NORTHERN ARIZONA UNIVERSITY

To: W.L. Gore & Associates, Inc.

From: Northern Arizona University Capstone Engineering Team

Subject: Portable Sanitization Chamber Project Proposal

Date: Wednesday, December 11, 2013

This document contains the project proposal for the portable sanitization chamber. The final design of a dual process hydrogen peroxide fogging and ultraviolet light system has been chosen. The attached document includes all research, concept generations, engineering analysis and our final design.

The final chosen design fits the cost constraint, including costs for research, materials, prototype and testing. The total cost of materials for the final design is approximately $1155.00. Additional costs for manufacturing bring the total estimated prototype cost to $1400.00, which is well under the cost constraint of $3000. Please note that additional material and or manufacturing costs may arise during our prototype testing phase.

If you have any questions or comments regarding the final design, costs, or anything contained within this document please contact our team via email.

Thank you.

Portable Sanitization Chamber

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Project Proposal

Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design I – Fall 2013

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Nomenclature

P = total output power of UVC radiation
A = area of projected light
I = intensity – power per area of UVC radiation
D = dosage – time of intensity
t(s) = time in seconds

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Executive Summary

Medical and food industries adhere to sanitary guidelines by exposing their devices and equipment to sanitation processes. Contemporary methods involve procedures that run long cycle times, needs excess user labor, are incompatible with fragile or complex materials, or exist in only large scale application. With these various methods having only specific applications, W.L. Gore & Associates, Inc. asks for a device that can work within any spectrum of operating environments. The design in question would be required to operate in the medical or industry setting while being inherently portable and sanitize various materials contaminated with *Bacillus atrophaeus* by inactivating one log unit of the initial specimen.

Sufficient research on the current state of sanitizing methods is measured by examining modern hospitals and research laboratories as examples, as well as any research currently testing the feasibility of new sanitizing processes. These resources provide a selection of methods that have the greatest potential to be incorporates for this case. Select methods that stand out are: dry heat autoclaves, chemical processing with hydrogen peroxide, electron beam sterilization, exposure to infrared wavelengths, and exposure to various ultraviolet wavelengths. Initial concepts can be created given conclusions drawn from the current state of the art research in sanitizing methods.

A detailed list of design specifications is generated by weighting the importance of each objective derived from the initial problem statement. Each concept is assessed based on the design requirements and verified as valid or invalid for integration for this application. Autoclave and infrared heat poses an issue when dealing with heat-sensitive materials, while electron beam devices exceed the budget limit and cannot be scaled for this smaller application. With feasible concepts at hand, engineering assessments are conducted. These evaluations result in any possible stress points, excess heat transfer, dangerous flow, or essentially any safety or functionality concern that requires design focus.

Shown through the analysis, one contender that proves to be most favorable is a contained chamber that executes a hydrogen peroxide vapor spray supplemented by ultraviolet germicidal irradiation (UVGI). The total cost of production is calculated for developing such a prototype. A detailed 3D model displays the physical characteristics of the proposed design.

Chapter 1. Problem Formulation and Project Plan

1.0 Introduction

The problem in question is assessed in the following sections. Based on information given by the client, the project goal, objectives, constraints, and working environments are developed. Research in the field of interest is conducted and a Quality Function Deployment (QFD) chart is generated.

1.1 Client Introduction

W. L. Gore & Associates, Inc. design products to be the highest quality in their class and revolutionary in their effect. Associates address technical challenges with innovative, reliable solutions and the organization seeks growth by unleashing creativity and fostering teamwork. W.L. Gore creates next-generation cable assemblies and components for the electronics industry, set the standard for outerwear comfort and protection, and solve difficult industrial problems with innovative materials and technology. Gore medical products work in harmony with the body's own tissues to restore normal body function.

1.2 Needs Description and Goal

The client currently has access to sterilization systems that use either harsh chemicals, or a large amount of heat that can damage various materials. The client needs a current sanitization device that is portable and safe for various materials such as plastics and papers.

The goal of the project is to develop a portable sanitization process that sanitizes bioburden amounts past acceptable levels and that is safe for various materials.

1.3 Objectives

Descriptive requirements of the sanitizing device are provided by the W.L. Gore associates, which can be broken down into project objectives. These objectives are derived from meetings and documents provided by the client. These objectives will show the main focuses of the project at hand.

Safety of the final design ties into the main focus: decreasing bioburden levels. These levels, along with the allowable exposure of certain substances that are deemed safe, will follow guidelines provided by the Occupational Safety and Health Administration (OSHA). Procedures and regulations for proper safety are quantified in their respective documentation, tabulated in concentration values. The sanitization process requires an ability to function with a variety of objects and components of mixed materials and geometries. W.L. Gore & Associates provide examples of a tackle box (plastic), a notebook (paper), and hemostats (medical equipment). These examples emphasize a temperature range for heat sensitive materials and no impact for malleable material. The temperature range can be limited by annealing levels and melting points of materials which must remain below 70°C. For the final product, the design must prove to be portable enough for the transportation of a single individual. The portability of the device in question can be defined as being able to fit through door frames and tight hallways while remaining under a weight threshold. Therefore, the maximum width shall be less than 3 feet and the maximum height less than 6 feet. Dimensions are estimated by comparing to common door sizes. The overall weight is limited by the average lifting of an individual and the weight limit allowable on free rotating wheels.

The expense of the product design follows the guidelines set by the budget provided. W.L. Gore is allowing a budget of $3,000 for research, presentation, and design prototyping. Estimations in need for research and presentations leave approximately $2,500 for the finalized design. This amount is more than affordable when compared to sterilization systems such as autoclaves, irradiation, and chemical processing.

Medical sanitizing requires a certain ease of use for the individuals running the device. Defining ease of use creates a criterion of characteristics as cycle time, process completion, and electrical comprehension. The cycle time must be kept within sixty minutes as this device will be sanitizing objects under immediate demand. To aid in process completion, the device should automatically end the process once sanitization is complete. All electrical components should be properly installed and allow for power through common wall outlets.

1.4 Working Environment

W.L. Gore will test sample strips with a known amount of *Bacillus atrophaeus* CFUs on the strip. After running the sanitization process, the strips will be analyzed to see how many CFUs are left on the strip. This data will determine if the process was successful or not.

Further testing must be done to ensure that the levels of hydrogen peroxide (H_2O_2) in the air are not above 1 part per million, in accordance with OSHA regulations. Hydrogen peroxide test strips will be placed one foot from the chamber in various directions and measure the levels of H_2O_2, to ensure user safety.

1.5 Constraints

In order to sanitize various materials with complex geometry, the sanitization chamber should comply with standard door sizes (limitation 3'x3'x6'). The total cycle time cannot exceed 60 minutes and cycle must end automatically. Ethylene oxide cannot be used as the source of the sanitization due to its harmful property to humans. To meet the portable requirement, the sanitization chamber should be transported and operated by one person easily.

1.6 State of the Art Research

The Center for Disease Control released a manual of requirements for disinfection called, '*Guideline for Disinfection and Sterilization in Healthcare Facilities'.* This document covers all bases on how to sterilize different materials and spaces and what safety requirements should be met.

Current processes that can sanitize objects in such ways do exist. The most common of these is an autoclave. An autoclave works very much like a dishwasher. They are enclosed metal boxes that spray scalding hot water and or steam within them. Autoclaves are widely used in environments in which sanitization is needed such as: hospitals, dental offices, tattoo parlors, and operating rooms. Although effective, there are two major fallbacks of using autoclaves. Autoclaves cannot sanitize objects that are sensitive to water or heat. Further, autoclaves can take up to two hours to properly sanitize, which is longer than desired for this project.

Lasers are also used in current sanitization processes. They can kill a variety of harmful bacteria by setting the lasers at different wavelengths. Lasers are so powerful that they are used to sterilize open wounds during surgery. However, lasers are used to sanitize very small areas, and would not be effective at sanitizing objects larger than a few millimeters. Also, the types of lasers used in these situations can be both extremely expensive and dangerous.

The most current and innovative types of sanitization are using ultraviolet light and hydrogen peroxide fogging techniques. An article by Owens at The College of Charleston in South Carolina titled, '*High Dose Ultraviolet C Light Inactivates Spores Bacillus Atrophaeus and Bacillus Anthracis on Non reflective Surfaces'* details the effectiveness of ultraviolet light on the Bacillus spores.

There are a few companies that use hydrogen peroxide fogging to sterilize on small and medium size bases by utilizing smaller machines that sanitize one or two objects at a time and larger tanks that can sanitize entire rooms. This method of sanitization is particularly impressive because it disinfects all exposed surfaces, slides into crevices and can penetrate some fabrics.

Both methods, ultraviolet light and vaporized hydrogen peroxide, are highly effective at killing bacteria and are currently in use in healthcare facilities. Additionally, these methods can be used on materials that cannot be introduced to water or heat.

The US National Library of Medicine has a number of articles on the effectiveness of a combined UV/H_2O_2 process on Bacillus spores. This special combination acts as a photocatalytic oxidizer and has been shown to inactivate even *Bacillus subtilis* spores, spores that are resistant to either method alone. An article by Braz in the Brazilian Journal of Chemical Engineering titled, '*Inactivation of Bacillus atrophaeus Spores in Healthcare Waste by UV Light Coupled with H_2O_2*' showed very impressive results. Inactivation percentages of 70-95% were found with an exposure time of 5-10 minutes with a UV/1% H_2O_2 solution.

1.7 Quality Function Deployment (QFD) and House of Quality

The customer indicated that three main things were wanted in the product: safety, ease of use, and ability to clean various materials. The client broke down ease of use where they wanted the device to have a short cycle time that ends automatically and that it can be easily transported by one person. Using this criterion, a quality function deployment and house of quality were made. The team met together and rated the importance of each of the customer's wants and rated them on a scale of 1-5, five being the highest priority. The client especially stressed safety and the ability to sanitize the sample materials without damage to them. While the team is in early stages of research and brainstorming on what methods will be used to accomplish the goals of the project, a short list of engineering requirements were developed.

These include:

● Size – The overall dimensions of the product. This must be manageable by one person while also being able to easily fit through standard doors. This is the cross sectional area.

● Weight – The weight of the device. This could lead to lower portability or higher cost.

● Cost to produce – Prototyping needs to fit within budget. It should be noted that W.L. Gore is known for not compromising a product due to cost.

● OSHA standards – Standards set by the Occupational Safety and Health Administration. The device needs to meet the standards that apply to the design and process.

● Low operating temperature – This is required to be able to sanitize various materials which includes a polymer that has relatively low melting temperature.

● Cycle time – Client requested a low cycle time. The team noted that autoclaves can sterilize in 15-20 minutes and is looking for a similar time.

● Power source – This will become more important depending on the sanitization process chosen but the device will need a safe and reliable power source.

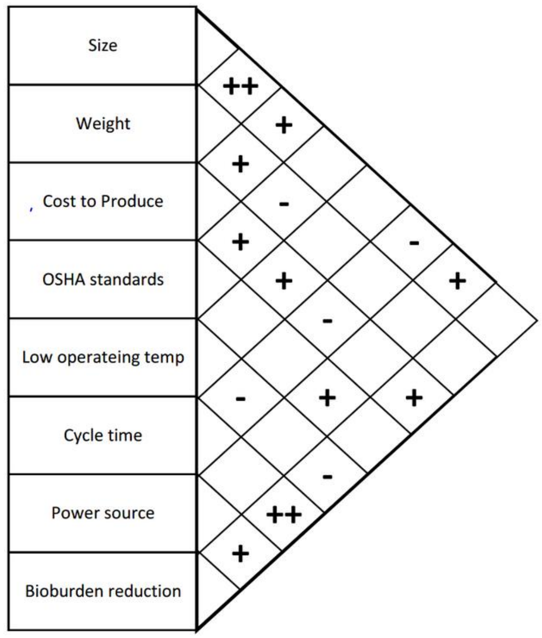
● Bioburden reduction – This is the main purpose of the device to reduce the bioburdens on the provided samples. This will be tested using a known amount of bioburdens and testing to see how much is left after one cycle.

The generated QFD matrix and House of Quality are shown below in Tables 1.1 and 1.2.

Table 1.1: QFD Matrix

Customer Requirements	Importance out of 5	% Importance	Size	Weight	Cost to produce	OSHA standards	Low operating temp.	Cycle time	Power source	Bioburden reduction	Autoclaves	Vacuum Hydro peroxide vapor proc
			Engineering Requirements								Benchmarks	
Easily transported by one person	3.5	17%	9	3	1	1				3	x	
Low cost	3	14%	1	1	9	3	3	3	1	3	x	
Safe	5	24%	3	3	3	9			1	3	x	
Sanitizes a variety materials	5	24%	3		3		9	1	3	9		x
Short cycle time	3	14%	3		1	1	1	9	3	3	x	x
Cycle ends automatically	1.5	7%			3	1		9	9		x	x
	Importance		3.5	1.4	3.2	3.0	2.7	2.6	2.2	4.2		
	% Importance		15%	6%	14%	13%	12%	11%	10%	19%		
		units	m^2	kg	$	varies	°C	min	W	%		
		Engineering Targets	<1	<35	2500	Yes	<70	<30	<1000	>50		

Table 1.2: House of Quality



The team discussed whether each of the customer requirements had a weak, medium, strong, or no correlation with the engineering requirements represented by 1, 3, 9, or 0 (blank) respectively. This creates a greater weight for those that are strongly correlated. Once this was done, the value was multiplied by the importance weight of the customer requirements and totaled for each engineering requirement. This leads the team to see that the most important design concern is finding a process that will lower the bioburden levels. The next important requirements are the size and cycle time with the cost staying within budget. Comparable processes or devices are the autoclave and a vacuum hydrogen peroxide vapor process. The autoclaves come in various sizes and are cheap. They sterilize in about 20 minutes but because of the steam process, they cannot be used due to potential damage to some of the items that the client provided. The vacuum hydrogen peroxide process is very quick, about 6 seconds to sterilize water bottles, but it is prohibitively expensive and not portable.

Chapter 2. Concept Generation and Selection

2.0 Background and Assumptions

With background knowledge in the subject matter, possible concepts can be generated. These concepts are deemed viable based on their compliance with the design objectives, constraints, and environment.

For analyzing purposes, all processes consider sanitizing the bacterial spore, *Bacillus atrophaeus*. At least one log reduction of the initial contamination is needed to justify the effectiveness of a process. This reduction amount proves to be more useful than simply approximating the number of spores deactivated since their numbers can be in the tens of millions. The spore selection is a client specified requirement and must be addressed for each concept.

2.1 Concept Design

There are many concepts for a sanitization device that can be used for this project. Based on the client requirements, five designs have been selected for further research to see which concept would best meet the client's needs.

2.1.1 Autoclave

An autoclave is a device that uses steam to sterilize equipment and other objects. This kind of sterilization can be effectively achieved at a temperature above 100°C [Rao, 2009]. This means that all bacteria, viruses, fungi, and spores are inactivated. However, prions, such as those associated with Creutzfeldt-Jakob disease, may not be destroyed by autoclaving at the typical 135°C for three minutes or 121°C for 15 minutes [Rao, 2009]. Some organisms, such as the archaeon *Geogemma barosii*, can survive at temperatures above 121°C [Rao, 2009]. Water boils at 100°C at atmospheric pressure, but if pressure is raised, the temperature at which the water boils also increases. In an autoclave the water is boiled in a closed chamber, so we can easily increase the temperature to certain value by increasing the pressure.

Steam treatment requires substantial energy produce the steam and pressure needed for sterilization. Sanitation by steam should not be carried out on surfaces that are not heat tolerant. In addition, high temperature can cause scale deposition.

Table 2.1: Autoclave Advantages and Disadvantages

Advantages	Disadvantages
More penetrative power than dry air	Economically inefficient
Readily available	Meet heat tolerant requirement
	Scale deposition

2.1.2 Chemical Processes and Fogging Techniques

One of the quickest and most efficient ways to sanitize is using chemicals. There are many chemicals that are used to sanitize/sterilize in both household and industrial applications. Many of these chemicals such as bleach, ammonia, ethanol, hydrogen peroxide and others can kill over 99% of bacteria when used in the correct concentrations. Anything that comes into direct contact with the chemical solutions will be effectively sterilized.

Some chemicals have negative interactions with certain materials. Some alcohols can negatively affect plastics causing deterioration with repeat exposure. Paper and other materials, such as the clean-room book, cannot be sanitized by chemicals because they are not able to withstand saturation.

Fogging is one way of utilizing chemical disinfecting properties by vaporizing the chemical into a dry fog. This vaporizing method allows the chemical to spread around an enclosed area reaching every surface of complex geometries without getting anything saturated. The most commonly used chemical for fogging is hydrogen peroxide. Hydrogen peroxide is the safest chemical to use for fogging sanitization. Unlike bleach, which would create a possibly harmful vapor, or ethanol which would be highly flammable, hydrogen peroxide vapor is relatively safe.

Hydrogen peroxide vapor is currently being used by hospitals to sterilize entire rooms. The process takes around 15-30 minutes, with an additional 1-2 hour waiting time before the room can be safely occupied, depending on the size of the room. In hospitals, a 7.5% hydrogen peroxide (H_2O_2) solution is used; higher H_2O_2 concentrations can corrode materials. The Environmental Protection Agency (EPA) has Vaporized Hydrogen Peroxide classified as a sterilant, defined by the EPA as eliminating all microbial life [Rutala, 2008].

A small fog machine with a 7% H_2O_2 solution should create enough vaporized hydrogen peroxide to sanitize a small enclosed area. Additionally, the chamber would need a small filter to filter out the vapor that is being fogged through the box. This design will quickly and efficiently sanitize any object placed within the box. A sketch of a hydrogen vapor concept is shown in Figure 2.1. Table 2.2 shows the advantages vs the disadvantages for using a chemical sanitization process.

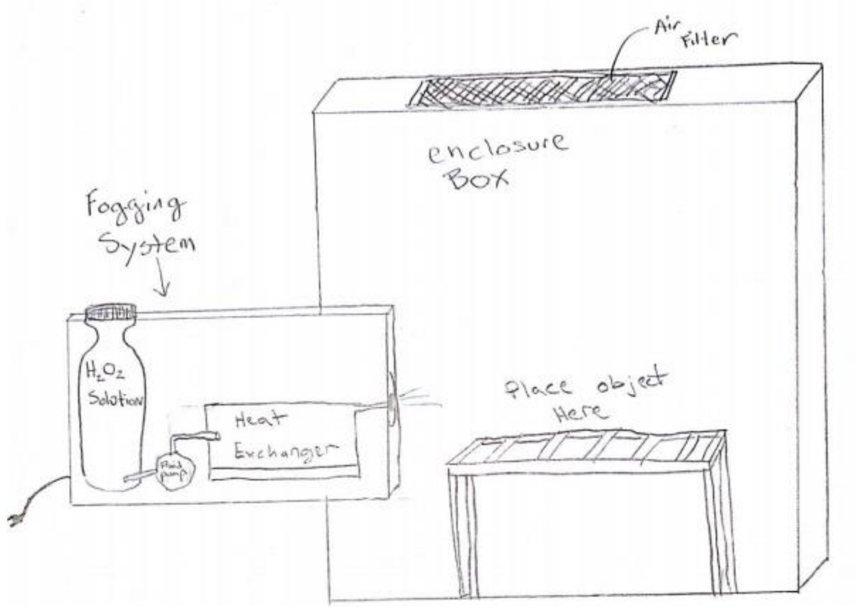


Figure 2.1: Sketch of H_2O_2 Fogging Concept

Table 2.2: Chemical

Advantages	Disadvantages
Highly effective	Vapor cannot be inhaled
Fog sanitizes all exposed surfaces	Solution must be refilled regularly
Inexpensive	

2.1.3 Electron-Beam

Electron-beam is a device that uses particulate ionized rays to sterilize materials [Rao, 2009]. The rays penetrate the objects and either destroy DNA strains or damages the DNA proteins beyond repair in small organisms. The Electron-beam is very convenient because there is no preparation for the materials. All materials can be sterilized in their packaging avoiding any accidental contamination after sterilization.

2.1.4 Laser

Using lasers to reduce bioburdens have been used in some applications, like sterilizing dental instruments and oral surgical wounds. From the preliminary research, specific wavelengths are used for different tasks. One machine by Lutronic comes with different hand pieces that are easily exchanged to modify the wavelengths. These can be used to sterilize open wounds during surgery or to remove unwanted tattoos.

It was found that some items that are space bound are sterilized by lasers. The laser can be used with other sensory devices on the end of a robotic arm to scan the large items in a sterile environment. Further research will be needed to find an ideal wavelength and power output to sanitize various products. Figure 2.2 below shows a sketch of how a laser system could be designed.

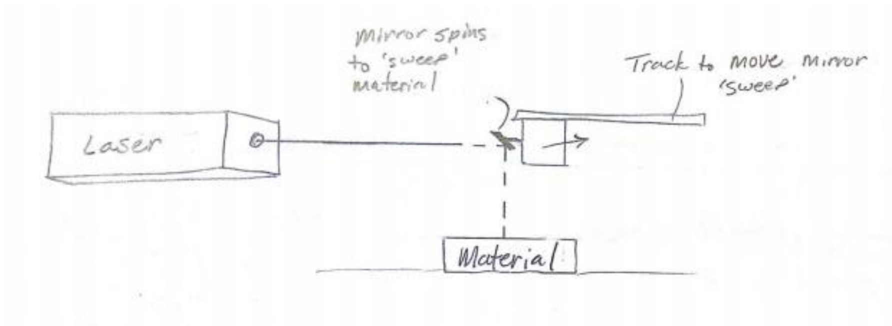


Figure 2.2: Sketch of Laser Design

Table 2.3 combines the advantages and disadvantages for electron beam and laser sanitization.

Table 2.3: Electron Beam

	Electron Beam	Laser
Pros	- sanitizes through items	- relatively low power
	- very fast	- quick
	- does a large variety of materials	- does various materials
	- Zero prep is needed for materials	- Already used by dentists
Cons	-May not be able to produce on a small scale	-May be cost prohibitive
	- Complicated control systems	- Power requirements are different for various lasers/wavelengths
	- Cost	- Doing large items may take too much time
	- Safety to the user	- only surface sanitized

2.1.5 Infrared Radiation

Many wavelengths within the light spectrum can be utilized in disinfection and sterilization processes. Infrared radiation (IR) falls on a longer wavelength, from 0.78µm – 1000µm, and exhibits high amounts of energy through heat transfer. The operating temperature for an IR system is a function of wavelength [Ellis, 2013], which allows for intensity control when applying these processes for disinfection purposes. Some companies, like Heraeus, utilize carbon IR emitters to provide effective disinfection systems for the food service industry. These products expose baked goods, and the equipment used to handle foods, to temperatures up to 160°C for 10–30 seconds [Heraeus Noblelight, 2013]. Table 2.4 shows the advantages and disadvantages of using infrared.

Table 2.4: infrared table

Advantages	Disadvantages
low cycle time < 1 minute	not viable for heat-sensitive materials
compact size	costly

2.1.6 Ultraviolet Light

Ultraviolet light sanitation, also known as Ultraviolet Germicidal Irradiation (UVGI), is an effective and efficient way to sanitize the surface of an object. UVGI is used in hospitals, HVAC, water sanitization, and chemistry labs. To properly sanitize a surface of an object there will only need to be one bulb that produces a wave length of about 240-280 nm, but more bulbs can be used to increase effectiveness [Carlson, C]. This wavelength is effective in inactivating viral and bacterial contaminants. Since there are existing designs of the bulb, it will be easy to design a chamber that suits the system.

Table 2.5: UV table

Advantages	Disadvantages
Maximum kill potential occurs within 2- 15 minutes depending on virus or microorganism	Over exposure of UV rays will cause damage to humans
Can adjust light sensitivity to produce better results	Effectiveness of UV light lessens over time
Cost effective	May damage rubber, paper and plastic over time
Sanitize all surfaces	Must clean UV light bulbs regularly

2.2 Decision Matrix

The decision criterions are rated for each concept on a -1,0,1 scale with -1 meaning that the characteristic has a negative correlation, 0 meaning it is neutral, and 1 meaning that it has a positive correlation. The system with the highest total points is the design that would best satisfy the customer and engineering requirements. Both the UV lights and the chemical spray have the highest rating out of all of the designs. It is possible to use both of them in one system so that it is more diverse and can kill more bioburdens. This has many advantages and disadvantages. The chemical process might affect how well the UV lights work and may require more maintenance. But it can be designed to only do one process at once or both simultaneously. Combining these designs is within the budget and the dimension constraints given by the client.

Table 2.6: Weighting Characteristics

	Safety	Material	Maintenance	Cycle Time	Cost	Power Required	Total + 1	
Safety		1	1	1	1	1	6	29%
Material	0		1	1	1	1	5	24%
Maintenance	0	0		0	1	1	3	14%
Cycle Time	0	0	1		1	1	4	19%
Cost	0	0	0	0		1	2	10%
Power Required	0	0	0	0	0		1	5%

Table 2.7: Decision Matrix

	Safety	Material Compatibility	Maintenance	Cycle Time	Cost	Power Required	Total
Autoclave	**0**	**-1**	**1**	**1**	**1**	**-1**	**0.14**
Chemical Process	**0**	**1**	**0**	**1**	**1**	**1**	**0.57**
Lasers	**1**	**1**	**1**	**0**	**-1**	**1**	**0.62**
Infrared Radiation	**0**	**-1**	**1**	**1**	**0**	**-1**	**0.05**
UV Light	**1**	**1**	**0**	**0**	**1**	**1**	**0.67**
Weights	29%	24%	14%	19%	10%	5%	

Chapter 3. Engineering Analysis

3.0 Engineering Analysis

The design contenders now undergo an engineering analysis and are strictly compared to themselves and the design requirements. Their components and materials are selected and projected cost analysis is addressed. Based on the predicted performance of each concept, a favored final design stands out as the optimal approach.

3.1 Chemical Fogging Analysis

This system uses a chemical fogging process of a 7% hydrogen peroxide (H_2O_2) solution. The solution is pumped into an aluminum block heat exchanger where it is vaporized. This flash of vaporization causes the gas to quickly increase in temperature and pressure. Since the heat exchanger is enclosed, vaporized H_2O_2 flows out of a nozzle at high velocity. As the vapor exits the nozzle, its pressure drops dramatically, also causing a significant drop in temperature (below boiling temperatures). This cooled vapor is contained inside of an enclosure and quickly sanitizes the materials contained within. This method is compatible for the materials in question as the chemical does not corrode or react with the materials and covers complex geometries. The cold steam is compatible with objects that are sensitive to heat, and because it is a vapor, it will not saturate materials that are affected by water. The vaporized hydrogen peroxide must be filtered, or allowed to decompose into water and oxygen before it is safe for human exposure.

3.1.1 Filters

For the hydrogen peroxide fogging process, a filter will need to be included in the design. The filter is needed to break down the H_2O_2 solution into water (H_2O) and oxygen (O_2), so that it is safe to be released around humans.

There are three common types of air filters. These include High Efficiency Particulate Air (HEPA) purifiers, activated carbon filters, and titanium oxide (TiO_2) photocatalytic oxidation filters. HEPA filters do not break down any chemicals, eliminating them from the filter analysis. Activated carbon filters can be used for simple chemical decomposition, such as the breakdown of some of the H_2O_2, but they must be replaced every 4-6 weeks.

Titanium oxide oxidation filtration uses a UV light photocatalytic process to break down bacteria and harmful chemicals. These filters are efficient, converting over 95% of harmful bacteria and chemicals into carbon dioxide and water, which falls well below OSHA concentration limits for hydrogen peroxide exposure [OSHA]. Due to the effectiveness of the titanium oxide filters, it is the top choice for decomposing hydrogen peroxide. These UV filters have a regular use of breaking down chemicals in non-sanitizing applications (when in isolation) essentially requiring the hydrogen peroxide to evacuate from the sanitizing chamber before exposure to UV light [Sakthivel, 2003].

3.1.2 Enclosure Materials

Materials for the enclosure and additional system components must be selected. The materials that will be included in the design must be compatible with hydrogen peroxide. A few materials were considered due to their excellent compatibility with H_2O_2 at concentrations from 10-100%. These materials include: PVC, aluminum, polycarbonate, PTFE, and titanium. All of these materials show no effective corrosion, discoloration, or degradation when exposed to H_2O_2 at a concentration of 10%. At higher concentrations, titanium shows minimal effects [Cole-Parmer]. Because PVC, aluminum, PTFE, and polycarbonate all withstand exposure to H_2O_2, any of these materials would work well with the chemical process system [Cole-Parmer]. Due to the strength of the materials (comparing Modulus of Elasticity), aluminum will be used for the overall enclosure. This will also include the door, handle, hinges, rack, and any other small connecting pieces.

For additional pieces, including the H_2O_2 solution container, tubing, and nozzle; PVC and PTFE will be used.

In Figure 3.1 below, the concept of how the potential fogging chamber works is shown. The section that is cut out on the top is where the filter would go. The side compartment shown on the left is where the fog unit will be placed.

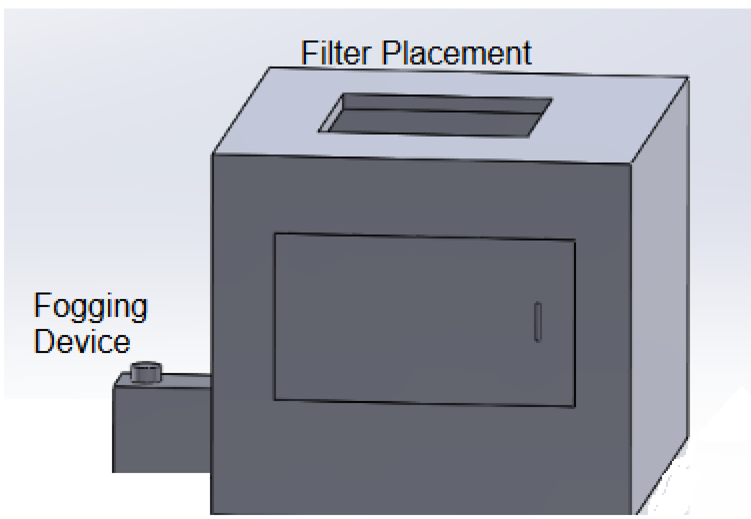


Figure 3.1 Solidworks Design of H_2O_2 Fogging Chamber

3.2 UVGI Disinfection

Ultraviolet Germicidal Irradiation is a common method used for air, water, and surface sterilization. The UVGI process uses a 254 nm wavelength in order to inactivate microorganisms. To sanitize the surface of an object, it needs direct exposure from the lights for a given amount of time depending on the microorganism. In the case of *Bacillus atrophaeus*, to achieve a 2 log reduction, it would require a UV light exposure (dose) of 50 mW s/cm2 [Carlson]. In order to determine the amount of time it takes to achieve this reduction, the specifications of the bulb is needed.

Four bulbs were chosen based on their height and power output. The specifications can be viewed in Table 3.1 below.

Table 3.1: Ultraviolet bulb specification

Bulb Model	Life (hr)	Lamp Wattage (W)	UV-C Radiation (W)	Length (cm)	Diameter (cm)	Weight (g)
TUV PL-L 95W	9000	95	27	53.5	3.8/1.8	134
TUV 18W 1SL	9000	18	4.5	60.4	2.8	100
TUV 10W SLV	9000	10	2.5	34.5	2.8	62
G25T8 (GE-T8)	7500	25	7	45.7	2.8	N/A

Using these four bulb types, the time it takes to achieve a 2 log reduction using the known exposure of 50 mW s/cm2 [Carlson] can be found. The intensity can be found using Equation 1,

$$I = \frac{P}{A} \tag{1}$$

where P is the output power of the UVC radiation and A is the projected area of the light. The area of each light is calculated using the length of the bulb times 0.3 m in the radial direction. The intensity of each light can be seen in Table 3.2. The Dosage can be found using Equation 2,

$$D = I * t(s) \tag{2}$$

Solving for time, the time it takes each bulb to achieve a 2 log reduction and 3-4 log reduction at an exposure of 4647 mWs/cm2 [Carlson] can be seen in Table 3.2. The time it takes for a 3-4 log reduction shows how much longer it would take to achieve a greater state of sanitization.

Table 3.2: Effective application of each bulb

Bulb Model	Intensity (mW/cm^2)	Time For 2log (sec)	Time For 3-4log (sec)
TUV PL-L 95W	9.28	1.25	500.93
TUV 18W 1SL	1.56	7.45	2984.78
TUV 10W SLV	1.51	7.66	3068.78
G25T8 (GE-T8)	2.86	4.06	1626.01

Based off the time it takes to achieve a 2 log reduction, the TUV PL-L 95W bulb is the most effective for the design. The full specifications of the bulb can be seen in Appendix D. Since the bulb is now known, other components such as the ballast and base, can now be selected.

Below are the concept designs for the UV chamber. Figure 3.2 shows the overall design and Figure 3.3 shows how the placement will look inside the chamber.

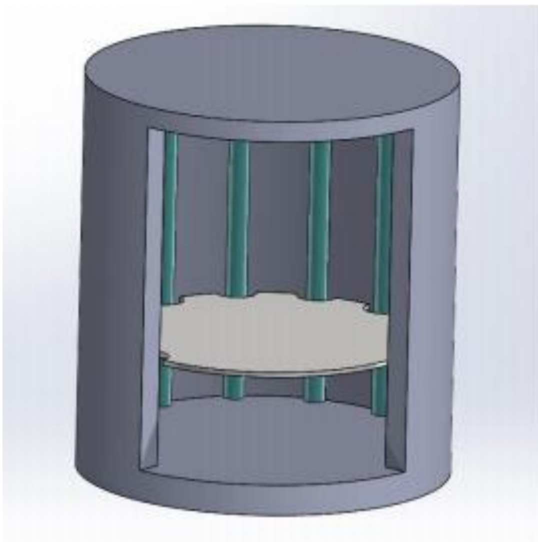


Figure 3.2: UV Chamber Design

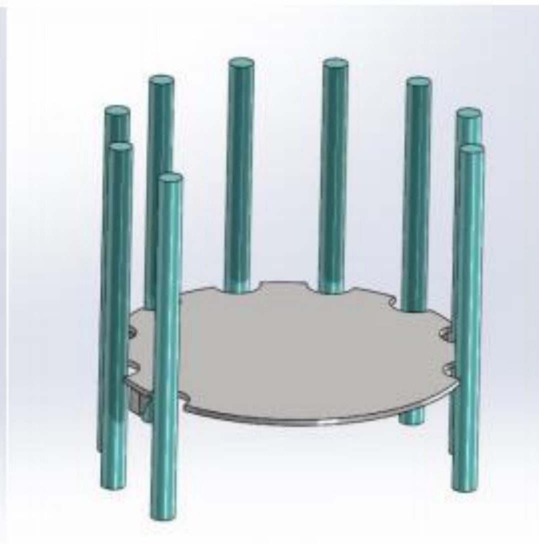


Figure 3.3: Inside View of UV Chamber

3.3 Deep UV (UVC) Laser Disinfection

UV lasers are similar to the effectiveness of UVC light as they both use the same mode of disinfection. Producing lasers in the UVC wavelength is a complex process and is cost prohibitive. At this point in time, the technology is still in the early stages of development.
A study by Sharp Laboratories of Europe, Ltd. [Carlson], demonstrated the effectiveness of the UVC laser in inactivating different bacteria and viruses, and decontaminating drinking water. They used a 205 nm through 230 nm wavelength lasers at 1 mW. In their experiments, they focused the laser to a 0.05 cm diameter dot. Assuming that they need a dosage of 50 mW s/cm2 to reduce *Bacillus atrophaeus* spores by 2-log and 100-4,000 mW s/cm2 to have 3-4-log reduction [Terra Universal], the required time to achieve the above dosage can be found by substituting Equation 1 into Equation 2 while rearranging to solve for time:

$$t(s) = \frac{DA}{P} \tag{2a}$$

Using Equation 2a and 1 mW laser would result:

$$t(s) = \frac{50\,\frac{mW \cdot s}{cm^2} \cdot 1.96x10^{-3} cm^2}{1mW} = 0.098\ s$$

for 2-log reduction and similarly 0.196 – 7.859 second pulse for 3-4-log reduction. This results in a required time for 2-log reduction over an area of size of 8.5” x 11” paper of 30,240 seconds or 8.4 hours.

At this time, the required time for just 2-log reduction is far too long to be acceptable. If the laser output could reach 100 mW for a continuous beam, the required time would be reduced to 5 minutes for 2-log reduction and 10 – 403 minutes (0.168 – 6.72 hrs) for 3-4-log reduction. This is far more acceptable for quick disinfection as it falls within the 20 minute goal.

Factoring in that the design to use a laser would require a mirror to scan the items, all above times would need to factor the reflectivity of the mirror. Using bare aluminum mirrors from Rocky Mountain Instrument Company, the expected reflectivity is between 90% and 93%. This means that an ideal 5 minute scan would be between a 5.4 – 5.6 minute real scan. The disinfection chamber will be made of aluminum, which will reflect and stop all laser beams from reaching the user when the system is running.

3.4 Combined UV/H_2O_2 Process

There are many advantages in using a multi-process ultraviolet/H_2O_2 system. A filtration system could be entirely eliminated by introducing the UV light process into the chemical fogging system. By running the UV lights immediately after the fogging, the hydrogen peroxide would be safely decomposed. Additionally, the UV light would add extra sanitization.
This two-step photocatalytic process of using H_2O_2 followed by UV light, also creates free hydroxyl radicals, OH-, that are strong oxidizing agents. These hydroxyl radicals lack an electron, making them highly unstable, reacting with the first chemical they come into contact with. Organic contaminants are degraded almost entirely by the radicals, creating safe byproducts such as water, carbon dioxide and various salts. These radicals degrade a variety of additional toxins such as: benzene, dichloroethylene, Freon 113, and various pesticides. The combined UV/ H_2O_2 process successfully inactivates *Bacillus atrophaeus* spores [Iannotti].

3.4.1 Material Selection

Again, aluminum was chosen for the enclosure due to its strength and compatibility with H_2O_2. The fogging system used in the chemical process would be exactly the same, including the same material selections. The main issue with the collaborative system is keeping the UV lights clean from the potentially corrosive H_2O_2 solution. To do this, the lights would have to be covered by some sort of transparent glass or plastic. This keeps the H_2O_2 fog from reaching the UV lights. PVC and PTFE are both found in transparent form, but are UV light resistant. Meaning, the UV rays that would be sanitizing and decomposing the H_2O_2 would not penetrate the plastics. Borosilicate, also known by the brand name Pyrex, is a highly UV-transmitting glass. By surrounding the cylindrical enclosure with a UV transmissive tube, such as borosilicate, the UV lights would be protected from the hydrogen peroxide and from dust and other potential threats, while the UV light still reaches the objects in the enclosure.

3.4.2 Mass Calculation for Combined UV/H2O2 Process Chamber

The group determined to use concentric cylindrical for combined UV/H_2O_2 process design. The interior cylinder is shorter than the exterior cylinder, and in this situation the enclosure cylinder can contained the whole chamber completely, see Table 3.3. To keep the UV lights clean from the corrosive H_2O_2, some transparent glass should be used to keep the H_2O_2 fog reaching the UV lights. The group determined to use Borosilicate as the cover material. For the enclosure material, the group determined to use aluminum since it has a proper compatibility with H_2O_2, see Table 3.3.

Table 3.3: Chamber Dimensions and Mass

Components	Dimensions	Values
Interior Height	h (m)	0.99
Exterior Height	h (m)	1.00
Inside Plastic	di (m)	0.500
Thickness	t (m)	0.005
Outside Diameter	do (m)	0.505
Volume	V (m^3)	0.198
Material Volume	V (m^3)	0.004
Density	ρ (kg/m^3)	2230
Mass of Inside	m (kg)	8.713
Spacing	s (m)	0.050
Outside Al	di (m)	0.555
Thickness	t (m)	0.001
Outside Diameter	do (m)	0.556
Volume	V (m^3)	0.243
Material Volume	V (m^3)	0.003
Density	ρ (kg/m^3)	2700
Mass of Outside	m (kg)	8.93
Rack Diameter	di (m)	0.500
Thickness	t (m)	0.005
Volume	V (m^3)	0.001
Density 304L	ρ (kg/m^3)	8000
Mass Rack	m (kg)	7.85

The total mass of the whole chamber is approximately 30.43 kg, which meet the requirement of portability as seen in Table 3.4.

Table 3.4: Total Chamber Mass

Parts	QTY	Unit Mass(kg)	Total Mass(kg)
Chamber	1	17.64	17.64
Rack	1	7.85	7.85
UV Lights	4	0.13	0.54
Lampholder	4	0.05	0.18
Ballast	4	0.45	1.82
Fog Machine	1	0.14	0.14
Misc. /Hardware	1	2.27	2.27
		Total mass(kg)	30.43

3.5 Analysis Selection

After analyzing all of the concepts, chemical fogging and UV lighting would work well to meet the requirements of the client. Lasers are good at sanitizing for small applications, such as cleaning teeth during a surgery. Laser sanitization does not meet the requirements of the client since larger applications require increases in process time and mechanical complications that become safety hazards and a cost burden. There are many advantages and disadvantages to using two processes. Chemical fogging is effectively disperses into the enclosure, covering any complex geometries that require sanitizing. A filter would be needed to reduce the amount of H_2O_2. UVGI applications perform well within the time constraint, but create a maintenance burden due to the nature of wavelength penetration.

From this analysis, developing a design that combines two processes proves to be the favorable option. The ultraviolet process compliments chemical fogging and can be integrated simply by keeping the UV lights within the sanitizing chamber and running them for a given length of time after chemical decomposition is complete. Utilizing both methods provides a wider range of sanitization (since certain spores are resistant to specific methods), proving to be a more effective design than either individual process.

Chapter 4. Cost Analysis

4.0 Cost Analysis

The cost is covered in the following sections: bill of materials, manufacturing costs, cost of work hours, and total cost of production.

4.1 Bill of Materials

In Table 4.1 below, the cost of materials is shown. The table covers the description of each material that is needed, along with the quantity, and unit cost. Materials that are included in the cost are the material of the chamber, the racks that go into the chamber, the UV lights, UV components, fog machine and miscellaneous hardware. The material for the chamber includes the aluminum, protective lining, and the shell that encases everything. The miscellaneous hardware includes everything from wiring to bolts. The total estimated cost for the bill of materials is $1153.90.

Table 4.1: Bill of Materials

Description	Quantity	Unit cost ($)	Total ($)
Chamber	3	100	300
Rack	2	30	60
UV lights	4	24.99	99.96
Lampholder	4	2.66	10.64
Ballast	4	110.83	443.32
Fog machine	1	40	40
Misc. /hardware	1	200	200
		Total	1153.9

4.2 Manufacturing Costs

In Table 4.2 the estimated cost for manufacturing is calculated. The manufacturing that is foreseen to be used is fabrication and welding. The rate is estimated based off how much professionals make. The total cost is expected to be $190.

Table 4.2: Manufacturing Costs

	Hour	Rate ($/hr)	Cost ($)
Fabrication	5	30	150
Welding	2	20	40
		Total	190

4.3 Cost of Work Hours

To determine the overall cost of man powered the estimated hours per person and pay per person needed to be calculated. In Table 4.3 below the estimated hours per person is estimated. The tasks include research, design, analysis, prototype, and testing. The hours are based off what was already done and what is expected to be done in the future. The total amount of hours per person is 65 hours.

Table 4.3: Estimated Hours per Person

Tasks	Estimated time per person (hr)
Research	10
Design	10
Anlaysis	5
Prototype	20
Testing	20
Total	65

A flat pay rate of $30 is charged for each engineer. Benefits and overhead costs were also added. The team is not for profit, therefore there is no additional percent charged. With these charges, the billable rate for each engineer is $58.5/hr.

Table 4.4: Estimated pay for group

Person	Base pay ($/hr)	Benefits (%)	Actual Pay ($/hr)	Overhead (%)	Billable Rate ($/hr)
Beauchamp, Robertson	30	30	39	50	58.5
Blackburn, Jacob	30	30	39	50	58.5
Kieffer, Lauren	30	30	39	50	58.5
Nation, Elliot	30	30	39	50	58.5
Soto, Angel	30	30	39	50	58.5
Zha, Dangxian	30	30	39	50	58.5
				Total	351

Using the estimated hours and pay for the group, the total cost for the group is shown in Table 4.5 below. The cost for the group is calculated to be $22895. To calculate the total cost of manpower the travel expenses between campus and W.L. Gore are included. The travel expenses come out to be $80. The personnel and travel costs make up the total cost of manpower which is $22895.

Table 4.5: Total cost of manpower

1.0 Personnel	# of Person	Estimated time per person (hr)	Rate ($/hr)	Total Cost ($)
	6	65	58.5	22815
2.0 Travel	# of Local meeting	Distance (miles)	Cost per mile ($/mi)	Total cost of Meetings ($)
Gore	4	8	0.5	**16**
Campus	64	2	0.5	**64**
			Total	22895

4.4 Total Cost of Production

Knowing the bill of materials, manufacturing costs and the cost of work hours gives what is needed to find the overall cost. The overall cost is estimated to be $24238.92 which is found in Table 4.6. This value includes the bill of material, manufacturing and manpower. The subtotal shows if design is within our budget. Since the budget is $3000 and the subtotal is $1343.92, we are well within our budget.

Table 4.6: Overall cost

Type of Cost	Cost ($)
Bill of Material	1153.92
Manufacturing	190
Subtotal	1343.92
Man Power	22895
Total	24238.92

5.0 Conclusion

W.L. Gore is looking for a portable chamber that sanitizes the surface of given materials. *Bacillus atrophaeus* is the spore that will need to be reduced by one log in order to satiate standardized sanitary tests conducted by W.L. Gore. Five designs were researched including UV lights, infrared radiation, electron beams, chemical processes, and autoclaves. Chemical processes and UV lights were the two concepts that were chosen to be analyzed. From the engineering analysis, each design would work really well for the client. Upon further analysis, using the two processes together would work best. The total cost for all of the materials required for the project is estimated to be about $1300.

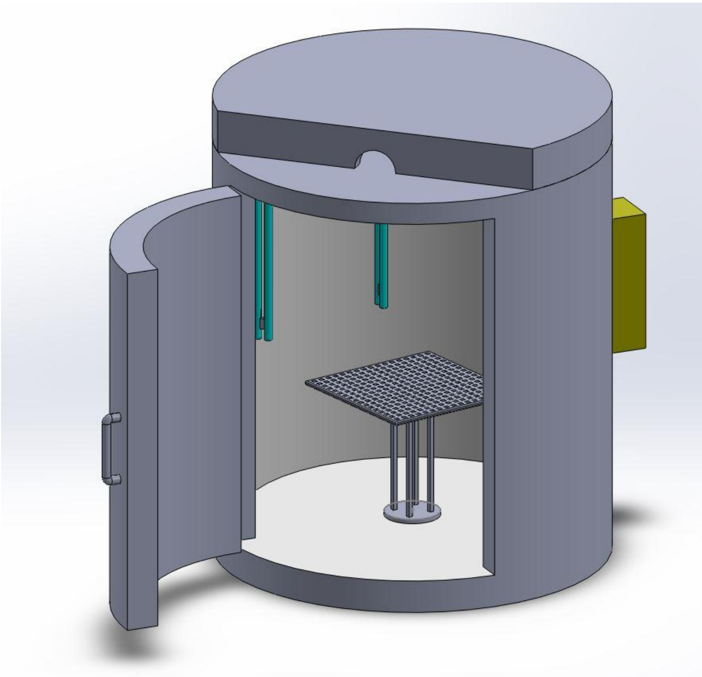


Figure 5.1: Final Design Model

The final design will consist of both the UV light and chemical processes. It will be contained in a cylindrical chamber that contains the UV lights. The chemical fogging machine will be installed on the outside of the cylindrical chamber.

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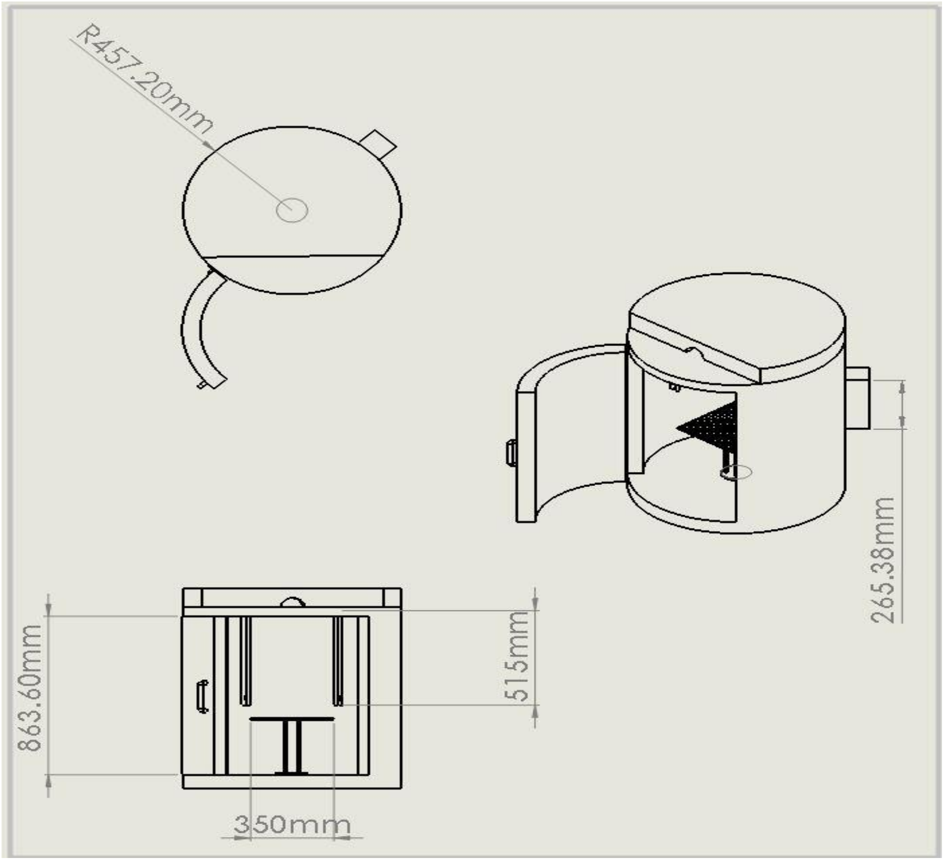
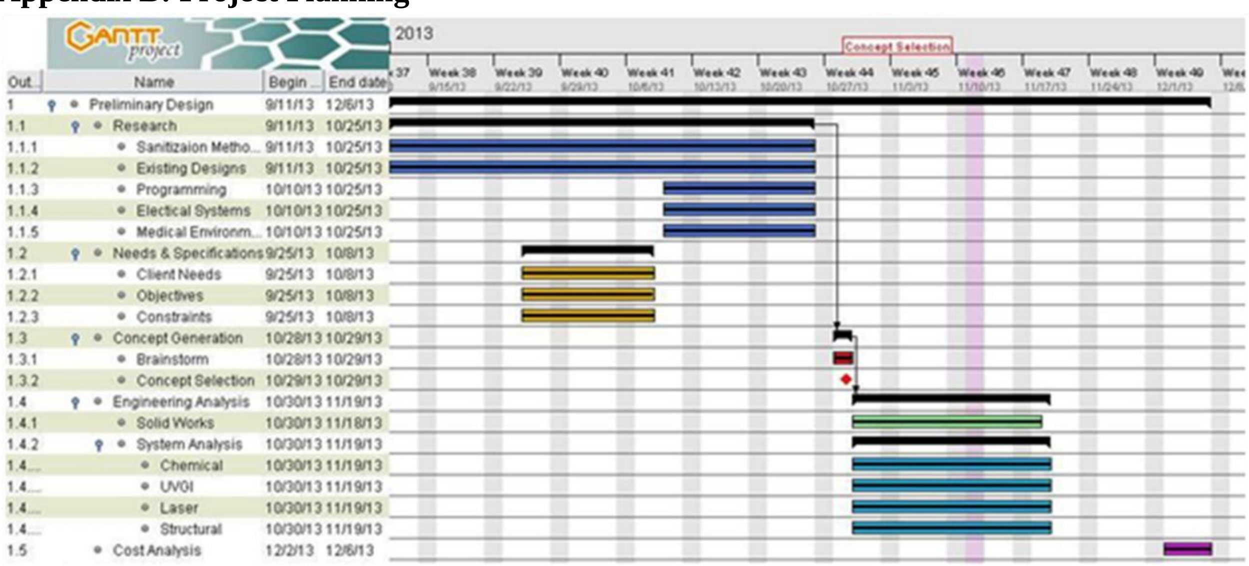
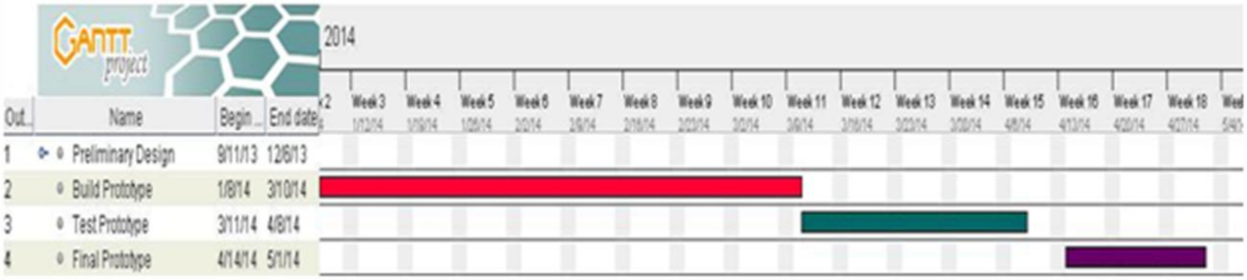
Appendix A: Engineering drawings



Appendix B: Project Planning



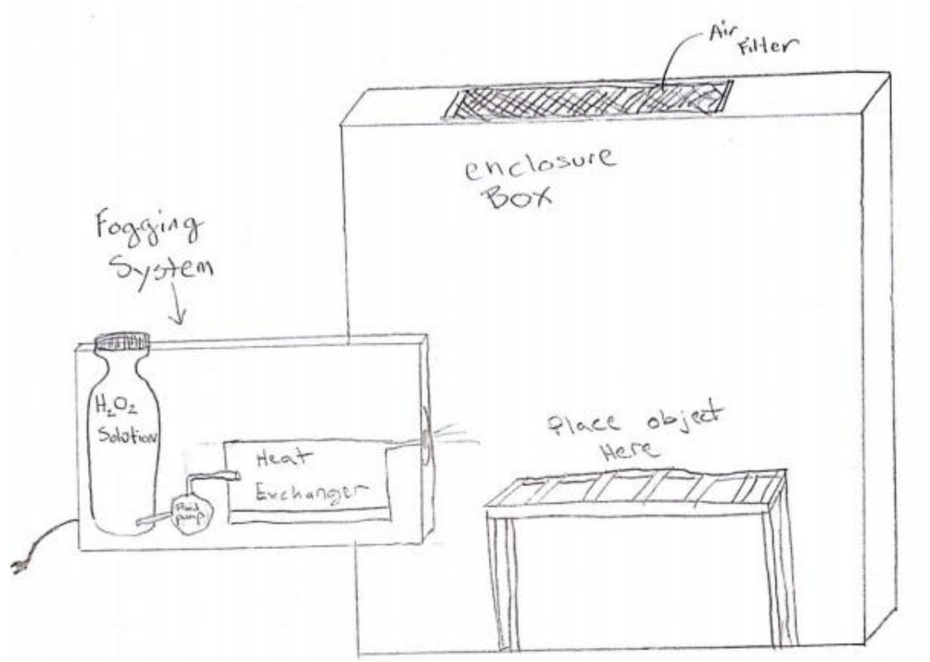


Appendix C: Miscellaneous material

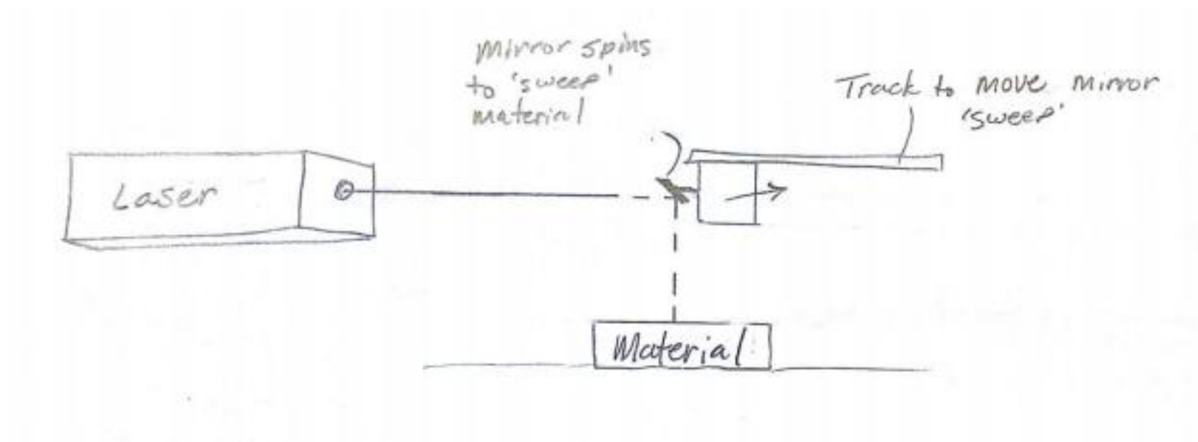
From Concept Generation and selection

	Advantages	Disadvantages
Autoclave	• More penetrative power than dry air • Readily available	• Economically Inefficient • Meet heat tolerant requirement • Scale deposition
Chemical	• Highly effective • Fog sanitizes all exposed surfaces • Inexpensive	• Vapor cannot be inhaled • Solution must be refilled regularly
Electron Beam	• Sanitizes through items • Very fast • Does a large amount of materials • Zero preparation is needed for materials	• May not be able to produce on a small scale • Complicated Control system • Cost • Safety to user
Laser	• Relatively low power • Quick • Does various materials • Already used by dentists	• May be cost prohibitive • Power requirements are different for various lasers/wavelengths • Doing large items may take too much time • Only surface sanitized
Infrared	• Low cycle time (< 1 minute) • Compact size	• Not viable for heat-sensitive materials • Costly
UV Light	• Maximum kill potential occurs in a short amount of time • Cost effective • Sanitizes all surfaces	• Over exposure causes damages to certain materials and humans over time • Effectiveness of light bulbs lessen over time • Bulbs must be kept clean

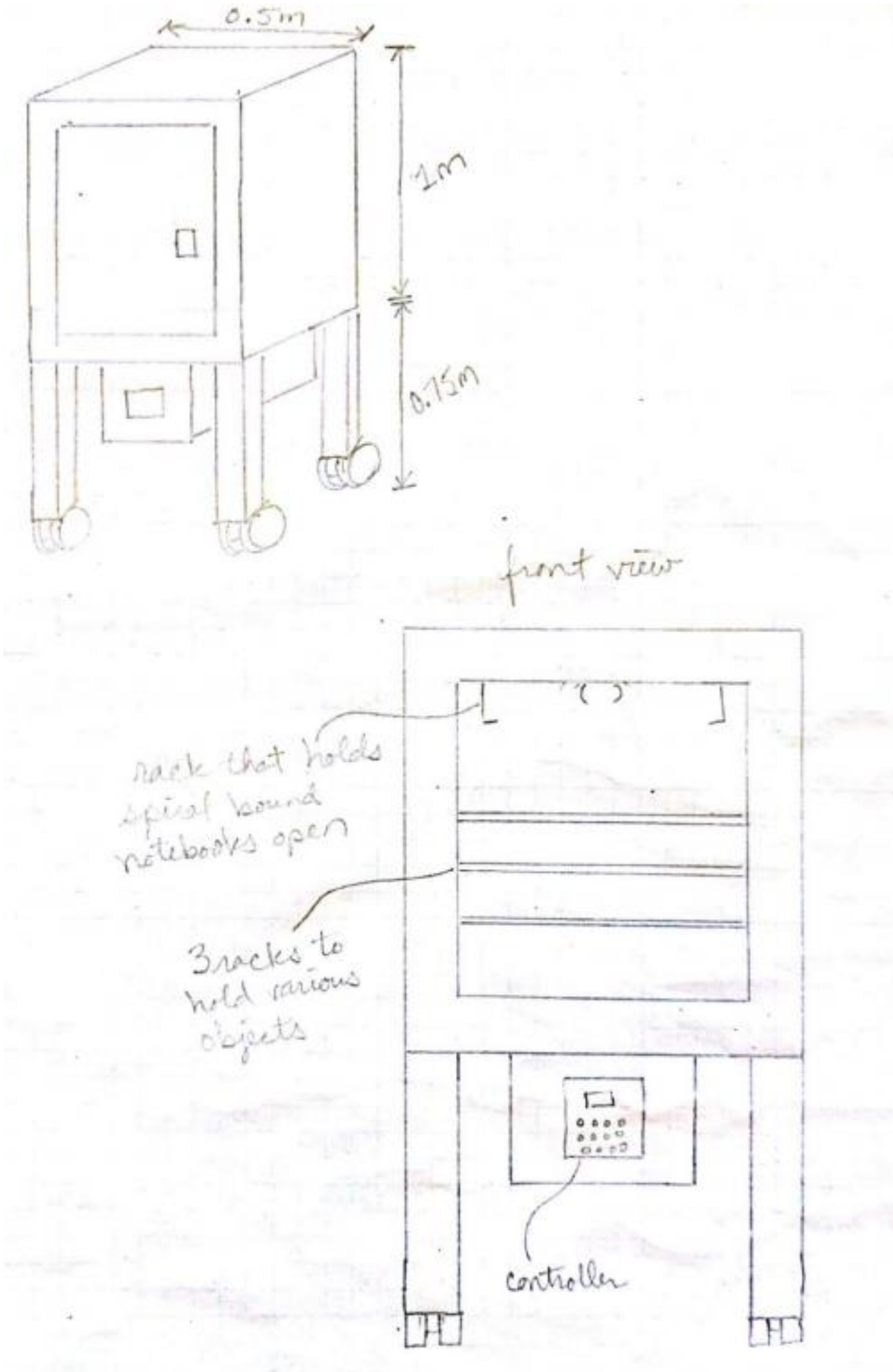
Chemical Process



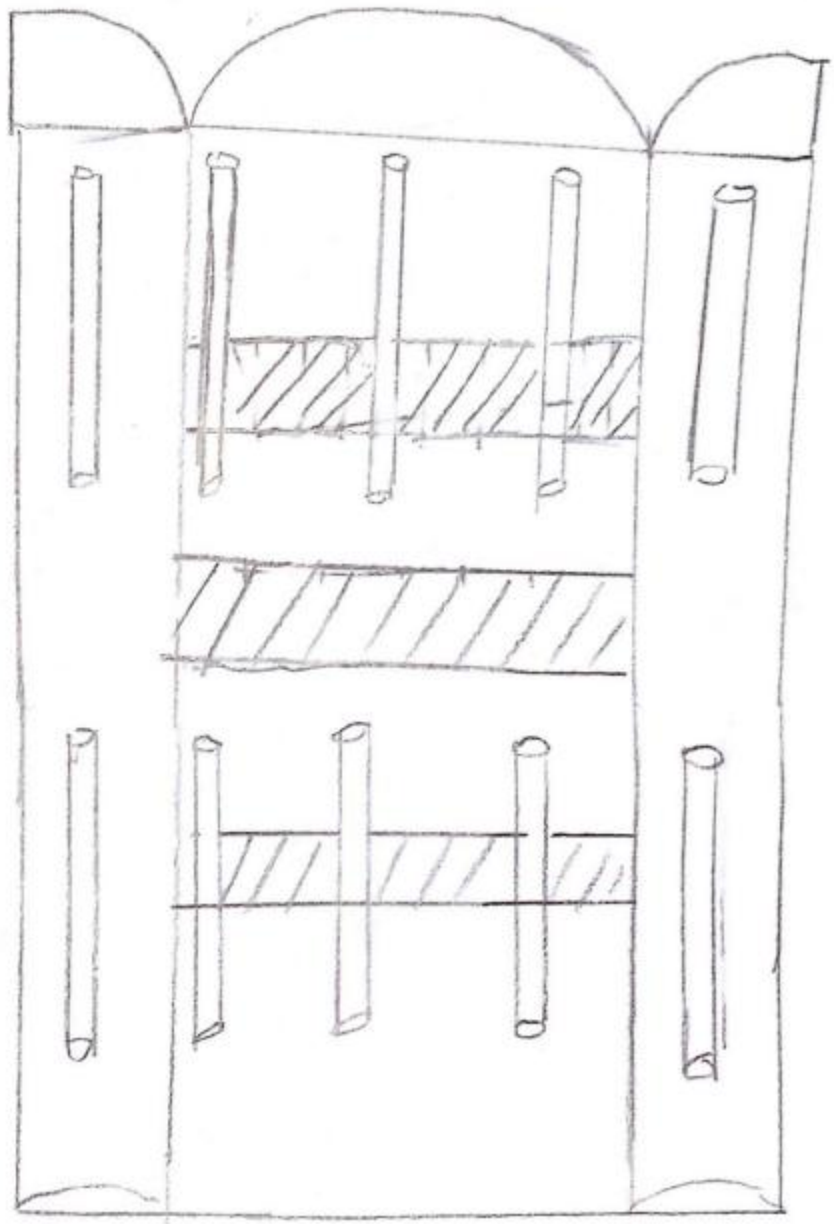
Laser Sanitization Process



Infrared Radiation Design



UVGI Design



Design specifications table with customer requirements and justifications

Customer Requirements	Design Specifications	Reasoning and justification	Quantity or Pass/Fail
CLEANLINESS STANDARD reduce the bioburden to less than routine final bioburden levels	Process effectively elimiantes bacterial spores (e.g. *Bacillus atrophaeus*)	Client specified	1 log unit reduction
SAFETY No harmful materials Users are not at risk of exposure to sanitizing source Applicable OSHA safety standards met	Physical components do not cause user harm	OSHA employee safety guidelines	pass/Fail
	Chemical concentration	Allowable substance exposure from OSHA standard	H_2O_2: 1.4 mg/m^3 No eye exposure to light
	Electrically grounded Non-pinching hinge	User electrical guidelines from OSHA standards	pass/fail
EASE OF USE Short cycle time Cycle ends automatically when complete Easily transported by one person	Duration of process	Compared to common autoclave	20 minutes
	Control System	signals automatically execute process shutdown	pass/fail
	weight	Human lifting average	35 kg
	footprint area	Fits through doorways and on client countertops	1 m^2
SANITIZE VARIOUS MATERIALS e.g. Tackle Box Cleanroom Notebook Hemostats	Temperature	Avoid glass transitioning temperature of common polymers (polycarbonate)	120°C
	Stresses applied	Minimum modulus of elasticity to prevent deformation	2 Gpa
	Does not saturate material	Prevents adverse function effects for pourous materials	pass/fail
	substance covers every aspect of material	Complex geometries may provide small crevices that require sanitizing	pass/fail
BUDGET	Cost to generate	Client specified	$3,000

UVGI lamp chosen

TUV PL-L

TUV PL-L 95W

TUV PL-L lamps are compact UVC (germicidal) lamps used in professional water and air disinfection units. The compact size of the lamp allows for a small system design and design flexibility. TUV PL-L lamps offer almost constant UV output over their complete lifetime, for maximum security of disinfection and high system efficacy. Thanks to the single-ended lamp base, lamp replacement is easy.

Product data

- General Characteristics

System Description	High Frequency
Cap-Base	2G11
Cap-Base Information	4 Pins
Bulb	2xT16
Execution	-
Main Application	Disinfection
Useful Life	9000 hr

- Light Technical Characteristics

Color Code	TUV
Color Designation (text)	-

- Electrical Characteristics

Watts	95 W
Lamp Wattage Tech-nical	90 W
Lamp Voltage	115 V
Lamp Current	0.8 A

- UV-related Characteristics

UV-C Radiation	27.0 W

- Product Dimensions

Base Face to Base Face A	505 (max) mm
Insertion Length B	530 (max) mm
Overall Length C	535 (max) mm
Diameter D	38 (max) mm
Diameter D1	18 (max) mm

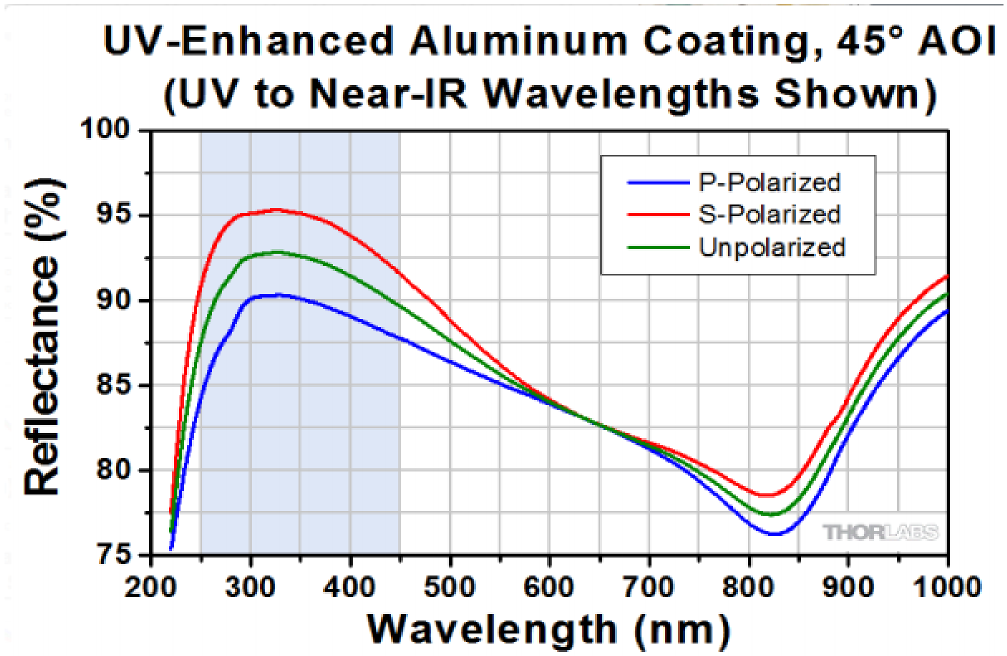
- Product Data

Product number	137257
Full product name	TUV PL-L 95W/4P HO 1CT
Short product name	TUV PL-L 95W/4P HO 1CT/25
Pieces per Sku	1
eop_pck_cfg	25
Skus/Case	25
Bar code on pack	8711500888297
Bar code on case	8711500888303
Logistics code(s)	927909804007
eop_net_weight_pp	134.000 gr

Dimensional drawing

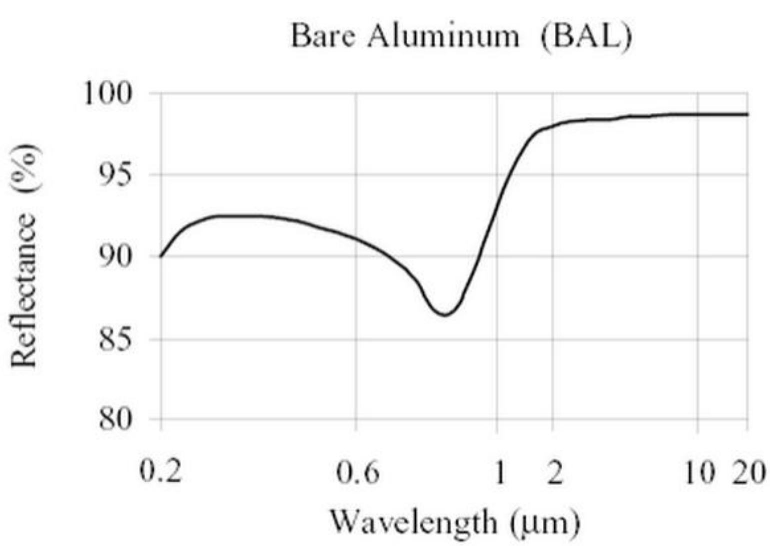
PHILIPS
sense and simplicity

Reflectivity of aluminum for ultraviolet design



http://www.thorlabs.us/newgrouppage9.cfm?objectgroup_id=264

Effective reflection of UV by Aluminum



http://rmico.com/coatings-specifications/metal-hybrid/bare-aluminum-bal

Material Properties

Material	**Density(kg/m^2)**
PVC	1300
Al	2700
Polycarbonate	1200
PTFE	2200
Ti	4506
Borosilicate(Pyrex)	2230