501-028	Drive Motor Mount	2	ABS
163	EML4501-029	Drive Gear Link	2	Aluminum Alloy
164	EML4501-030	Shift Gear Link	2	Aluminum Alloy
165	EML4501-031	Linear Actuator Mount	2	ABS
166	EML4501-032	Pump Mount	1	ABS
167	EML4501-033	Fluid dispenser Mount	1	ABS
168	EML4501-034	Deposit	3	PMMA
169	EML4501-035	Deposit Mount	6	ABS
170	EML4501-036	1/4" elbow	11	Hard PVC
171	EML4501-037	1/4" triple connector	2	Hard PVC
172	EML4501-038	Gas Tank	5	Cross-Linked Polyethylene
173	EML4501-039	Air Deposits Mount	1	ABS
174	EML4501-040	3/8" rigid PVC curved tube	1	Rigid PVC
175	EML4501-041	Exit pipe	1	Stainless Steel
176	EML4501-042	Steel Enclosure Frame	1	Stainless Steel
177	EML4501-043	Fan Panel	1	6061 Aluminum
178	EML4501-044	Exhaust Panel	1	6061 Aluminum
179	EML4501-045	AC Duct Louver	1	Stainless Steel
180	EML4501-046	Removable Panel Track	2	6061 Aluminum
181	EML4501-047	Removable Roof Panel	1	6061 Aluminum
182	EML4501-048	Environmental Management Enclosure	1	6061 Aluminum
183	EML4501-049	Sanitation Housing	1	3003 Aluminum
184	EML4501-050	Retractable Panel	1	Polypropelyne
185	EML4501-051	Fixed Panel	1	3003 Aluminum
186	EML4501-052	Mini Gear Motor Mount	1	3003 Aluminum
187	EML4501-053	Waste Tray	1	Polyethylene
188	EML4501-054	Wide Drain Panel	2	3003 Aluminum

189	EML4501-055	Small Drain Panel	2	3003 Aluminum
190	EML4501-056	Drain Gate	1	3003 Aluminum
191	EML4501-057	Nozzle Adapter	9	ABS
192	EML4501-058	Reservoir Tank	2	ABS
193	EML4501-059	Reservoir Supply Head	2	ABS
194	EML4501-060	Pump Mount	2	ABS
195	EML4501-061	Detachable Clamp	4	ABS
196	EML4501-062	Mounted Clamp	4	ABS
197	EML4501-063	Side Panels	2	ABS
198	EML4501-064	Top and Bottom Panels	2	ABS
199	EML4501-065	Front Wall	1	ABS
200	EML4501-066	Left Insulation Panel	1	S-FiberGlass
201	EML4501-067	Right Insulation Panel	1	S-FiberGlass
202	EML4501-068	Top and Bottom Insulation Panels	2	S-FiberGlass
203	EML4501-069	Back Insulation Panel	1	S-FiberGlass
204	EML4501-070	Front Insulation Panel	1	S-FiberGlass
205	EML4501-071	Metal North Pole	1	6061 T6 Aluminum Alloy

Purchase Order

The total cost of all materials is 9645.47 USD.

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

1. Purchase Order Number:	1
2. Group requesting item(s):	10
3. Account to be charged:	MAE Mechanical Design 2
4. Group member issuing PO:	Denisse Pensa-Valerio

BOM Part Number	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
EML4501-OTS1	Stepper Motor Nema 17 Bipolar 40mm 84oz.in (45 N cm) 2A 4 Lead 3D Printer Hobby CNC	17HS16-2004S	2	each	\$ 12.99	\$ -	\$ 25.98	Amazon	410 Terry Ave. North	Seattle, WA, 98109	1-888-280-4331
		Web Site:	https://www.amazon.com/Stepper-Motor-Bipolar-64oz-Printer/dp/B00PNEQI7W/ref=asc_df_B00PNEQI7W?tag=hyprod-20&linkCode=df0&hvadid=309777532761&hpos=&hnetw=g&hvrand=13854771092843132055&hzone=&hptwo=&hqrnt=&hvdev=c&hvcmid=&hvlocint=&hvlocphy=9011698&hvargid=pla-458488325758&psc=1&tag=&ref=&adpgid=63226431993&hzone=&hptwo=&hvadid=309777532761&hpos=&hnetw=g&hvrand=13854771092843132055&hvcmid=&hvlocint=&hvlocphy=9011698&hvargid=pla-458488325758								
EML4501-OTS2	High-Strength Class 10.9 Steel Hex Head Screw, M5x0.8mm 20mm long	91310A124	1	pack	\$ 9.66	\$ -	\$ 9.66	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site:	https://www.mcmaster.com/91310A124/								
EML4501-OTS3	Button Head Hex Drive Screw Pasivated 18-8 Stainless Steel, M3x0.5 mm Thread, 16 mm	92095A472	1	pack	\$ 6.20	\$ -	\$ 6.20	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site:	https://www.mcmaster.com/92095A472/								
EML4501-OTS4	Aluminum Sleeve Bearing Carriage for 7 mm Wide Rail, 17 mm Wide	9829K1	3	each	\$ 21.91	\$ -	\$ 21.91	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site:	https://www.mcmaster.com/9829K1/								
EML4501-OTS5	MXL Series Lightweight Timing Belt Pulley, 6mm Maximum Belt Width, 13mm OD, 17.5 mm Wide Overall, 1 Flange	7717N18	2	each	\$ 9.44	\$ -	\$ 18.88	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site:	https://www.mcmaster.com/7717N18/								
EML4501-OTS6	High-Strength Class 10.9 Steel Hex Head Screw, M5x0.8mm 10mm long	91310A121	1	pack	\$ 8.18	\$ -	\$ 8.18	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site:	https://www.mcmaster.com/91310A121/								
EML4501-OTS7	Low-Profile Mounted Shielded Steel Ball Bearing with Aluminum Housing, for 8mm Shaft Diameter	8600N13	5	each	\$ 33.18	\$ -	\$ 165.90	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site:	https://www.mcmaster.com/8600N13/								

EML4501-OTS28	Compact Round Face DC Motor 12V DC, 5782 RPM @ 0.81 in-oz	6331K21	2	each	\$ 106.73	\$ -	\$ 213.46	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/6331K21/									
EML4501-OTS29	PQ12-R Micro Linear Servos for RC & Arduino	PQ12-R	2	each	\$ 70.00	\$ 22.89	\$ 162.89	Actuonix	Unit 201-1753 Sean Heights	Saanichton, BC	1-206-347-9684
		Web Site: https://www.actuonix.com/Actuonix-PQ12-R-micro-linear-servos-for-RCs/pq12r.htm									
EML4501-OTS30	Compact Round Face DC Motor 12V DC, 3000 RPM @ 21 in-oz	6331K13	2	each	\$ 112.03	\$ 7.50	\$ 231.56	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/6331K13/									
EML4501-OTS31	Clamping Two-Piece Shaft Collar for 1/4" Diameter, 2024 Aluminum	6436K131	2	each	\$ 4.19	\$ -	\$ 8.38	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/6436K131/									
EML4501-OTS32	Clamping Two-Piece Shaft Collar for 6mm Diameter, 2024 Aluminum	9520T3	2	each	\$ 8.20	\$ -	\$ 16.40	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/9520T3/									
EML4501-OTS33	Clamping Two-Piece Shaft Collar for 3/32" Diameter, Black Oxide 1215 Carbon Steel	6436K312	2	each	\$ 10.81	\$ -	\$ 21.62	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/6436K312/									
EML4501-OTS34	Metal Gear - 14 1/2 Degree Pressure Angle - Round/Machinable Bore, 16 Pitch, 36 Teeth	6325K77	4	each	\$ 41.42	\$ -	\$ 165.68	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/6325K77/									
EML4501-OTS35	Steel Hex Nut M12x1.75mm Thread	90592A028	2	Pack	\$ 15.52	\$ -	\$ 31.04	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/90592A028/									

EML4501-OTS48	Midew-Resistant Reusable Air Filter Rolls	2195K301	1	Rolls	\$ 4.62	\$ -	\$ 4.62	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/2195K301/									
EML4501-OTS49	M4x16mm Hex Screw	91290A044	1	Pack	\$ 9.14	\$ -	\$ 9.14	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/91290A044/									
EML4501-OTS50	FAN Low-Voltage Equipment-Cooling Fan 12V DC with Wire Leads, 3.15" Square x 1.5" Deep Overall, 130 CFM:	1939K116	1	Each	\$ 70.87	\$ -	\$ 70.87	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/1939K116/									
EML4501-OTS51	Low-Voltage Equipment-Cooling Fan, 12V DC with Wire Leads, 3.15" Square x 1" Deep Overall	1939K33	2	each	\$ 31.12	\$ -	62.24	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/1939K330/									
EML4501-OTS52	Button Head Torx Screws, 18-8 Stainless Steel, M4.5x0.75mm thread, 8mm Long	90910A960	1	pack	\$ 12.92	\$ -	\$ 12.92	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/90910A960/									
EML4501-OTS53	Heat Sink for Water with Copper Tube, 2200 Btu/hr. Cooling Capacity	35145K73	1	each	\$ 375.42	\$ -	\$ 375.42	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/35145K73/									
EML4501-OTS54/55	CCS175/M - Compact Spectrometer	CCS175/M	1	Single	\$ 2,157.75	-	\$2,157.75	Thorlabs	56 Sparta Avenue	Newton, NJ 07980	1-973-300-3000
		Web Site: https://www.thorlabs.com/thorproduct.cfm?partnumber=RPH									
EML4501-OTS55/56	RPH - Holder Block for Ø1/4" Fiber Optic Probes	RPH	1	Single	\$ 71.96	\$ 11.07	\$ 83.03	Thorlabs	56 Sparta Avenue	Newton, NJ 07980	1-973-300-3000
		Web Site: https://www.thorlabs.com/thorproduct.cfm?partnumber=CCS175/M&sel=page_1									
EML4501-OTS57	Arduino Uno Rev3	A000066	3	Single	\$ 21.90	-	\$ 65.70	Amazon	410 Terry Ave. North	Seattle, WA, 98109	1-888-280-4331
		Web Site: https://www.amazon.com/Arduino-A000066-ARDUINO-UNO-R3/dp/B008GRTSV6									

EML4501-OTS67	High-Temperature Rubber Seal Surface-Mnt, Hollow, Plain Back, 1-1/4" O'fall Wd., Blk	1129A130	1	Feet	\$ 8.54	\$ -	\$ 8.54	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/1129A130									
EML4501-OTS68	12V DC, 7 rpm @ 140 in/laz mini Gear Motor	6331K33	1	Each	\$ 125.36		\$ 125.36	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/6331K33									
EML4501-OTS69	Metal Gear - 20 Degree Pressure Angle, Round Bore with Set Screw, 24 Pitch, 24 Teeth	6832K62	1	Each	\$ 19.62		\$ 19.62	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/5172T14/									
EML4501-OTS70	Metal Gear Rack - 20 Degree Pressure Angle, Rectangular, 24 Pitch, 2 ft. Length	7854K150	1	Each	\$ 39.67		\$ 39.67	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/5174T1/									
EML4501-OTS71/74/75	Chrome-Plated 18-8 Stainless Steel Pan Head Phillips Screws, 10-32 Thread Size, 3/4" Long	94836A363	1	Packs	\$ 3.16		\$ 3.16	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/94836A363/									
EML4501-OTS72/75/76	Abrasion-Resistant PVDF Plastic Semi-Clear Tubing for Chemicals, 8 mm ID, 10 mm OD	52395K64	5	Feet	\$ 4.98	\$ -	\$ 24.90	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/52395K64/									
EML4501-OTS73	Compression Fitting for Chemicals, 90 Degree Elbow Connector for 12 mm Tube OD	52195K813	4	Each	\$ 86.00		\$ 344.00	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/52195K813									
EML4501-OTS74	Compression Fitting for Chemicals, Tee Connector for 12 mm Tube OD	52195K819	3	Each	\$ 106.12		\$ 318.36	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/52195K819/									
EML4501-OTS77	Impact- and Chemical-Resistant PVC Rod, 1/2" Diameter, 5 Feet Long	87025K31	1	Feet	\$ 10.35		\$ 10.35	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/87025K31									

EML4501-OTS78	PVDF Plastic Flat Spray Nozzle, 1/8 NPT Male, 0.1 gpm At 20 PSI, 90 Degree Spray Angle	3404K26	1	Pack	\$ 6.88		\$ 6.88	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/34845K29/									
EML4501-OTS79	Oil-Resistant Buna-N O-Ring 1 mm Wide, 9.5 mm ID	9262K612	1	Pack	\$ 6.17	\$ -	\$ 6.17	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/9262K612									
EML4501-OTS80	Routing Clamp, Steel with 2 Mounting Points, 13/16" ID, 4-1/8" Long, Packs of 50	9434T17	1	Pack	\$ 5.77		\$ 5.77	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/9434T17/									
EML4501-OTS81	Off-White Nylon Unthreaded Spacer, 3/8" OD, 9/16" Long, for Number 10 Screw Size, Pack of 100	94639A847	1	Pack	\$ 13.81		\$ 13.81	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/94639A847/									
EML4501-OTS82/83	Low-Strength Steel Hex Nut, Zinc-Plated, 10-24 Thread Size, Pack of 100	90480A011	1	Pack	\$ 1.90		\$ 1.90	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/90480A011/									
EML4501-OTS83/84	PVC Tubing for Chemicals, 7 mm ID, 10 mm OD	51825K47	3	Feet	\$ 0.75		\$ 2.25	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/51825K47									
EML4501-OTS85	EKWB EK-D6 PWM G2 Pump	-	2	Each	\$ 120.99		\$ 241.98	Amazon	410 Terry Ave. North	Seattle, WA, 98109	1-888-280-4331
		Web Site: https://www.amazon.com/EKWB-EK-D6-PWM-G2-Pump/dp/B07NPZZ7WD/ref=sr_1_4?keywords=D6+Pump&qid=1617382296&sr=84									
EML4501-OTS86	Steel Hex Nut, Medium-Strength, Class 8, M4 x 0.7 mm Thread, Pack of 100	90592A090	8	Pack	\$ 1.41		\$ 11.28	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/90592A090/									

EML401-OTS87	316 Stainless Steel Hex Drive Flat Head Screw, 90 Degree Countersink, M4 x 0.70mm Thread, 50mm Long, Pack of 25	9399A573	1	Pack	\$	12.00		\$	12.00	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/9399A573											
EML401-OTS889	High-Strength 2024 Aluminum Bar, 1" Thick x 1" Wide	8699K21	8	6ft	\$	108.46	\$	7.50	\$	835.18	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site:	https://www.mcmaster.com/8699K21/											
EML401-OTS90	Black-Oxide Alloy Steel Hex Drive Flat Head Screw, 90 Degree Countersink, M5 x 0.80 mm Thread, 40 mm Long, Pack of 50	9129A219	1	Pack	\$	12.47		\$	12.47	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/9129A219											
EML401-OTS91	Clear Scratch- and UV-Resistant Acrylic Sheet 24" x 48" x 1/4"	8589K84	1	Each	\$	62.45		\$	62.45	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/8589K84/											
EML401-OTS92	Rocker Switch, 2 Position, for 1/8" Panel Cutout Height, 2 Terminals	7395K11	1	Each	\$	7.50		\$	7.50	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/7395K11/											
EML401-OTS98	Emergency Stop Panel-Mount Push-Button Switch, 22 mm Panel Diameter, Pull Reset, 1 Circuit, 1-1/2"	6741K41	1	Each	\$	35.38		\$	35.38	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/6741K41/											
EML401-OTS94	Multi-Pole Neodymium Magnet with Countersink Unthreaded Hole, 1/8" Thick, 3/4" OD	2494N13	1	Each	\$	4.73		\$	4.73	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/2494N13/											
EML401-OTS95	#8-32 Thread Size 3/16" Long Hex Drive Flat Head Screw	92210A379	1	100	\$	10.73		\$	10.73	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/92210A379											
EML401-OTS96	Surface Mount Hinge with Holes 2" x 3/4" Door Leaf	1586A23	3	Each	\$	8.91		\$	26.73	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/1586A23/											
EML401-OTS97	#8-32 Thread Size 1" Long Flat Head Phillips Screw	91099A270	1	100	\$	9.96		\$	9.96	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/91099A270											

EML4501-001-012	Multipurpose 8061 Aluminum Rectangular Tube 1/8" Wall Thickness, 1" High x 1" Wide x 6' Long	6548K21- 6548K11	2	each	\$ 37.02	\$ -	\$ 74.04	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/6548K21-6548K11/									
EML4501-002-003-006-014-015-016-018	High-Strength Multipurpose 8061 Aluminum with Certificate Precision Ground on Top	3511T121	1	each	\$ 60.90	\$ -	\$ 60.90	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/3511T121/									
EML4501-004-005-007-010-011-017	High-Strength Multipurpose 8061 Aluminum with Certificate Precision Ground on All Surfaces	9057K55	1	each	\$ 54.63	\$ -	\$ 54.63	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/9057K55/									
EML4501-008-009-013	Multipurpose 8061 Aluminum Rectangular Tube 1/8" Wall Thickness, 1" High x 2" Wide x 3' Long	6548K39- 6548K392	1	each	\$ 33.16	\$ -	\$ 33.16	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/6548K39-6548K392/									
EML4501-019	High-Strength Multipurpose Neoprene Strip, 4" x 36", 1/64" Thick	/1294N31		Each	\$ 12.92	\$ -	\$ 33.16	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/1294N31/									
EML4501-020-021-022-023-025-027-028-031-032-033-035-057-058-059-060-061-062	HATCHBOX ABS 3D Printer Filament, 1 kg Spool, 1.75 mm, White	3D-ABS- 1KG1.75-WHT	4	Roll	\$ 22.04	\$ -	\$ 88.16	HATCHBOX	2685 Pomona Blvd.	Pomona, CA. 91768	support@hatchbox3d.com
		Web Site: https://www.amazon.com/HATCHBOX-3D-Filament-Dimensional-Accuracy/dp/B00J0H6NNM/ref=sr_1_3?dclid=18&keywords=ABS%2BFilament&qid=1617363170&sr=8-3&th=1									
EML4501-021	Multipurpose 8061 Aluminum Rod 5 mm Diameter	4634T31- 4634T313	2	3 ft	\$ 1.31	\$ -	\$ 2.62	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/4634T31-4634T313/									
EML4501-023	Multipurpose 8061 Aluminum Rod 7/8" Diameter	8974K12- 8974K309	2	0.5 ft	\$ 3.57	\$ -	\$ 7.14	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/8974K12-8974K309/									
EML4501-026-027	Multipurpose 8061 Aluminum 1" Thick x 2" Wide	8975K237- 8975K411	2	1'	\$ 17.88	\$ -	\$ 35.76	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000
		Web Site: https://www.mcmaster.com/8975K237-8975K411/									

EML4501-034	Poly(methyl methacrylate) Tube, Outside Diameter .50mm	ME307500-188-058-55	1	Each	\$ 152.00	\$ -	\$ 152.00	Good Fellow	Ermine Business Park	Huntingdon, Inglaterra PE29 6WR	+44 1480 424 800	
		Web Site:	https://www.mcmaster.com/8586K161/									
EML4501-038	Extra-Tough Super-Cushioning Foam Polyethylene Sheet, 24" x 24" x 1/2"	8885K21	1	Sheet	\$ 30.05	\$ -	\$ 30.05	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/8885K21/									
EML4501-039	ABS Sheet, 12" x 12" x 1/8"	8586K161	1	Sheet	\$ 10.21	\$ -	\$ 10.21	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/8586K161/									
EML4501-041	Polished Multipurpose 304 Stainless	89615K51	6	Sheet	\$ 39.42	\$ -	\$ 39.42	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/89615K51/									
EML4501-042	Low-Carbon Steel Sheet 12"x12"x0.120"	6544K65	1	sheet	\$ 24.62	\$ -	\$ 24.62	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/6544K65/									
EML4501-043/-044/-046/-047/-048	Multipurpose 6061 Aluminum Foil 0.10" thick	2677N2	1	25'	\$ 252.96	\$ -	\$ 252.96	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/2677N2/									
EML4501-045	Multipurpose 304 Stainless Steel Sheet	8963K66	1	each	\$ 79.74	\$ -	\$ 79.74	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/8963K66/									
EML4501-049	0.125" 3003-H14 Sheetmetal, 2x4 sq.ft		1	Panel	\$ 133.24	\$ -	\$ 133.24	MetalsDepot	4200 Revilo Road	Winchester, KY 40391	(859) 745-2650	
		Web Site:	https://www.metalsdepot.com/aluminum-products/aluminum-sheet									
EML4501-050	Polypropylene Bar Stock, 1/2" Thick, 4" Wide		2	Fl.	\$ 8.47	\$ -	\$ 16.94	Kmac Plastics	3821 Clay Ave. SW	Wyoming, Michigan 49548	(616) 406-0671	
		Web Site:	http://www.kmac-plastics.com/polypropylene-square-rectangular-bar-stock.htm									
EML4501-051/-052	0.125" 3003-H14 Sheetmetal, 1x2 sq.ft		2	Panel	\$ 37.06	\$ -	\$ 74.12	MetalsDepot	4200 Revilo Road	Winchester, KY 40391	(859) 745-2650	
		Web Site:	https://www.metalsdepot.com/aluminum-products/aluminum-sheet									
EML4501-053	Rectangular Plastic Tank, 2 1/2 Gallon	4439T31	1	Each	\$ 48.49	\$ -	\$ 48.49	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/4439T31/									
EML4501-054/-055/-056	Multipurpose 6061 Aluminum, 1/8" Thick x 2-1/2" Wide	8975K532	1	Length	\$ 1.84	\$ -	\$ 1.84	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/8975K532/									
EML4501-063/-064/-065	ABS Panel - BULK 0.250/72x96/HI/ABS		2	Panel	\$ 204.00	\$ -	\$ 408.00	A&C Plastics Inc.	6135 Northdale	Houston, TX 77087	(888) 702-6028	
		Web Site:	https://www.acplasticsinc.com/products/063-250-72x96-hi-065									
EML4501-068/-067/-069/-070	8.9 oz S FiberGlass - Satin Weave	6761	9	yds.	\$ 14.35	\$ -	\$ 129.15	US Composites	6670 White Drive	West Palm Beach, FL 33407	(561) 588-1001	
		Web Site:	http://www.uscomposites.com/cloth.html									
EML4501-071	6" L x 1/2" W x 2" H 6061 T6 Aluminum Alloy	8975K74	1	6"	\$ 6.71	\$ -	\$ 6.71	McMaster-Carr	P.O. Box 5370	Princeton, NJ 08543-5370	(609) 689-3000	
		Web Site:	https://www.mcmaster.com/8975K74/8975K903/									

Total \$9,645.47

Manufacturing and Assembly Costs

The overall manufacturing cost of the system was found to be \$834.78 for all machining operations required for the custom parts in the system. If we take the assembly time of the sanitation system as a basis, the total assembly will take approximately 1.5 hrs to build. With a wage of \$56.74 per hour, the assembly labor will cost \$85.11. Combining the purchase order, manufacturing costs, and labor costs, the total system will cost \$10,565.36.

VI. Conclusion

The main objective of this project was to create a new design for an autonomous micro bioreactor that successfully satisfied the customers' needs. Among other customer needs the autonomous unit had to include: well plate/ conical tube fluid handling; sample shakers; cell incubators; optical metabolic sensor and diagnostics; and operation support features such as environmental control and waste disposal.

This project specially focused in the Fluid Handling System which satisfactorily moves cultures suspended in liquid providing nutrients to the cells, as well as injecting and evacuating gases. This subsystem is key to the overall functioning of the bioreactor, and therefore, customer needs had to met accurately.

In addition, the whole engineering project could not exceed the given budget, had to fit into a lab benchtop and had to be automated. Dr. Clean not only stayed withing the given limits but also went beyond and included some revolutionary characteristics that make it different from any other bioreactor in the market.

This system will carry out an experiment from start to finish, being ready for the next experiment with little to no additional work to the user. The sanitation system incorporated in the bioreactor is able to safely dispose of culture materials and sanitize the equipment used, making the system ready for the next experiment. The well plates and conical tubes, still filled with cell culture media, are placed into a sanitation chamber that will cull the cell cultures and dispose of solid and liquid waste, leaving sanitized well plates and tubes for future use.

The overall manufacturing cost of the system was found to be \$834.78 for all machining operations required for the custom parts in the system. If we take the assembly time of the sanitation system as a basis, the total assembly will take approximately 1.5 hrs to build. With a wage of \$56.74 per hour, the assembly labor will cost \$85.11. Combining the purchase order, manufacturing costs, and labor costs, the total system will cost \$10,565.36.

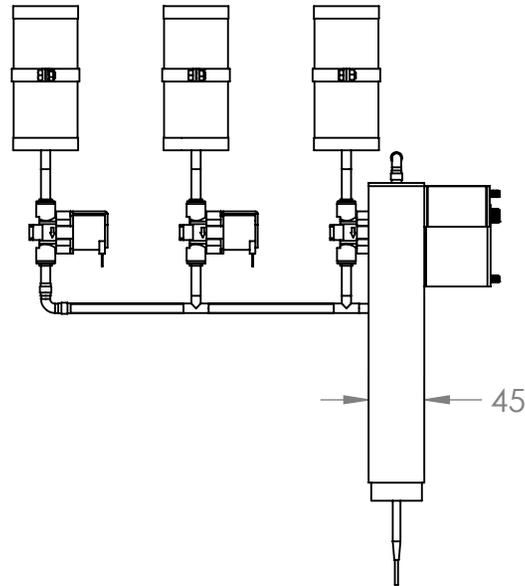
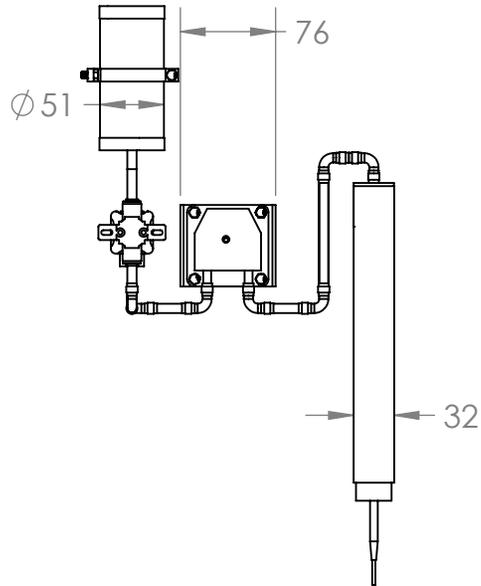
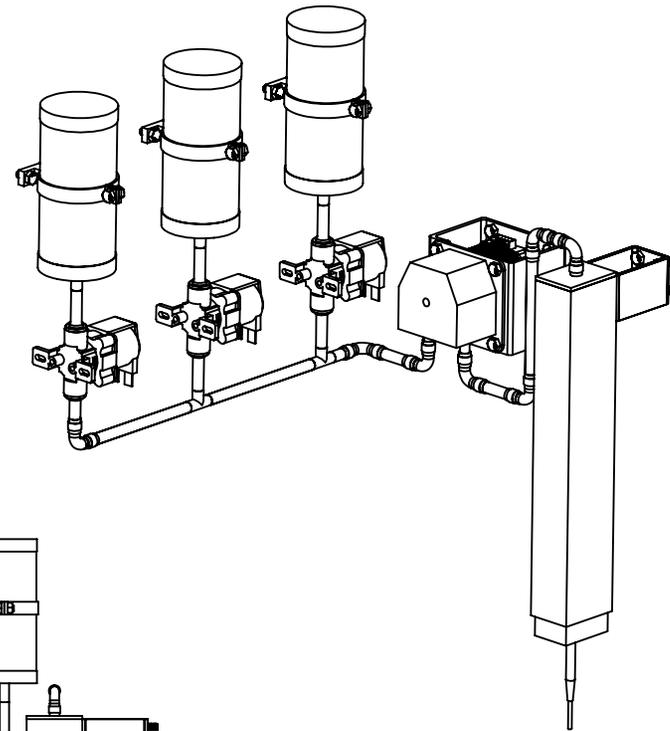
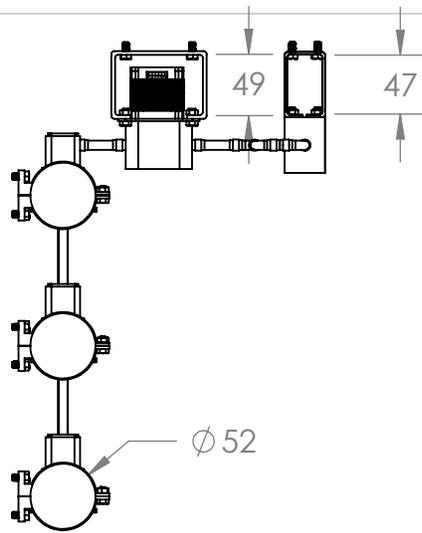
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VIII. Appendix A. Complete Part Drawings with Toleranced Dimensions

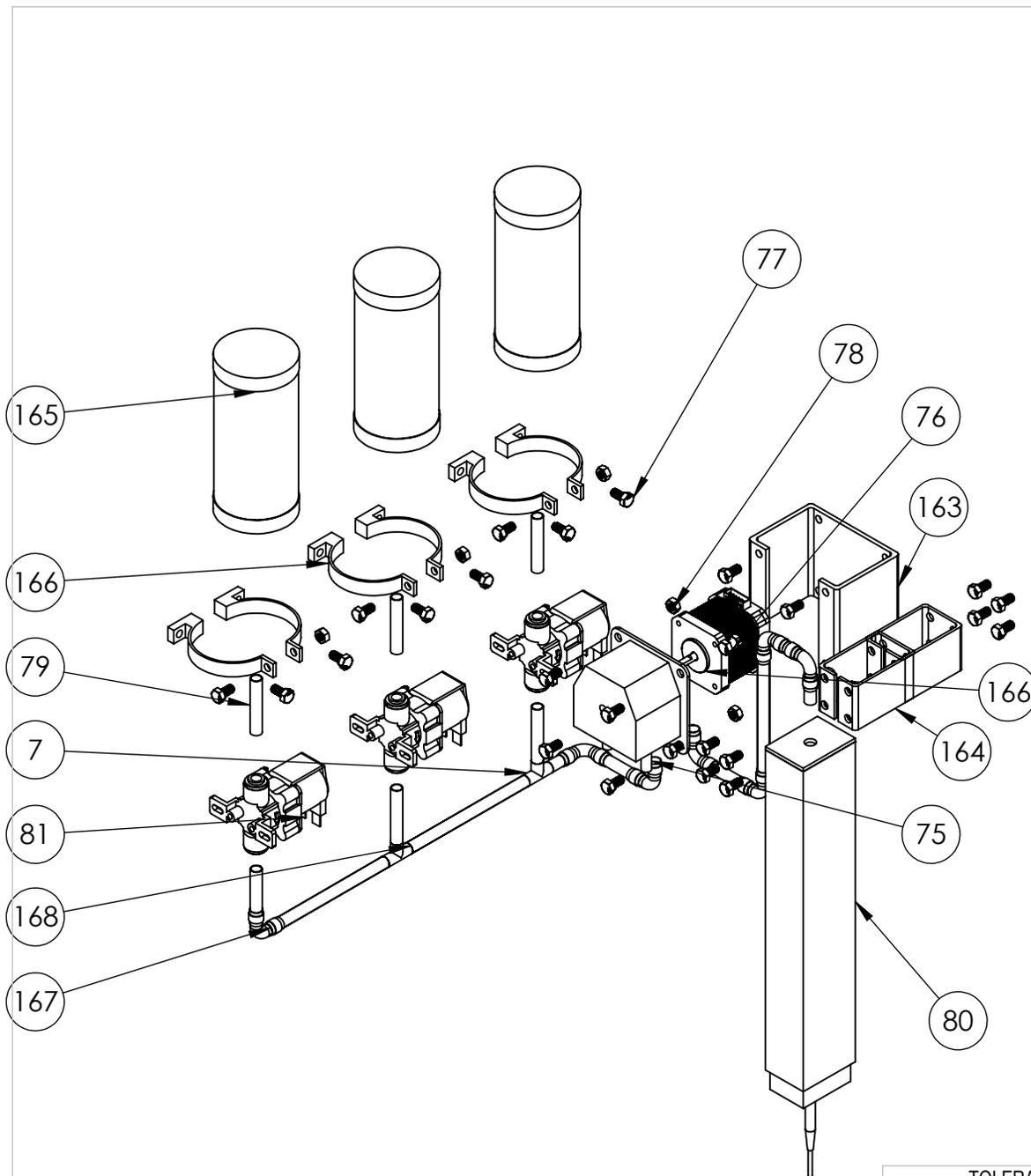
The assembly and manufactured part drawings for the system can be seen below.



NOTES:

1. _____
2. _____
3. _____
4. _____
5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Fluid Handling system ISOMETRIC		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-300	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:8		SHEET 1 OF 1



ITEM NUMBER	PART NUMBER	DESCRIPTION	QTY.
75	EML4501-OTS38	OEM Peristaltic Pump	1
76	EML4501-OTS39	Nema 17 Step Motor	1
77	EML4501-OTS40	M5X0.8 mm Thread Steel Hex Head	25
78	EML4501-OTS41	M5x0.8 mm hread Steel Hex Nut	11
79	EML4501-OTS42	PVC tube	1
80	EML4501-OTS43	KM8DC Dispensing Valve	1
81	EML4501-OTS44	Solenoid valve	3
163	EML4501-032	Pump Mount	1
164	EML4501-033	Fluid Dispenser Mount	1
165	EML4501-034	Deposit	3
166	EML4501-035	Deposit Mount	6
167	EML4501-036	1/4" Elbow	7
168	EML4501-036	1/4" triple connector	2

NOTES:

1. _____
2. _____

TITLE:
Fluid Handling system Assembly BOM

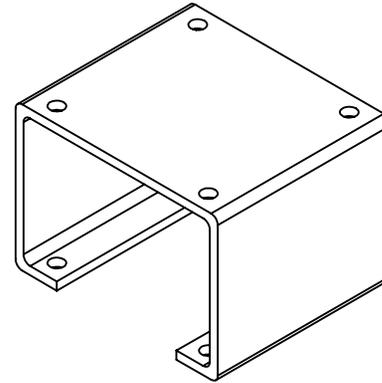
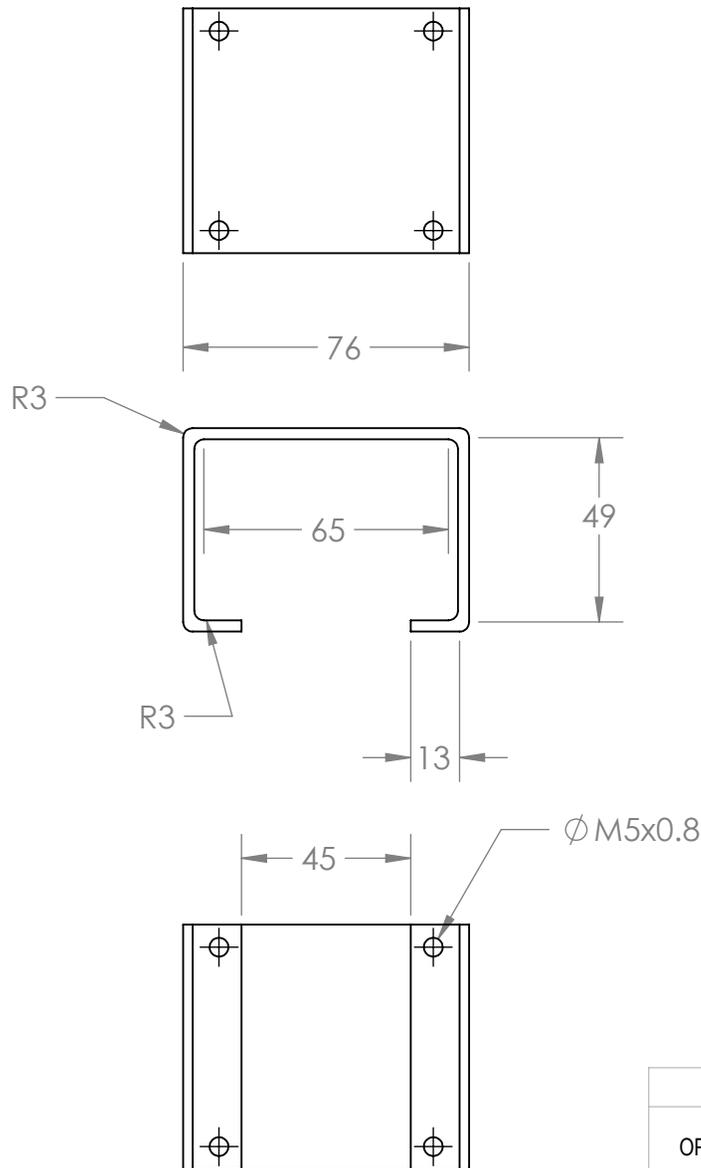
DRAWN IRATXE ASTIGARRAGA

DESIGNED IRATXE ASTIGARRAGA

SIZE	DWG. NO.	REV
A	EML4501-A-300	A

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

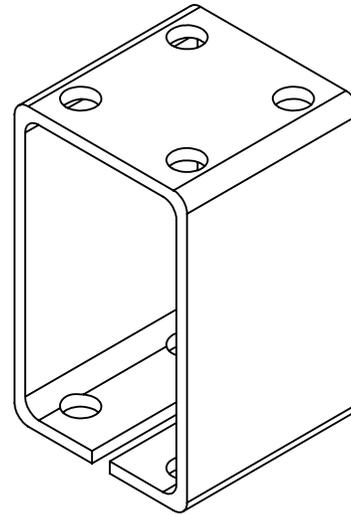
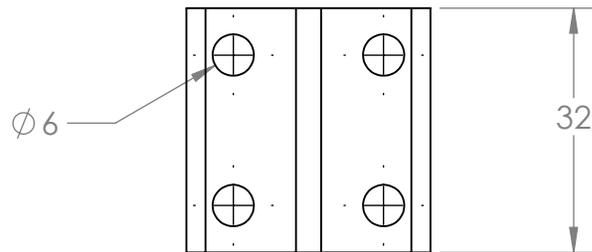
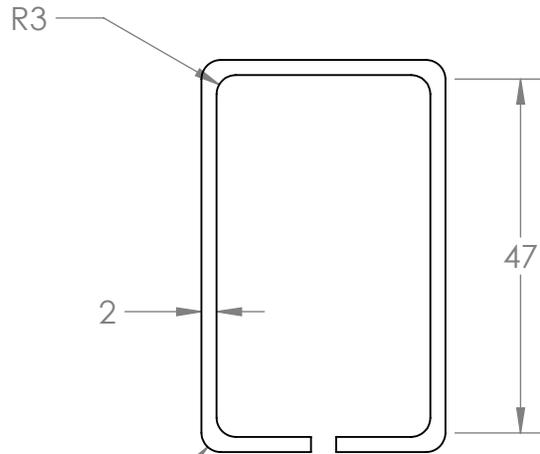
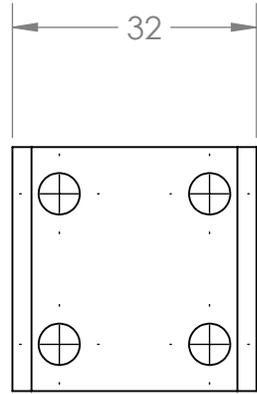
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NOTES:

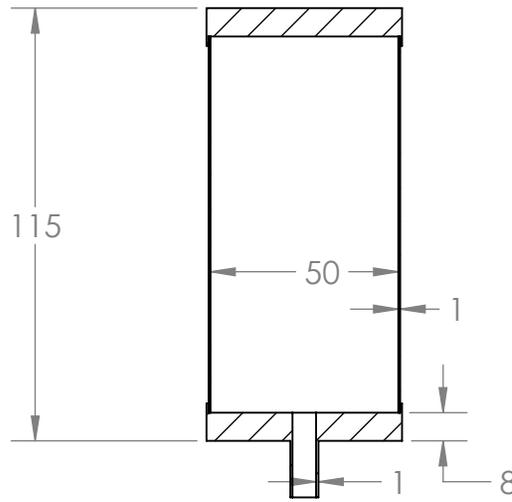
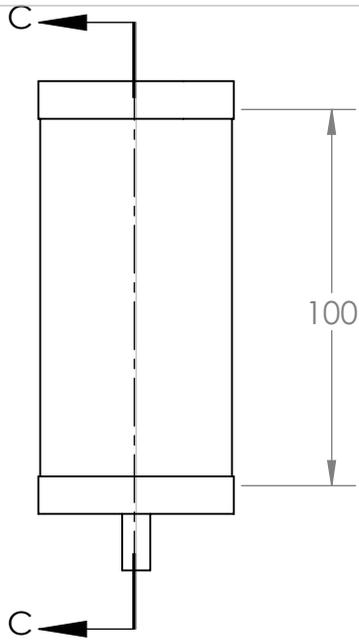
1. _____
2. _____
3. _____
4. _____
5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Pump Mount		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	± 0.050	± 0.020	± 0.005	DESIGNED	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	± 0.1	± 0.060		SIZE	DWG. NO.	REV
WELDING	± 0.1	± 0.060		A	EML4501-032	A
ANGULAR DIMS	± 5	± 2	± 0.5	SCALE: 1:2		SHEET 1 OF 1

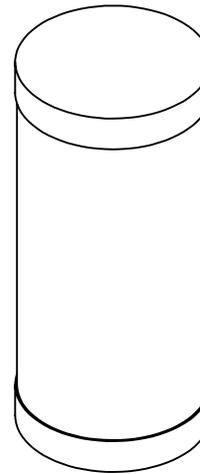
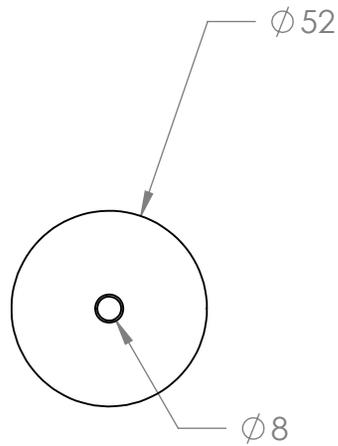


- NOTES:
1. _____
 2. _____
 3. _____
 4. _____
 5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Fluid Dispenser Mount		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-033	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:1		SHEET 1 OF 1



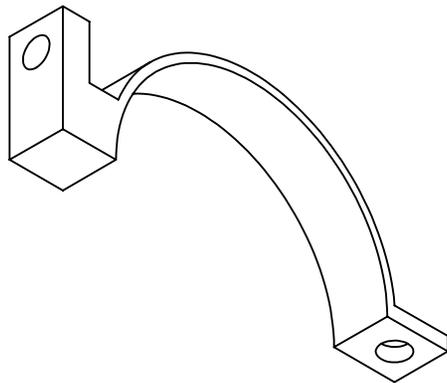
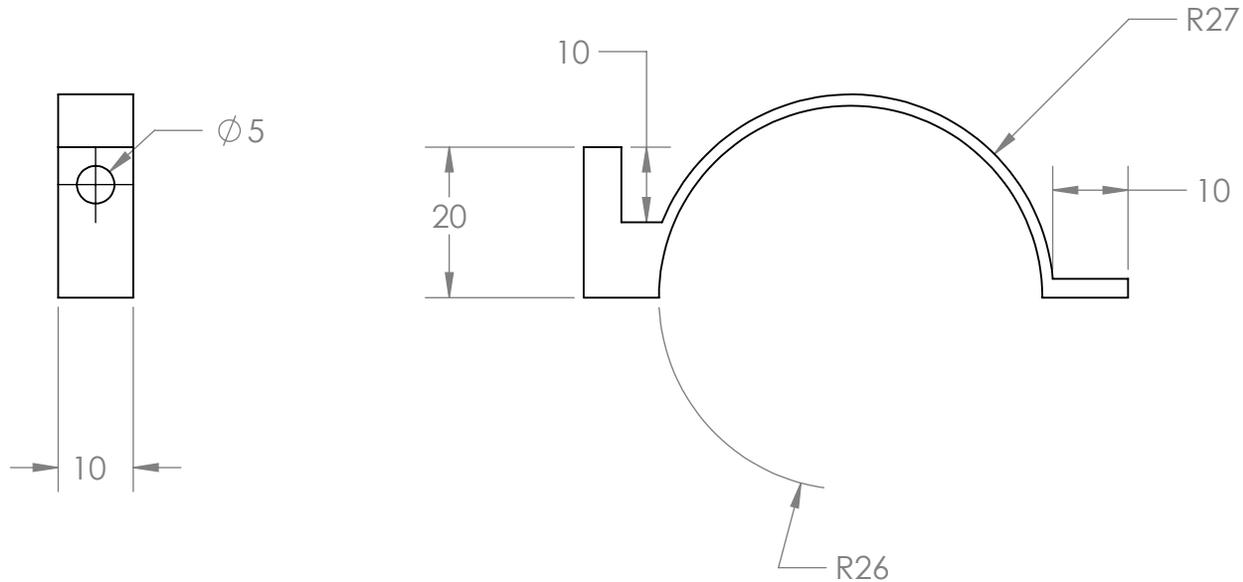
SECCIÓN C-C



NOTES:

1. _____
2. _____
3. _____
4. _____
5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Deposit		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	± 0.050	± 0.020	± 0.005	DESIGNED	IRATXE ASTIGARRAGA	
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: 1:2		SHEET 1 OF 1



NOTES:

1. _____
2. _____
3. _____
4. _____
5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Deposit Mount		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-035	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:1		SHEET 1 OF 1

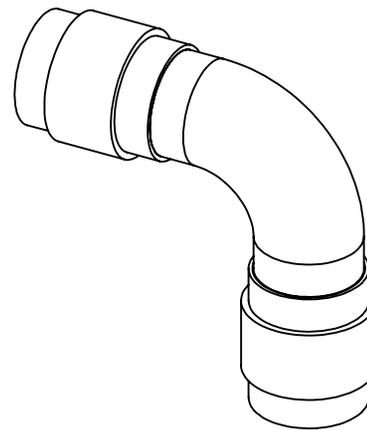
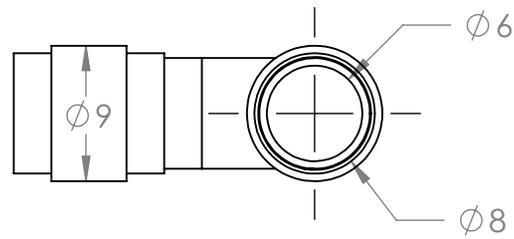
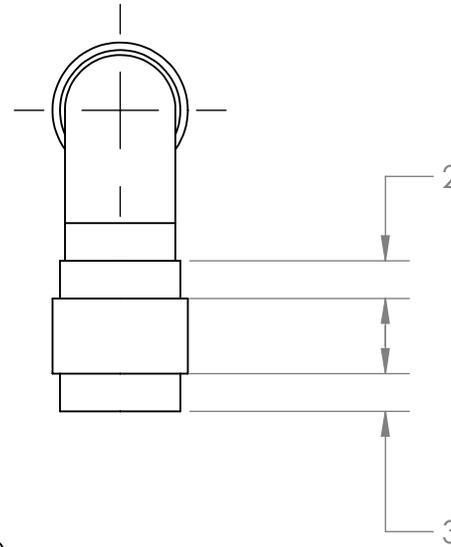
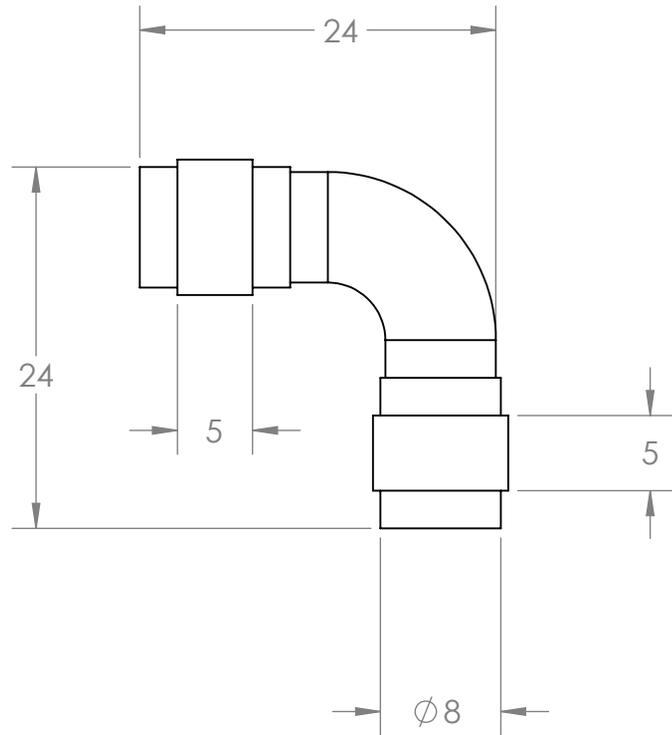
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4

3

2

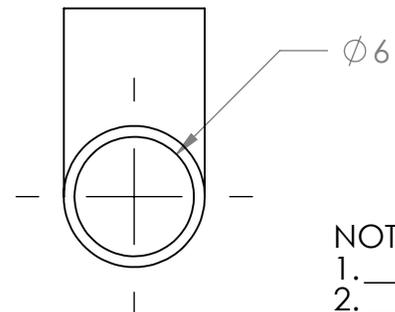
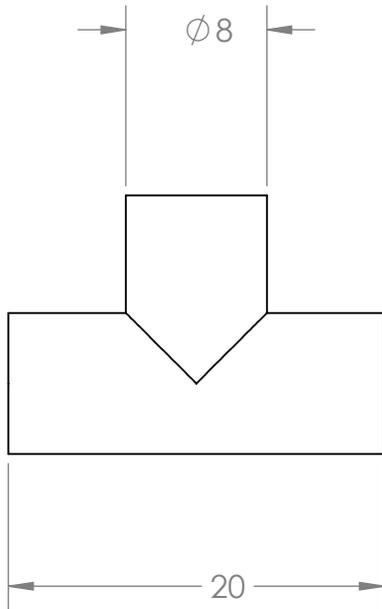
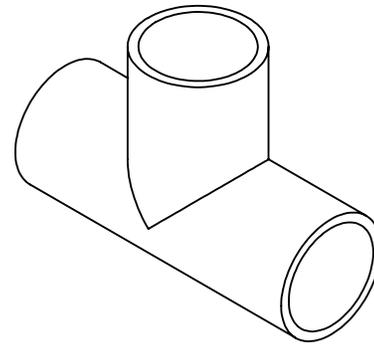
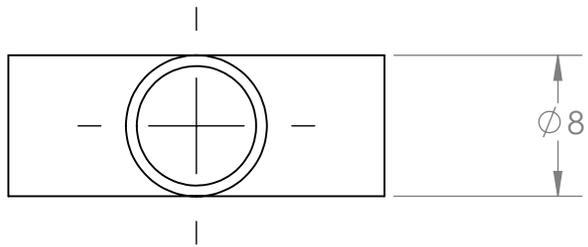
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NOTES:

1. _____
2. _____
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5. _____

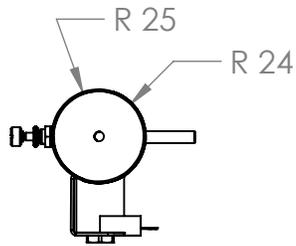
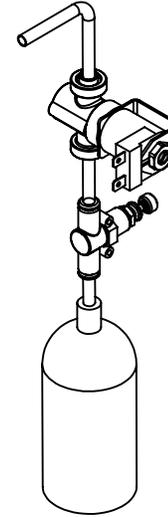
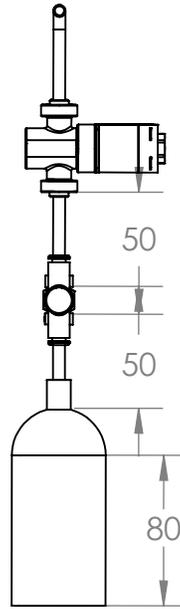
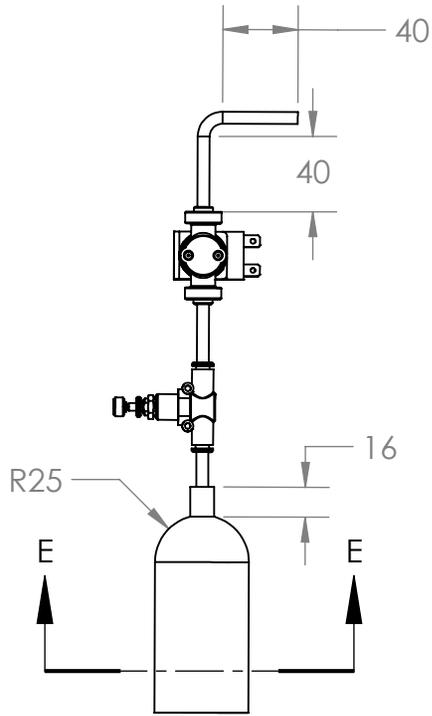
TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Elbow		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-036	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 2:1		SHEET 1 OF 1



NOTES:

1. _____
2. _____
3. _____
4. _____
5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Triple connector		
	0.0	0.00	0.000			
MACHINING	±0.050	±0.020	±0.005	DRAWN	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		DESIGNED	IRATXE ASTIGARRAGA	
WELDING	±0.1	±0.060		SIZE	DWG. NO.	REV
ANGULAR DIMS	±5	±2	±0.5	A	EML4501-037	A
				SCALE: 2:1	SHEET 1 OF 1	



SECTION E-E

NOTES:

1. _____
2. _____
3. _____
4. _____
5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Air Injection Assembly ISOMETRIC		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-304	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:4		SHEET 1 OF 1

5

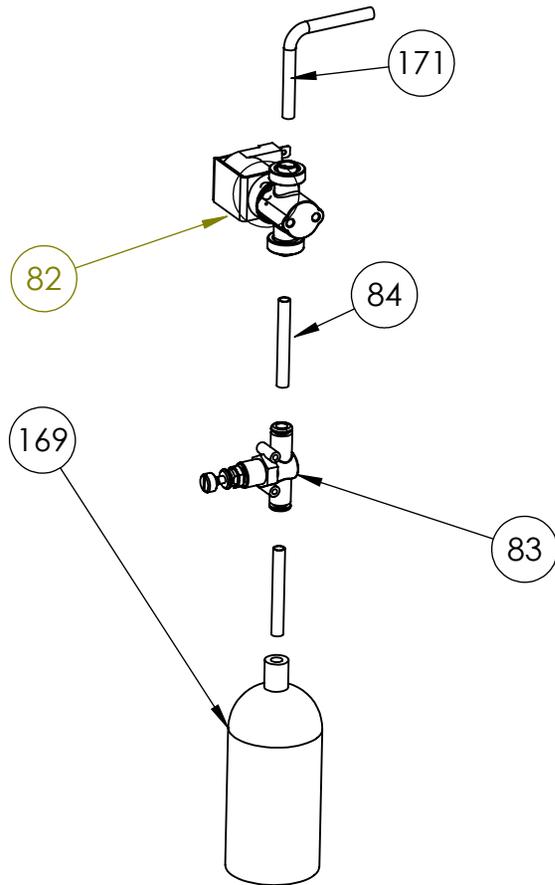
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1

ITEM NUMBER	PART NUMBER	DESCRIPTION	QTY.
82	EML4501-OTS45	Automatic Gas Solenoid Valve	5
83	EML4501-OTS46	Compressed Air Regulator	5
83	EML4501-OTS47	1/4" Rigid PVC tube	10
169	EML4501-038	Gas Tank	5
171	EML4501-040	Rigid PVC 1/4" curved tube	5

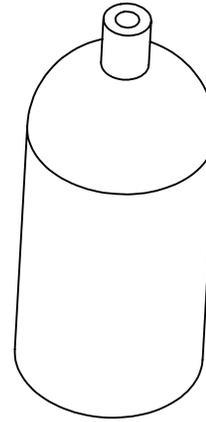
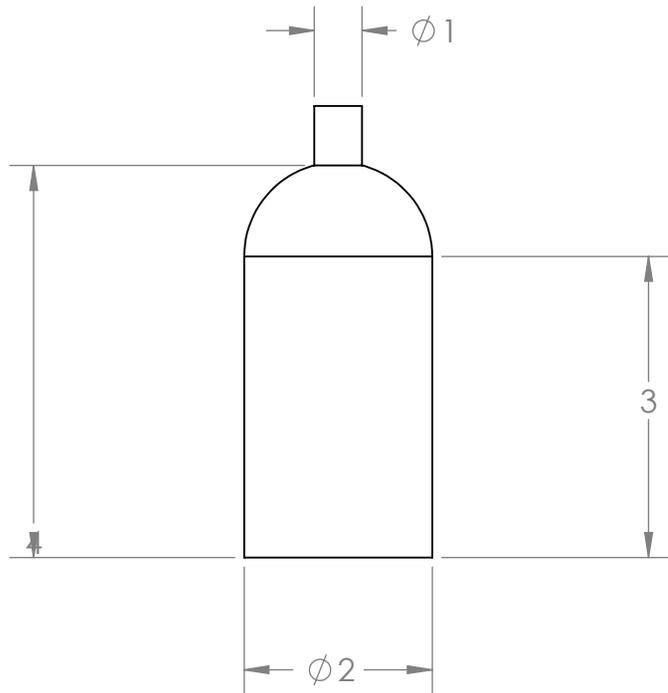
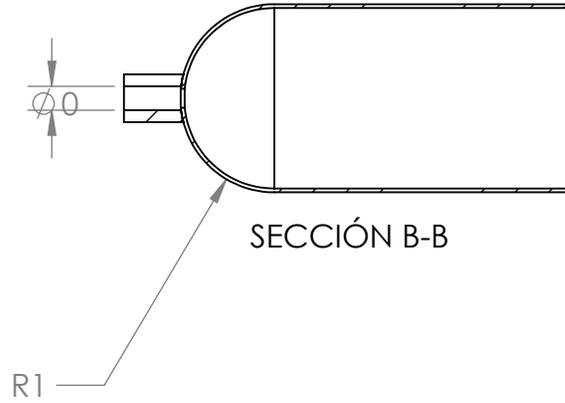
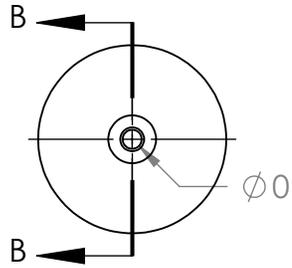


NOTES:

1. _____
2. _____

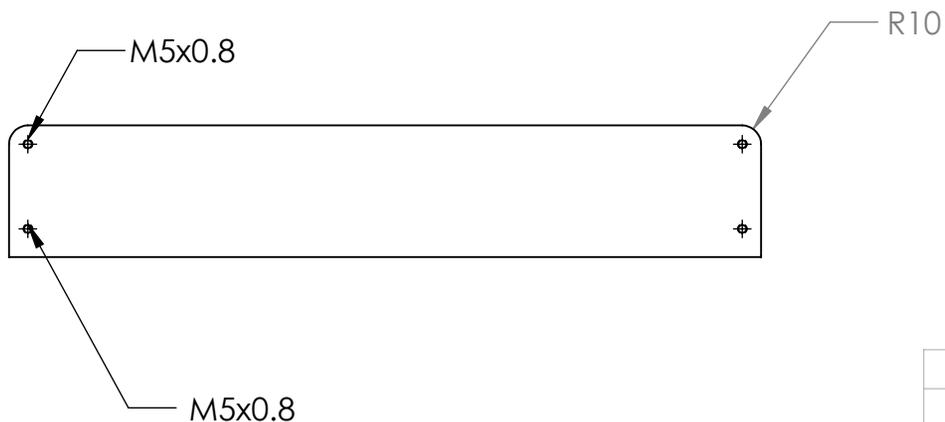
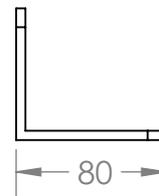
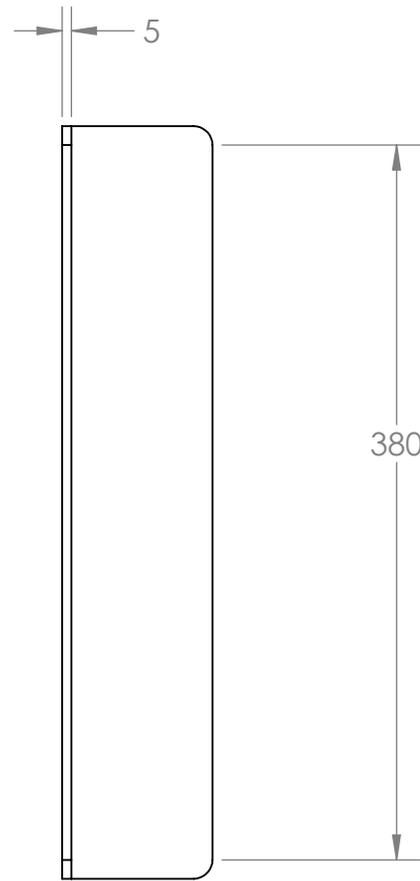
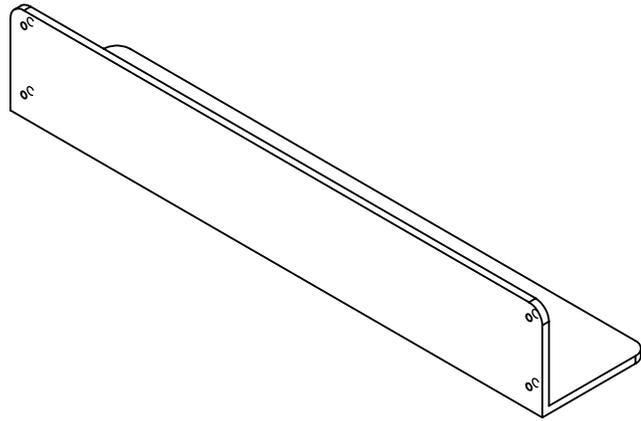
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DRAWN				IRATXE ASTIGARRAGA	
DESIGNED				IRATXE ASTIGARRAGA	
TOLERANCE UNLESS NOTED		SIZE	DWG. NO.		REV
DIMENSION TYPE	PLACES IN DIMENSION			A	EML4501-A-304
	0.0	0.00	0.000		
LOCATIONAL	±0.050	±0.020	±0.005		A
ANGULAR	±5	±2	±0.5	SCALE: 1:8	SHEET 1 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



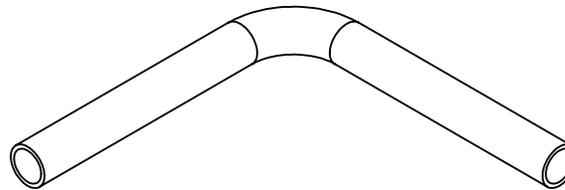
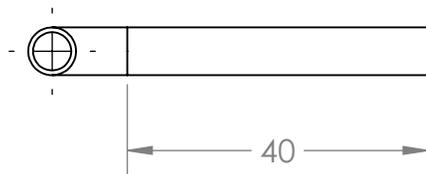
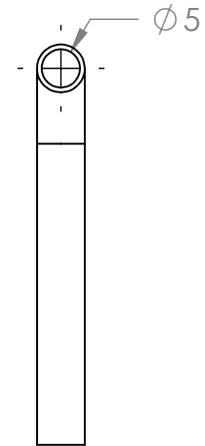
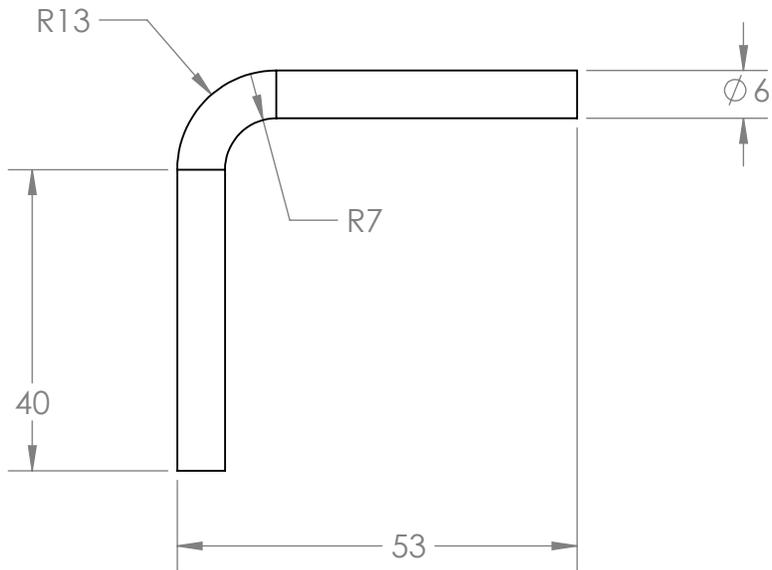
- NOTES:
1. _____
 2. _____
 3. _____
 4. _____
 5. _____

TOLERANCE UNLESS NOTED				TITLE: Gas Tank		
OPERATION	PLACES IN DIMENSION			DRAWN	IRATXE ASTIGARRAGA	
	0.0	0.00	0.000		DESIGNED	IRATXE ASTIGARRAGA
MACHINING	± 0.050	± 0.020	± 0.005	SIZE	DWG. NO.	REV
CUT OFF (SAW, BURN, SHEAR)	± 0.1	± 0.060	//	A	EML4501-038	A
WELDING	± 0.1	± 0.060	//			
ANGULAR DIMS	± 5	± 2	± 0.5	SCALE: 1:2	SHEET 1 OF 1	



- NOTES:
1. _____
 2. _____
 3. _____
 4. _____
 5. _____

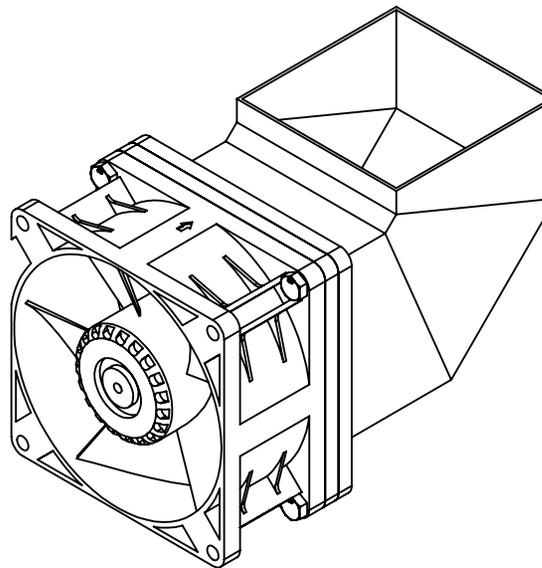
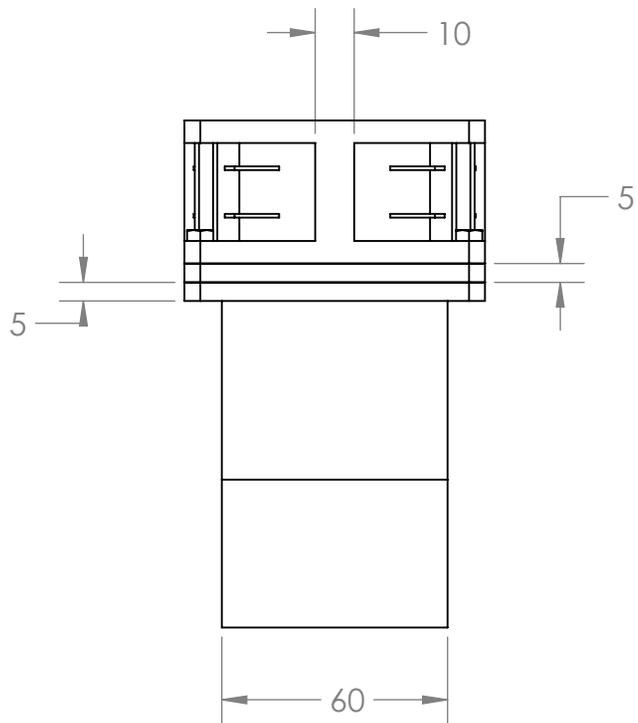
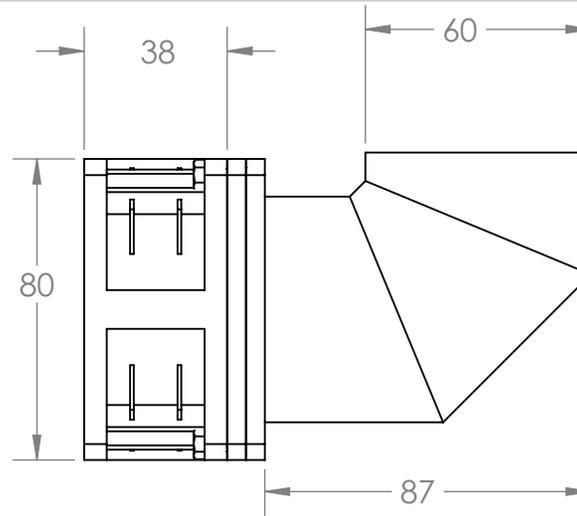
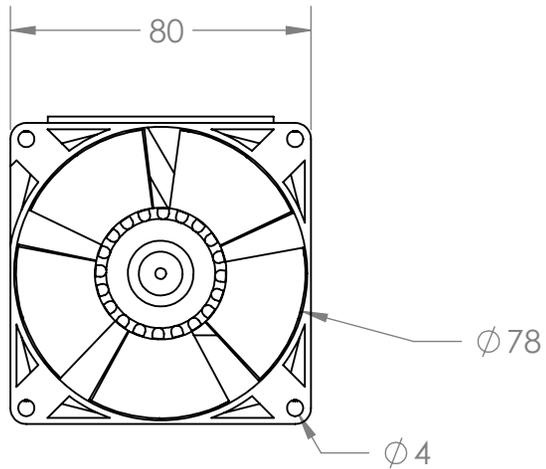
TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Air deposits mount		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-039	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:4		SHEET 1 OF 1



NOTES:

1. _____
2. _____
3. _____
4. _____
5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Rigid PVC curved tube		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-040	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:1		SHEET 1 OF 1

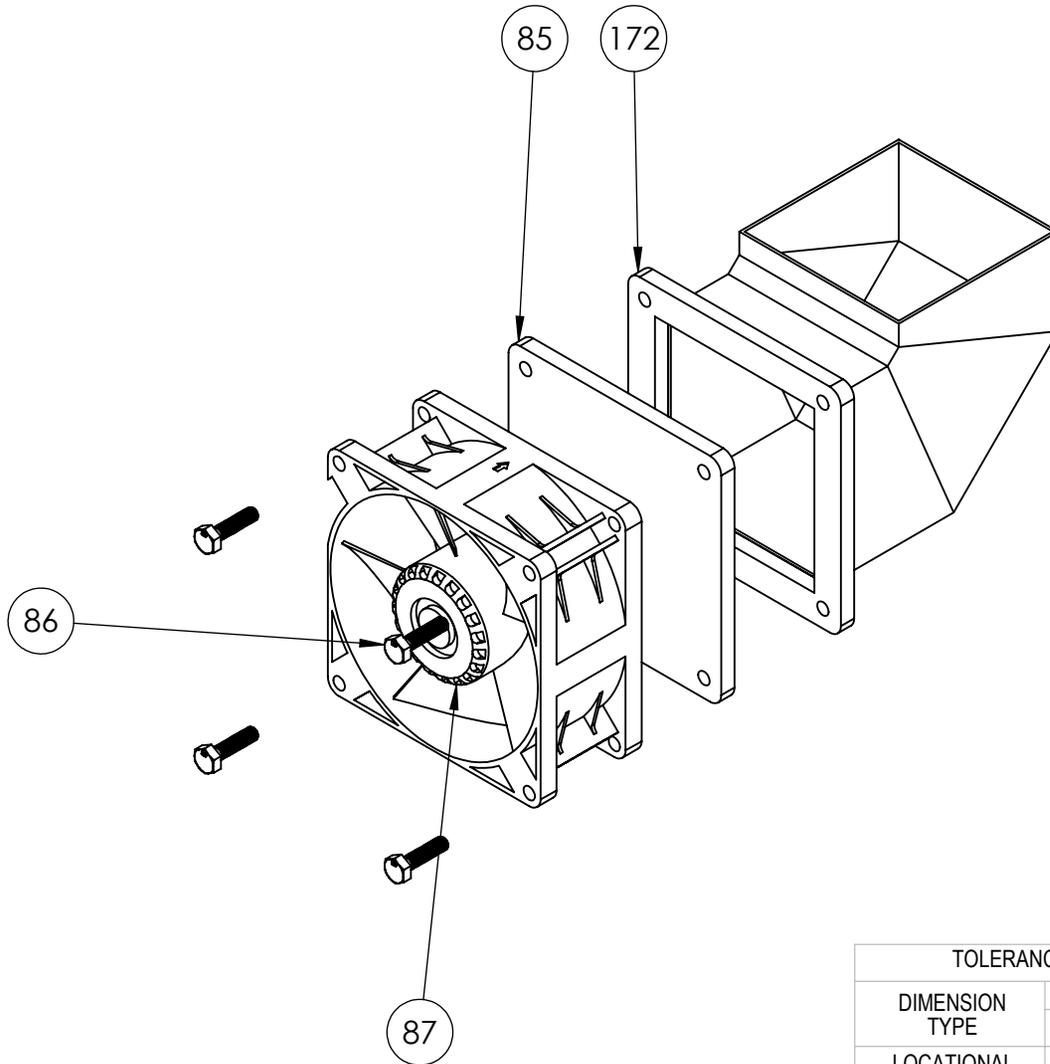


NOTES:

1. _____
2. _____
3. _____
4. _____
5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Air Evacuation Assembly ISOMETRIC		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	± 0.050	± 0.020	± 0.005	DESIGNED	IRATCE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	± 0.1	± 0.060	//	SIZE	DWG. NO.	REV
WELDING	± 0.1	± 0.060	//	A	EML4501-305	A
ANGULAR DIMS	± 5	± 2	± 0.5	SCALE: 1:4		SHEET 1 OF 1

ITEM NUMBER	PART NUMBER	DESCRIPTION	QTY.
85	EML4501-OTS48	Mildew-Resistant Reusable Air Filter	1
86	EML4501-OTS49	M4x16mm Hex Screw	4
87	EML4501-OTS50	Exit pipeLow Voltage Equipment Cooling Fan	1
172	EML4501-041	Exit pipe	1



NOTES:

1. _____
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TITLE:
Air Evacuation Assembly BOM

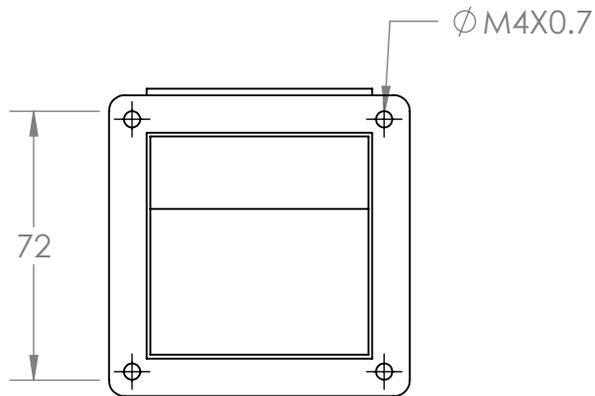
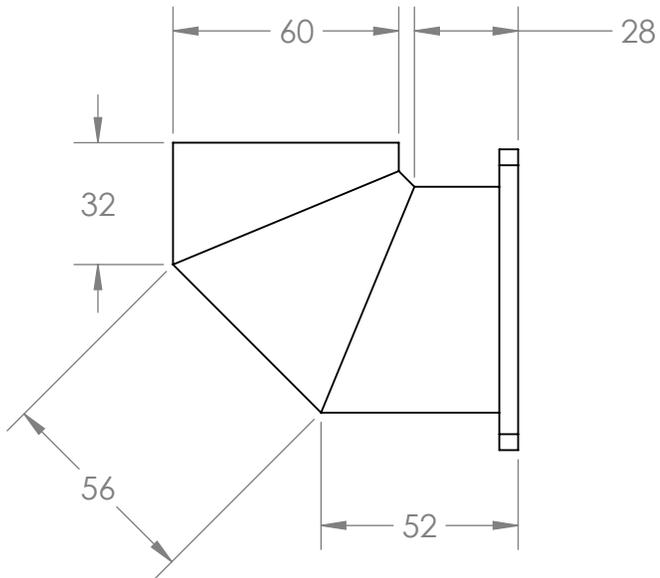
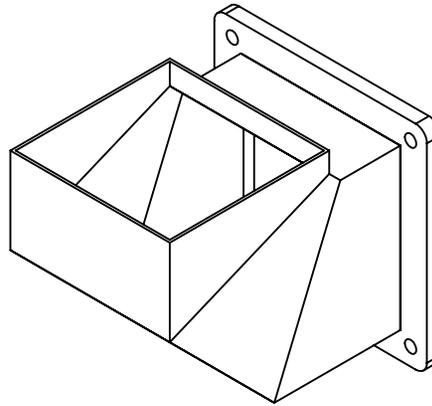
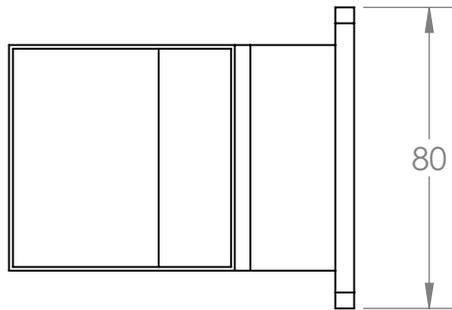
DRAWN IRATXE ASTIGARRAGA

DESIGNED IRATXE ASTIGARRAGA

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-305	A

SCALE: 1:4 SHEET 1 OF 1



NOTES:

1. _____
2. _____
3. _____
4. _____
5. _____

TOLERANCE UNLESS NOTED				TITLE:		
OPERATION	PLACES IN DIMENSION			Exit pipe		
	0.0	0.00	0.000	DRAWN	IRATXE ASTIGARRAGA	
MACHINING	±0.050	±0.020	±0.005	DESIGNED	IRATXE ASTIGARRAGA	
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060		SIZE	DWG. NO.	REV
WELDING	±0.1	±0.060		A	EML4501-041	A
ANGULAR DIMS	±5	±2	±0.5	SCALE: 1:2		SHEET 1 OF 1

5

4

3

2

1

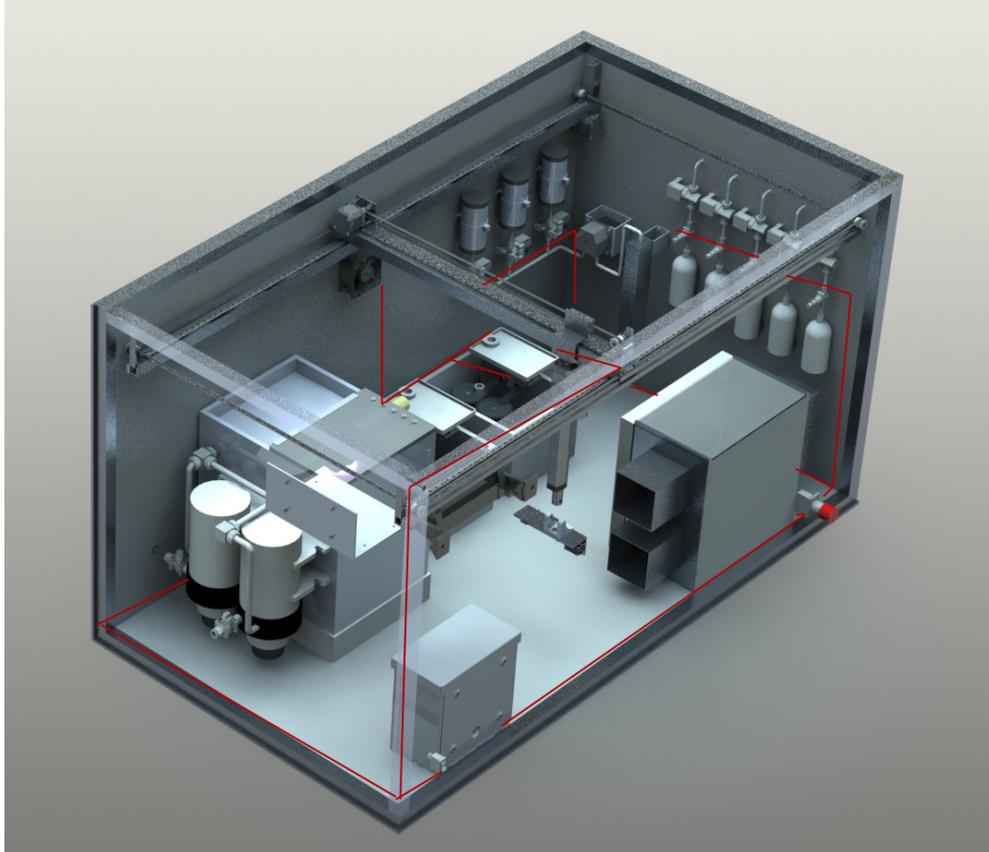
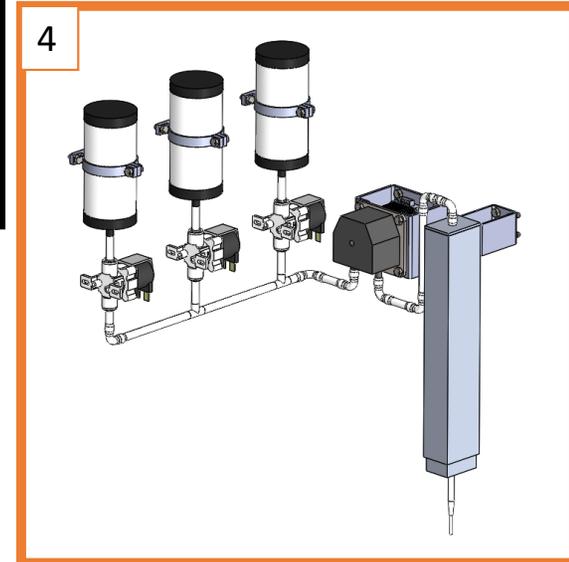
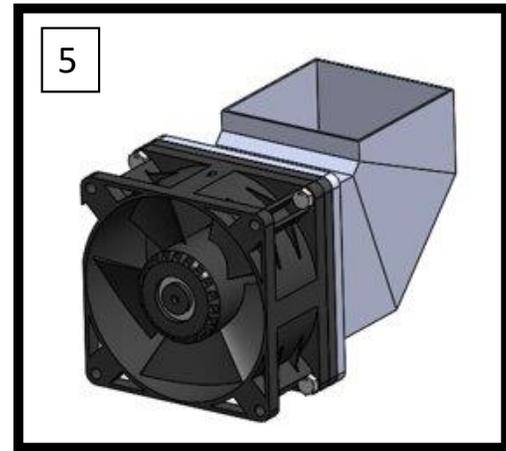
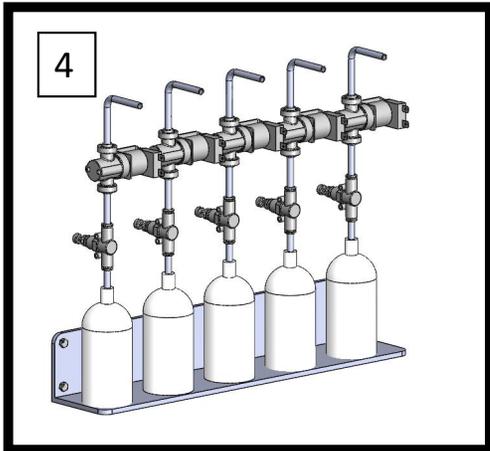
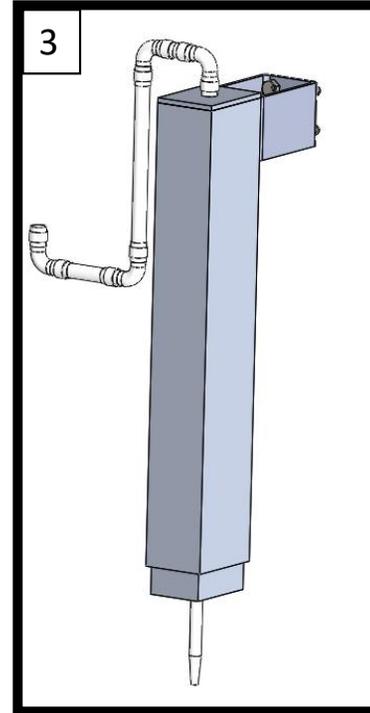
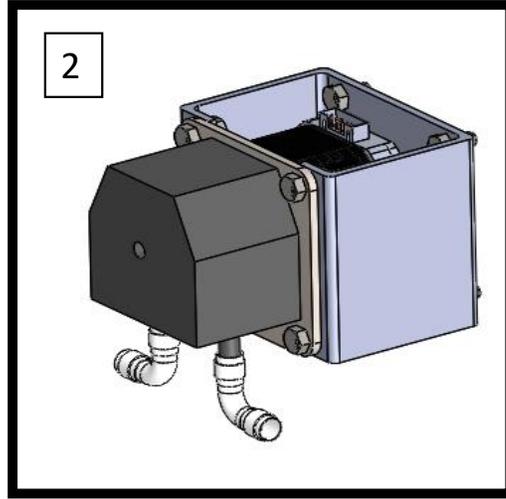
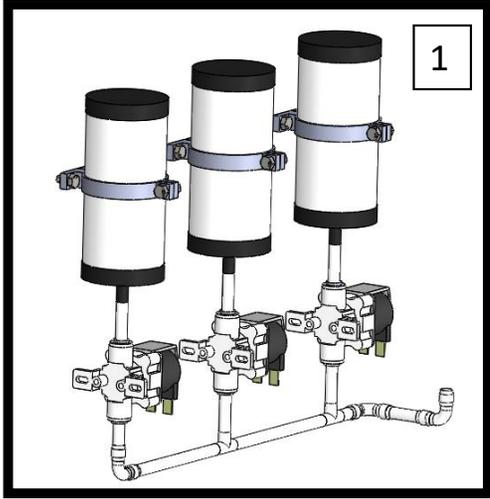
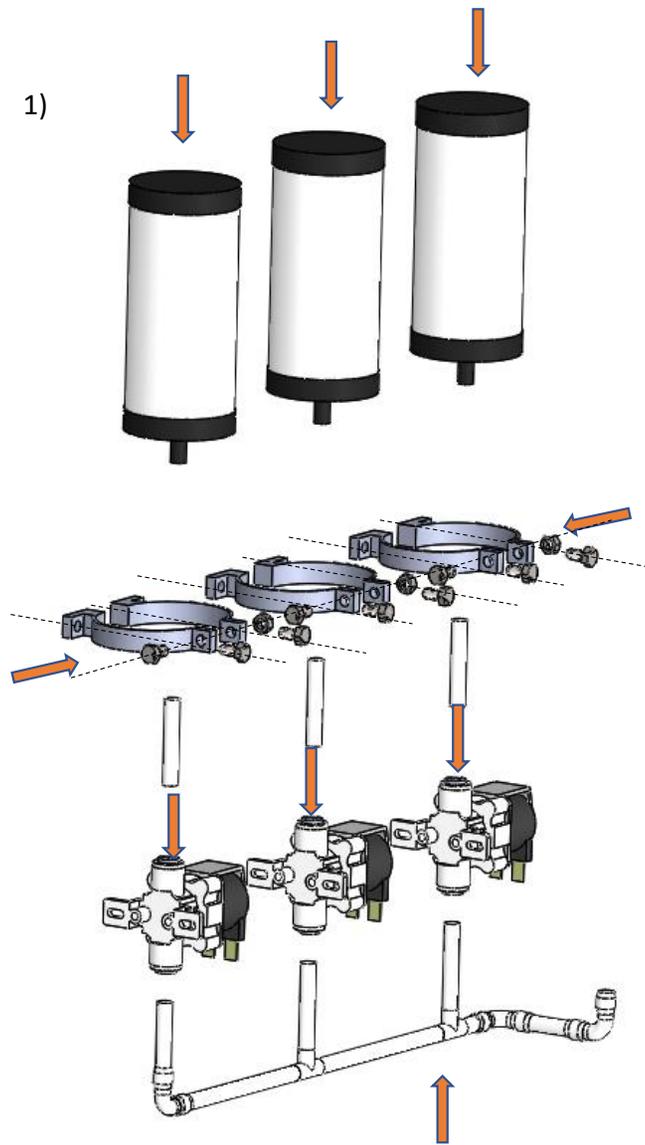
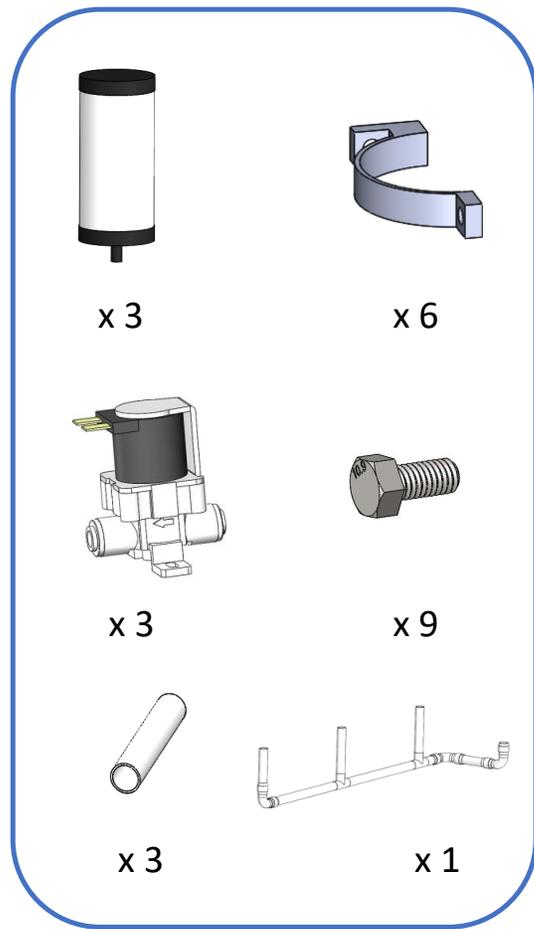
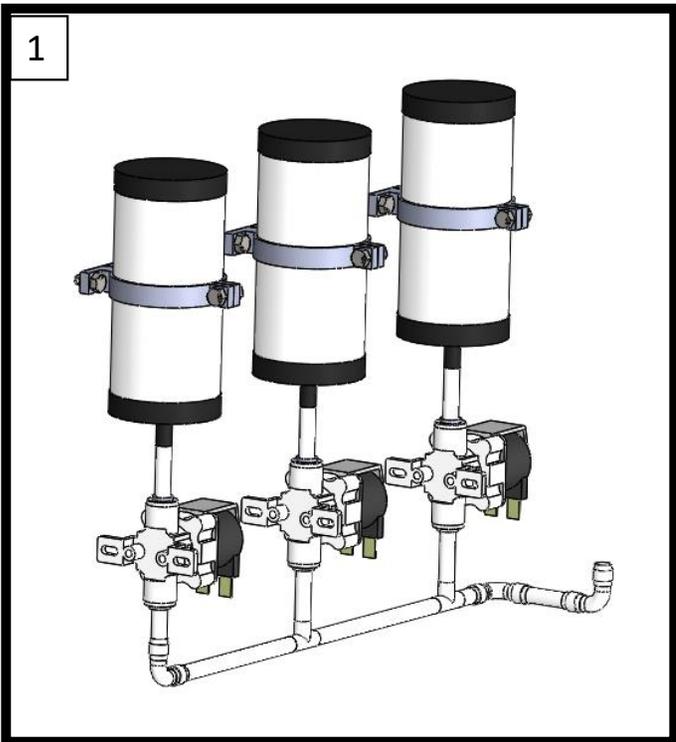


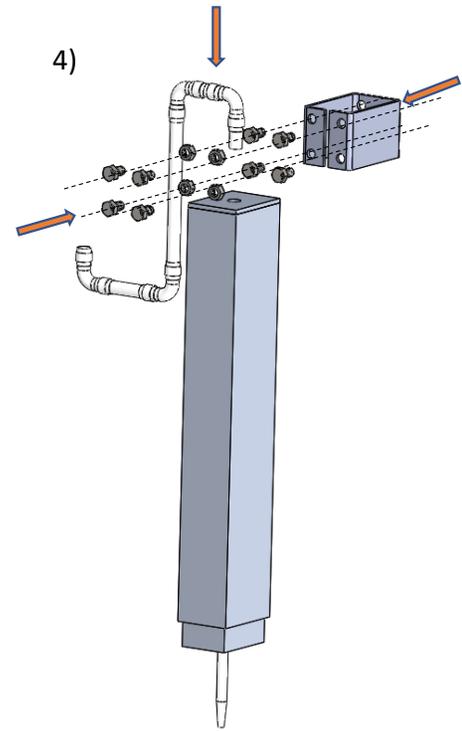
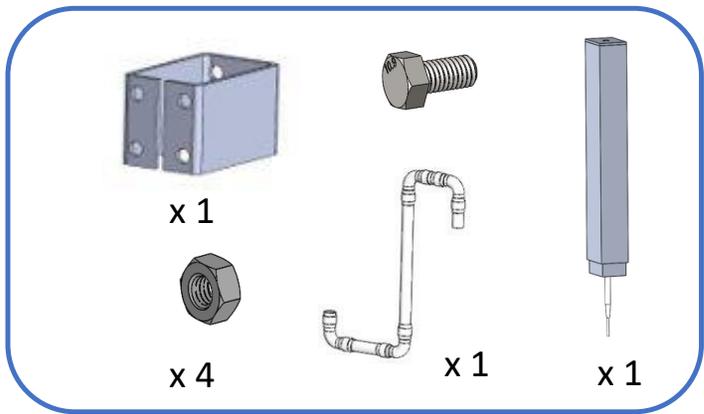
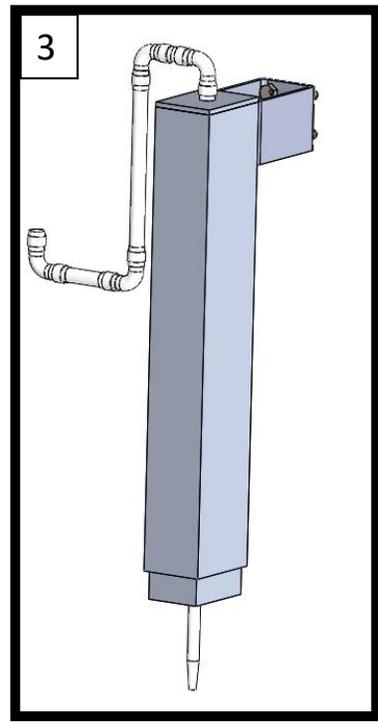
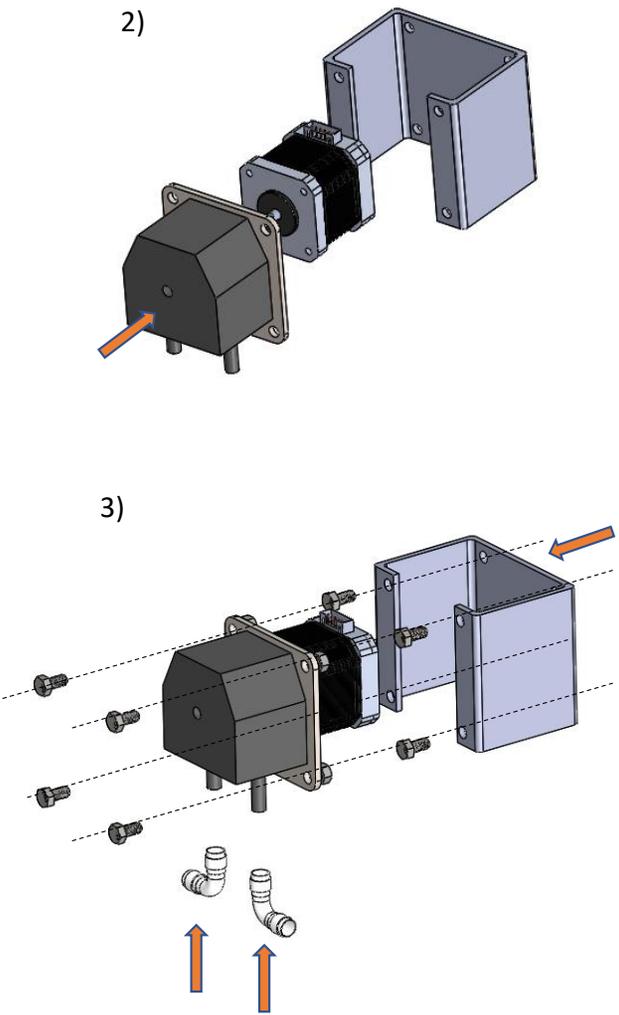
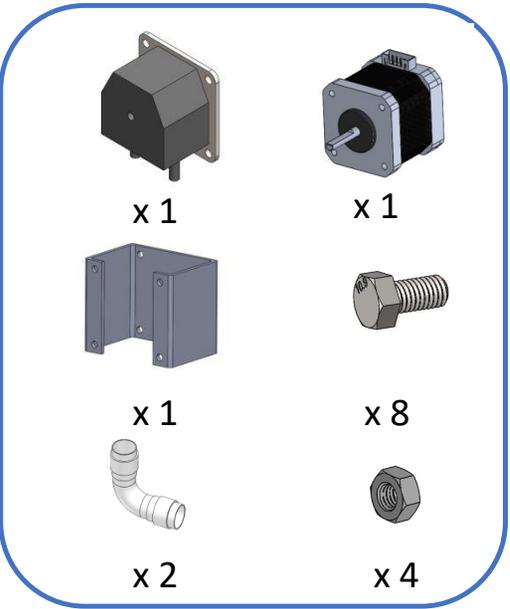
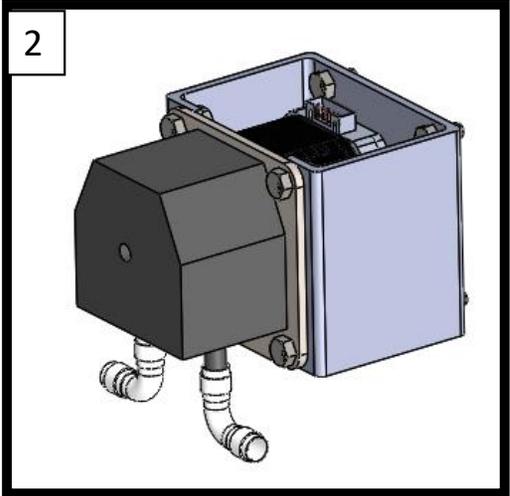
Fig. 43 System Wiring Locations

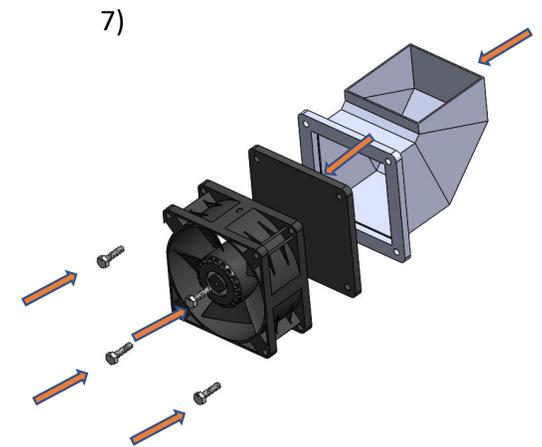
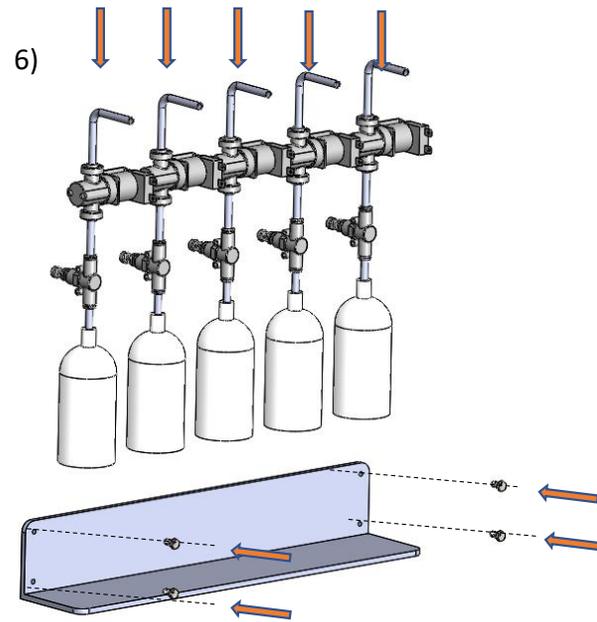
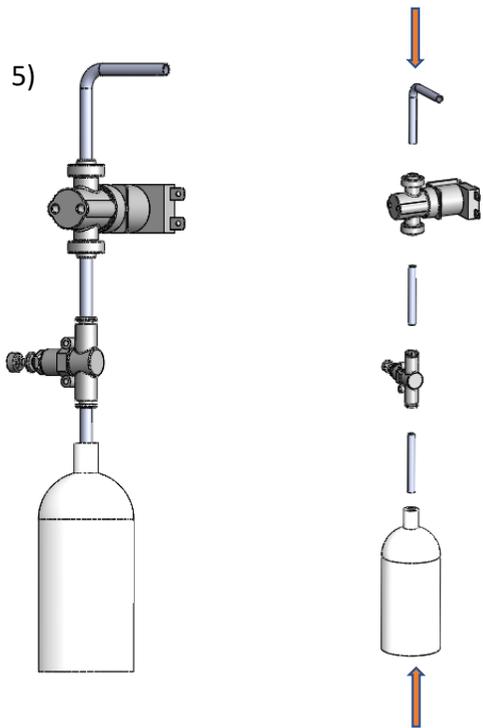
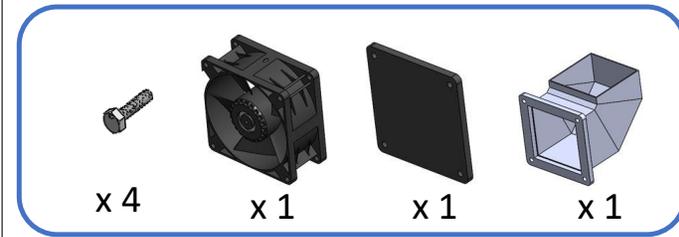
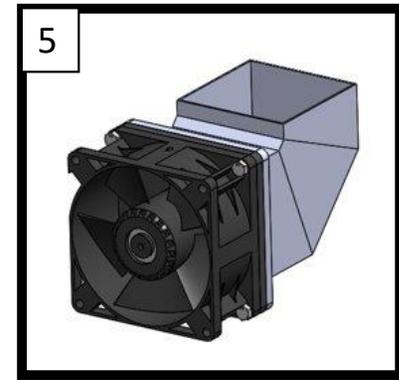
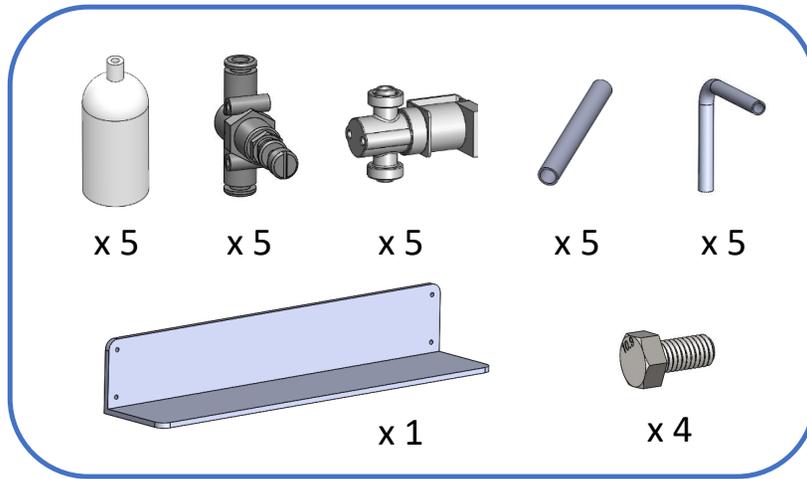
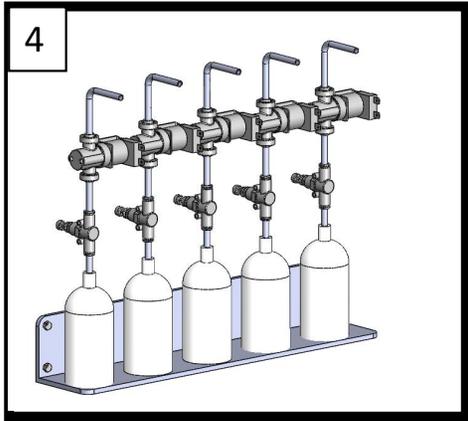
IX. Appendix B. Manual Assembly Plan

The instructions for assembling the system can be found below, as well as manual handling and insertion times for all assembly steps for the sanitation system and controls using Boothroyd and Dewhurst Insertion and Handling Charts. If we take the sanitation system as a basis, the total assembly will take approximately 1.5 hrs to build. With a wage of 56.74 USD per hour, the assembly labor will cost \$85.11.









X. Appendix D. SDG

This project has been done taking into account the 17 objectives of substantial development growth. Among all of them, the Autonomous Benchtop Microbioreactor specially contributes to the numbers 9 and 12 which correspond to Industry, Innovation and Infrastructure and Responsible Consumption and Production.

The Sustainable Development Goals (SDGs) are a collection of 17 global goals designed to be a blueprint to achieve a better and more sustainable future for all. As citizens, we should all try to contribute to these goals with the objective of building up a better world. SDGs can be related to the biosphere, society or economy, although all of them work in conjunction with one another. The project I am doing, which is the design of a bioreactor with specific characteristics, contributes mostly in the economic dimension. Since the bioreactor will be used for research, this project is therefore related to innovation, as well as production.

- SDG 9: Industry, innovation and infrastructure. The UF course Mechanical Engineering Design 2 is sponsored by some companies and the UF University as well. Money is invested every year to be able to carry out these kind of projects. They are important industrial companies that drive scientific Research, promote innovation and therefore, contribute to economy.
- SDG 12: Ensure responsible consumption and production. The UF Biofoundry is concerned about the management of waste and chemicals; actually, one of the Customer needs was related to sanitation and waste removal. Additionally, the design had to be suitable to work in a BLS 2 environment. Dr. Clean Bioreactor goes beyond the initial requirements set by the client and incorporates a special system for sterilization and waste removal, alongside with a system of gas filtering that follows international frameworks. At the same time, since the bioreactor has been designed for culturing E-coli for research, which is a bacteria found in the stomach and very important to avoid some diseases, Dr. Clean is also contributing to human health.
- SDG 3: Good Health and well-being. As explained in the previous paragraph, due to the nature of the agent being cultured in the micro bioreactor, Dr. Clean is contributing to reduce the number of deaths and illnesses.

When studying the impact of the Dr. Clean bioreactor in the 17 SDGs, I would say the most relevant contribution is in terms of contamination. With the revolutionary sanitation system the user prevents the cultures from going down the sink which can have fatal consequences depending on the type of culture. The air evacuation system also plays a very important role with filters the gases prior to being expelled to the outside. Thanks to this mechanism the air in the outside is completely free of any kind of toxic agents, contributing to the wellbeing of the environment.