Far-UVC Applications in Healthcare

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1.Abstract

Current methods of sterilizing environments are insufficient, which has been exemplified by the current pandemic. At the moment, there is not a safe way to consistently and thoroughly eliminate viruses from high traffic areas during the hours that people (possible carriers) are passing through them. This makes areas, namely hospital rooms, where there is an increased rate of carriers, high risk for virus transmission. Although Germicidal UVC light (254 nm) is effective at inactivating viruses, it is not a reliable source as it is a safety risk when in contact with humans. A Far-UVC light (222 nm) disinfection device would allow for complete safety when humans are in contact with the light, while still maintaining its disinfecting role. Far-UVC wavelength is too small to penetrate human skin cells, but can still inactivate viruses. Our Far-UVC overhead light device has a large coverage area (10.20 m^3), 99.9% sterilization efficacy, and is safe for non-target organisms, specifically humans. As it is a permanent ceiling light, it does not interfere with the operations of hospital rooms. After utilizing Beer-Lambert's Law and performing dosage, intensity, and optics efficacy tests, we determined that our final design has a 99.9% inactivation rate of HCoV-OC43 in 29.06 min, of HCoV-229E in 41.7 min, and of SARS-CoV-2 in 29.06 - 41.7 min while following the regulatory exposure limit of 0.05 $mJ/cm^2/min$. This design thus provides for easy implementation into public settings to significantly reduce the spread of fatal viruses.

2.Introduction

2.1 Motivation

With emergence of the novel coronavirus SARS-CoV-2, increased attention has been drawn to keeping environments sterile. Chemical disinfectants are commonly used but can cause pathogens to develop resistance, have negative effects when in contact with humans, and are ineffective against aerosolized pathogens [1]. Germicidal UVC lights have been developed to address the drawbacks of chemical disinfectants, providing a way to deactivate surface adherent and aerosolized pathogens, thereby rendering them unable to develop resistance [2]. However, UVC radiation outside of the range of Far-UVC (207 - 222 nm) is still harmful to humans, causing afflictions such as cancer and cataracts [2]. Without being able to expose humans directly to UVC light to remove harmful substances, populated areas remain hotbeds for pathogen transmission. Far-UVC light addresses this issue as its short wavelengths should not be able to penetrate the outer cell layer of skin or eye tissue [3]. As Far-UVC lights are not a risk to humans, they can be implemented across any public setting and be utilized even in high traffic areas. This constant disinfection will significantly reduce virus spread and transmission, specifically in high traffic/high risk areas, such as hospitals, creating a safer and more sterile environment.

2.2 Competing Designs

A wide range of disinfection devices that incorporate Far-UVC light exist, but many are not commercially available as of right now and have price points ranging from $500 to multiple thousands of dollars. Additionally, many of them only disinfect small, targeted areas and have short or unspecified ranges. Our design aims to innovate current products by increasing the coverage and efficacy of current models and provide a permanent solution that can easily be implemented across various public settings.

2.2.1 222 nm Far-UVC Light

Figure 1 shows a 222nm excimer lamp that comes with a 120V power supply that operates at 150W. This device is priced at $1,000 and provides a narrow emission line of 222 nm light. No quantitative information is provided on its effectiveness against pathogens, but the description does state that it “prevents the regrowth of bacteria” [4].

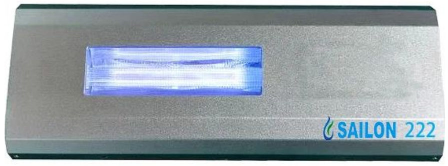


Figure 1: Sailon UVC - 222 nm Far-UV Light - 150W. Source: [4]

2.2.2 Standing Far-UVC Lamp

The Sterilray ADV is a vertical standing, autonomous Far-UVC disinfection device that senses and navigates through a room within 45.72 cm of target objects (Figure 2). The speeds and routes can be manually modified and archived for increased targeting of high contact areas, and the device is capable of autonomous charging. Sterilray has performed tests on the effectiveness of their Far-UVC light against certain bacteria but only at a distance of 5.08 cm [5]. Pricing is only available upon request for the device.

Figure 2: The Sterilray Autonomous Disinfection Vehicle. Source: [5]

2.2.3 Far-UVC Disinfection Light Fixture

As shown in figure 3, this Far-UVC light fixture includes 3 Far-UVC lamps in parallel contained in a metal, overhead housing. This fixture claims a 99% disinfection rate of viruses and other germs but does not provide specifications on coverage or testing. Additionally, there is a safety warning listing loss of vision and skin irritation as possible effects when looking into the light source or after prolonged exposure. With dimensions of about 91.4 × 213 cm, coverage can be assumed to be somewhat large, but the cost is high at approximately $7,000 [6].

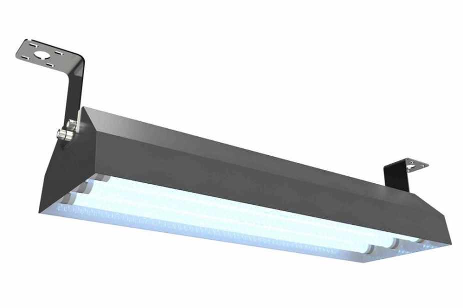


Figure 3: 120W Far-UVC Excimer Disinfection Fixture. Source: [6]

2.2.4 Far-UVC Box Sanitizer

The sanitation box in figure 4 provides 360° disinfection using 2 separate Far-UVC lights. A 99.99% sterilization rate is guaranteed after 1 minute of exposure, and the box requires a 1500W power source. Additionally, the wavelength of light can be tuned, and the manufacturer claims easy operational use with an automatic cutoff system [7]. However, pricing is only provided upon a request of the device, and delivery is estimated at 8-10 weeks.

Figure 4: Far-UV Sterilray™ Pathogen Reduction Box (PRB) Model S1000. Source: [7]

2.2.5 Far-UVC Disinfection Wand

The Far-UVC wand design is beneficial for its mobility and quick and easy use (Figure 5). High contact areas can be targeted and disinfected quickly and often with this device. Sterilray claims a “high level of disinfection” when passing the light 2.54 - 5.08 cm over the target area at about 60.96 cm per second [8]. As previously stated in section 2.2.2, controlled testing of just the light against a variety of bacteria and viruses has shown significant but variable results, which are dependent on exposure time, distance, and intensity. This product also requires a request for pricing.

Figure 5: Excimer Wave Sterilray Disinfection Wand. Source: [8]

2.3 Problem Statement

Germicidal ultraviolet light (254 nm), referred to as GUVC light, has been proven as an efficient source of killing pathogens with 99.9% effectiveness. Unfortunately, due to the nature of this longer wavelength, GUVC light can only be utilized in settings where no humans are present, as prolonged exposure to this light can cause temporary or permanent eye and skin damage. As an alternative, Far-UVC light (~220 nm) has been proposed to have little to no health risks due to less penetration into human skin from its shorter wavelength, while still maintaining the same effectiveness rate as GUVC light. As these results have only come from short term and limited empirical studies, our goal is to perform a meta-analysis to further investigate the effectiveness of Far-UVC light in preventing coronavirus strains HCoV-229E, HCov-OC43, and SARS-CoV-2 from existing on surfaces and in the air. We will determine its efficacy at different light dosages, distances, and durations by utilizing literature, probability models, and survival formulas. Based on our findings, we will design a product that will use Far-UVC light to kill airborne and surface adherent viruses in a fully furnished 10.20 m^3 clinical patient bathroom with 99.9% effectiveness. By using probability equations and models (Beer-Lambert's Law), we will theoretically prove the product's efficacy.

3.Background

3.1 Background Research

With the SARS-CoV-2 global pandemic disrupting everyday life around the world, light has been at the forefront of disinfecting technologies. Its history as an inhibitor of microorganism growth dates back to 1877 when Arthur Downes and Thomas P. Blunt observed that light could prevent pathogen growth. After studies and understanding grew about light and its effects, William F. Wells pioneered the first use of ultraviolet germicidal light as a disinfectant against microorganisms in 1935. Between 1950-1990, there was a lull in utilizing light against organisms, but a re-emergence of UVC light as a disinfectant began in 1992 after a rise in tuberculosis in the United States [9]. It has been on an upward trend since and has now been put on center-stage due to the current situation. However, the current light disinfectant, GUVC light, poses health risks to humans via direct exposure. Therefore, Far-UVC light has become a focus of current studies as a safer alternative that can be utilized to kill pathogens as they establish in populated areas. Does it have the same efficacy as GUVC light? How is it safer? How can it be incorporated into products for commercial and clinical use? These questions will be answered in the following sections.

3.1.1 Physics of UVC Light*

All waves have a wavelength (λ) and a frequency (f). For light, the wavelength multiplied by its frequency will result in the speed of light ($c \approx 3.00 \times 10^8$ m/s). UVC light consists of light that produces wavelengths in a range of 200-280 nm. According to the equation, $\lambda \cdot f = c$ [10], these wavelengths correspond to a frequency range of 1.1e9 - 1.5e9 MHz. Converting these frequencies into energy per mol by using the equation, Energy $\cdot$ (6.022e23 mole^{-1}) = (6.63e-34 Js) $\cdot f$ [11], it is found that a wavelength range of 200-280 nm relates to an energy range of 427-598 kJ/mole. GUVC light is the main source of disinfectant used currently with a wavelength of 254 nm. This generates a frequency of 1.2e9 MHz at 471 kJ/mole. On the other hand, Far-UVC light has a wavelength of 222 nm and a frequency of 1.4e9 MHz at 539 kJ/mole [12].

3.1.2 UVC Light as a Disinfectant* (Biological Interaction)

The wavelength of GUVC light and Far-UVC light is long enough to penetrate through cells and emits radiation with high enough energy to disrupt these cells. Radiation kills cells through the disruption and damage of DNA. As DNA is required for cell division or binary fission (prokaryotes), DNA damage can lead to disruption of cell division and thus become fatal to an organism [13]. As the wavelength of these lights can easily penetrate through at least one cell membrane, their radiation is successful at killing viruses. Thus, the radiation can act as a successful disinfectant for targeted areas. For example, GUVC light has been determined to be 99.9% effective at inactivating various pathogens at low doses of 1.7 and 1.2 mJ/cm^2 [14].

3.1.3 UVC Light Safety*

Although GUVC light has been proven to be effective at killing pathogens, its health risks only allow the light to disinfect areas when humans are not present. Due to its longer wavelengths, it can penetrate through the human stratum corneum (epidermis), the ocular tear layer, and the cytoplasm of individual human cells, creating skin or eye irritation for humans [14]. In instances of prolonged direct exposure, temporary eye and skin damage may occur, such as cornea injury. This generally heals after a couple of days. Short-term effects may also include redness or ulceration of the skin. At high levels of exposure, burns can be serious. For long-term exposures, there is also a cumulative risk of premature aging of the skin and skin cancer [15].

On the other hand, despite Far-UVC light's higher energy and frequency, its shorter wavelengths make it a safer alternative as a disinfectant. The human stratum corneum (the outer dead-cell skin layer), ocular tear layer, and cytoplasm of individual cells consists of 15 to 20 layers of corneocytes with a 10 - 40 µm thickness. As Far-UVC light has a penetration range in biological materials of less than a few micrometers, it cannot reach living human cells in the skin or eyes. This reduced range is due to its strong absorption by proteins and other biomolecules, severely limiting its ability to penetrate biological materials. However, as viruses are extremely small, Far-UVC light can still penetrate and kill them [14]. Far-UVC light is thus a safe alternative to GUVC light and should be able to remain permanently on in settings even with humans present.

3.1.4 Far-UVC Studies*

There have been two current case studies performed with Far-UVC light that proves that it has the same efficacy as GUVC light at killing viruses. The first study was by the Columbia Medical Center of Research. They tested the effectiveness of Far-UVC light on HCoV-229E (VR-740) and HCoV-OC43 (VR-1558) using human diploid lung cells infected with the virus. The tests were performed with Excimer lamps (Figure 6) at distances 22 cm away from the virus, spanning back and forth across a 26 cm × 25.6 cm × 254 µm UV-transmitting plastic window. The results concluded that HCoV-OC43 and HCoV-229E were ~90% inactivated in ~8 minutes, 95% in ~11 minutes, 99% in ~16 minutes, and 99.9% inactivation in ~25 minutes. Based on the data, inactivation of the two human coronaviruses by 222-nm light followed a typical exponential disinfection model, with an inactivation constant for HCoV-229E of $k = 4.1\ cm^2/mJ$ (95% C.I. 2.5–4.8), and $k = 5.9\ cm^2/mJ$ (95% C.I. 3.8–7.1) for HCoV-OC43. These values imply that 222 nm UV light doses of only $1.7\ mJ/cm^2$ or $1.2\ mJ/cm^2$ respectively produce 99.9% inactivation (3-log reduction) of aerosolized HCoV-229E or HCoV-OC43. Both of the studied coronavirus strains have similar high sensitivity to Far-UVC inactivation. As all human coronaviruses have similar genomic sizes which is a primary determinant of UV sensitivity, it is reasonable to expect that Far-UVC light will show similar inactivation efficiency against all human coronaviruses, including SARS-CoV-2 [14].

The second study was performed by Hiroshima University and included SARS-CoV-2 containing solutions. Tests were conducted with a 100 microliter solution containing the virus (ca. 5 × 106 TCID50/mL) spread onto a 9-cm sterile polystyrene plate [16]. The researchers allowed it to dry in a biosafety cabinet at room temperature before placing the Far-UVC lamp 24 cm above the surface of the plates. This in vitro experiment showed that 99.7% of the SARS-CoV-2 was inactivated after just a 30-second exposure to 222 nm UVC irradiation at 0.1 mW/cm^2 [16].

Both tests were conducted using the Ushio Care222TM krypton-chloride excimer lamp see in figure 6 below and both proved that this Far-UVC light source was successful in deactivating viruses, with 99.9% effectiveness. Unfortunately, the light source is only a part of a light stand causing it to have limited maneuverability, range, and coverage. Therefore, a design that will be able to transmit Far-UVC light across a full room to kill 99.9% of the viruses is needed.

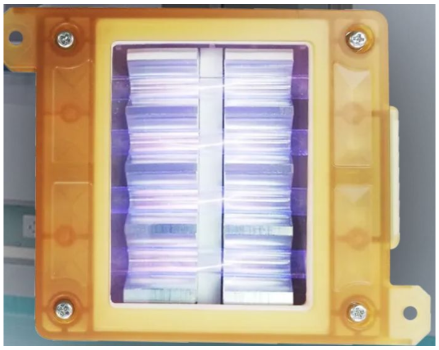


Figure 6: Ushio Krypton-Chloride Excimer Lamp. Source: [17]

3.1.5 Physiology of Coronavirus Strains*

Out of the three strains of coronavirus, HCoV-229E, HCov-OC43, and SARS-CoV-2, they all have similar genomic sizes, physical sizes, and nucleic acid configurations. The genome sizes of HCoV-229E, HCov-OC43, and SARS-CoV-2 are 27.5 kb, 30 kb, and 29.8 kb to 29.9 kb respectively [18]. As physical and genomic size are the main factors that contribute to radiation and UV sensitivity [14], all three strains should experience similar deactivation effects. Further, as SARS-CoV-2 has a closer genome size to HCoV-OC43, we can expect that it will have closer results to HCoV-OC43 in our testing compared to HCoV-229E.

3.1.6 Far-UVC Lights*

We compared current commercially available Far-UVC lights to determine which one had the highest Far-UVC 222 nm power output and thus which light could be implemented into our design. The first lamp we found was the Sailon lamp from Figure 1. It has a 222 nm intensity output of 35 µWatts/cm^2 at 100 cm [4]. The Larson Electronic Far-UVC Excimer lamp has an intensity output of 80 µWatts/cm^2 at 3.9878 cm [19] and can be seen in figure 7 below. The third commercially available Far-UVC lamp that we found was the Ushio Krypton-Chloride Excimer Lamp (Figure 6). It can have a power output of .2 Watts, making it the lamp with the highest power output. We performed tests on all three types of lamps to see how they compared, but we performed a majority of our tests and moved forward with the Ushio Lamp, as it has the highest intensity output and thus can provide the fastest disinfection rate, as seen in the testing section below.

Figure 7: Larson Electronic 80 μWatts/cm^2 Excimer Lamp. Source: [19]

3.1.7 LED Lights*

As our design incorporates Far-UVC lights with light emitting diodes (LEDs), the functions and properties of LEDs were required to understand how this would be possible. LEDs are used much more frequently today due to their high efficiency in turning electricity into energy in the form of light. However, incandescent bulbs are much lower in efficiency, turning most of its electrical energy into heat, rather than light [20].

LED lights start with the anode (positive charge) and cathode (negative charge) wires, which then connect respectively to the p-type and n-type materials of the semiconductor. The p-type material contains positively charged “holes” while the n-type material contains negatively charged electrons. When an electrical current is applied, the holes and electrons will move towards each other until they combine and release energy. This is due to an equilibrium shift from electrons entering the n-type and holes entering the p-type. As the energy for the n-type electrons is higher than the p-type holes, the electrons must give away some of its energy to combine with the holes. This released energy is turned into photons, which emits the visible light from a LED [21].

The different types of visible light emitted from LEDs is due to the “band gap”. The band gap is the difference in energy between the electrons from the n-type and holes from the p-type. Different band gaps can cause for more or less energy to be released from the electrons in order to combine with the holes. Different materials for the n-type and p-type can provide for differences in energy levels in their respective electrons. This energy variance is what leads to the different wavelengths of light produced from the diode[21].

3.1.8 Power Supply and Circuitry

Our design will be implemented into hospital bathrooms and should be compatible with standard U.S. wall plug power supplies. Generally, the standard U.S. wall plug supplies electricity of 120 volts and 15 amps totaling 1800 watts [22]. We plan on implementing LEDs into the design which draw power based on length and the specific type of LED. The total wattage of an LED is equal to the length multiplied by the watts/length given by the LED's manufacturer. Additionally, should we use existing Far-UVC lamps in our final design, the wattage will be provided and will simply add to the power consumption of the device. However, they will have to be wired in parallel to each other to ensure full power input and output [23]. The concept of including variable intensities was an attractive concept to our client and can be done with the use of dimmer switches. Power output, which corresponds with light intensity for both LEDs and excimer lamps, can be modulated through dimmer switches which modulate the electricity flow into the lights. This is done by cutting off and releasing the flow of electricity 120 times per second. The amount of time the flow is cut off for is controlled by the user interface, with longer times corresponding to lower power input and lower intensity and vice versa [24].

3.2 Client Information

Our client is Dr. Ernesto Brauer, a Critical Care Physician at Aurora St. Luke's Medical Center. As he is exposed to diseases and viruses at work, he created a mini Far-UVC disinfecting room for himself. He would like further research done to determine its efficacy as well as a product designed that could become widespread to help disinfect clinical settings.

3.3 Design Specifications

Our goal is to perform a meta-analysis to investigate the effectiveness of Far-UVC light in deactivating HCoV-229E, HCoV-OC43, and SARS-CoV-2 on surfaces and in the air. We will determine its efficacy at different light intensities, dosages, distances, and durations by utilizing literature, probability models, and experimentation. Based on our findings, we will design a product that will use Far-UVC light to kill airborne and surface adherent viruses in a fully furnished 10.20 m^3 clinical patient bathroom with 99.9% efficacy. This efficacy will be achieved in under 60 min. This design will consist of a Far-UVC light that must have a shelf life of 50,000 hours. It will not cause harm to human skin or eyes even after prolonged exposure and will adhere to current International Commission of Non-Ionizing Radiation Protection (ICNIRP) safety standards; the current regulatory exposure limit of 222 nm light to the public is ~3 mJ/cm^2/hour with a maximum regulatory limit of 23 mJ/cm^2 per 8-hour exposure [25]. Our design will then be available for others to implement in public settings. The full product design specifications can be found in section 11.1 of the Appendix.

4.Preliminary Designs

4.1 General Concept

The following designs were created through brainstorming with the entire team and draws on the research of Far-UVC light and existing Far-UVC products. Our designs aimed to adhere to our client's goals, the problem statement, and the product design specifications (section 11.1 in the appendix). The main focus was to implement our design in a clinical patient room environment where the spread of viruses must be contained. Use of a disinfecting light that is safe for human exposure can more easily prevent the spread of airborne viral pathogens and is an important sterilization system to have to promote a safe environment, especially during a pandemic. Each design includes a detailed drawing/rendering of the desired concept along with a summary of the overall functions.

4.2 Preliminary Designs

4.2.1 Design 1: Far-UVC Light Emitting Diode (FULED)

The FULED design is an overhead light fixture with LED lights to create an efficient product that emits Far-UVC light (Figure 8). The overhead light is a 61 cm × 183 cm frame that is 15.48 cm deep to hold the individual bars of LED lights. Wires can attach to ceiling fixtures and the top of the light fixture, allowing for easy installation and transportation. The frame will be made of 6.35 mm steel to protect the lights from any damage. The LED light bars are made of plastic and are hollow rectangular shapes. Inside the rectangle are the wires and resistors that connect to each LED light. The LED lights on the outside of the bar are spaced 2.54 cm apart from each other and are 0.645 cm thick.

This design's main focus is to provide Far-UVC light using LEDs lights into a common overhead light fixture design. There are existing UV-LED lights on the market but there is relatively incomplete documentation on Far-UVC LED lights. The problem with creating Far-UVC LEDs is the amount of energy the LED can produce. Smaller wavelengths require more energy to produce and more energy to stabilize that wavelength. Implementing LEDs that create Far-UVC light will not just allow for products such as an overhead light, it would allow this light to be used for a more universal purpose and apply to many products. LED lights are also more energy-efficient (see section 3.1.7) and will allow for a longer shelf-life than standard fluorescent bulbs that produce Far-UVC.

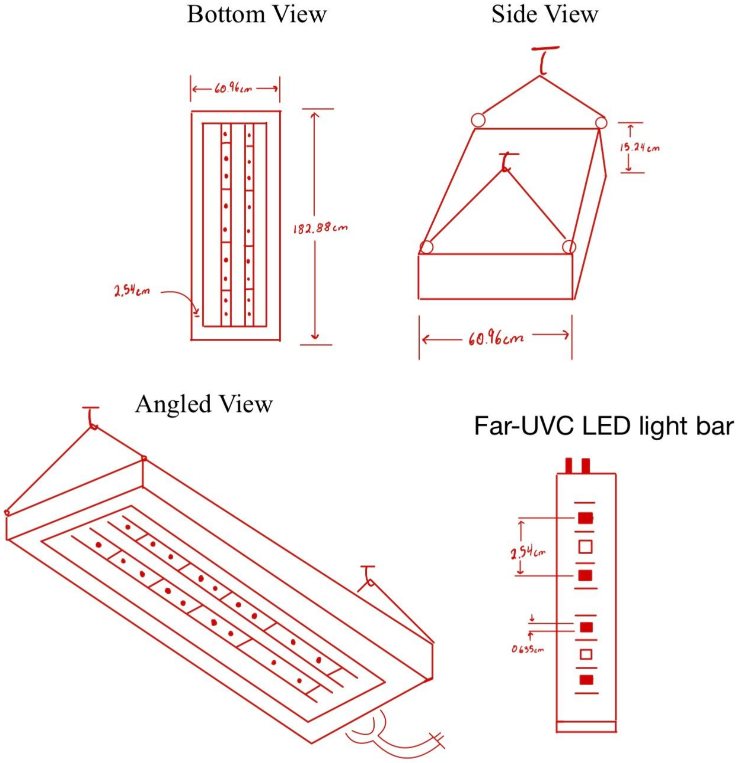


Figure 8: The FULED is attached to the ceiling by hooks with wire supports and features the Far-UVC light bar attached to the light fixture.

4.2.2 Design 2: 2-in-1 Air Purifier and Far-UVC Sanitation

The 2-in-1 solution shown in Figure 9 below features an air disinfection unit and a box to disinfect personal items. The entire unit is a 122 × 61 × 61 cm stationary box. The air disinfection portion acts as an air purifier, filtering air into the unit to be effectively cleaned by Far-UVC light. This passive unit can remain on throughout the day to clean the air throughout the room. The personal item sterilization box makes up the top 30.5 cm of the unit, giving the box a 30.5 cm depth. This box is targeted for high contact items that easily transport germs, such as phones, pens, stethoscopes, and other related items. The user can place these items for a specified amount of time in the enclosed box, allowing the user to disinfect these materials periodically throughout the day. The enclosed box feature allows for the entire surface area of an object to be exposed to the Far-UVC light. Switches for controlling the air purifier and sterilization box will be located on the side with options for changing intensity.

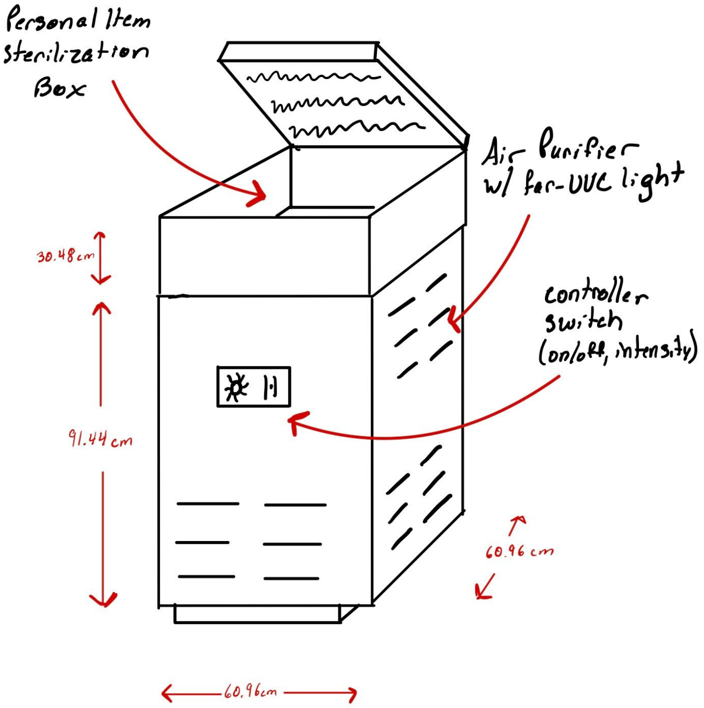
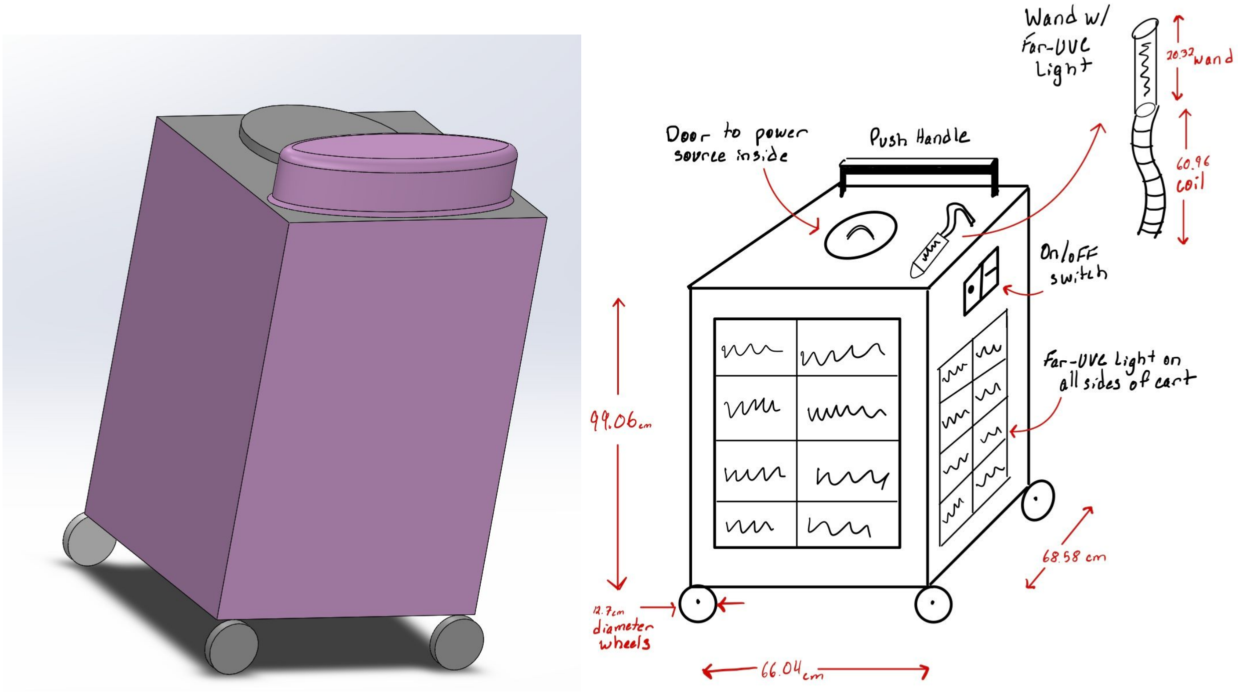


Figure 9: The 2-in-1 Air Purifier and Far-UVC Sanitation solution is a stationary design to be used in rooms.

4.2.3 Design 3: Mobile Light Cart - Easy Access

The Mobile Light Cart solution (Figure 10) is a transportable cart that features passive and active solutions for airborne and surface disinfection using Far-UVC light. The main cart is a 70 × 67.1 × 101 cm rectangular cart with 12.9 cm diameter wheels for transportability. It contains Far-UVC lights on all outward sides of the cart. There is also a 62 cm long extendable handheld Far-UVC light wand for the user to hold and allows the user to focus the Far-UVC light on shadowed areas or high contact surfaces such as doorknobs. The Far-UVC light that shines from the sides of the cart will not be able to reach every area of a room or bathroom, emphasizing the utility and importance of this wand. There will be shadowed areas and surfaces that the Far-UVC light from the cart cannot effectively disinfect, so the handheld wand becomes especially useful as the user can actively use the more directional light from the wand to reach these areas. The safety of Far-UVC light makes it safe for the user to actively disinfect shadowed areas while the cart lights are continuously on. There is also a handle on the top of the cart to push the cart with ease and protruded edges on the sides of the cart protect the Far-UVC light on the sides of the cart. The cart features a compartment in the middle holding the power source with a hatch in the middle of the top side to access it.

This solution can utilize the technology and benefits of Far-UVC light in healthcare by being transportable and versatile. While current Far-UVC light production is limited and very expensive [14], the versatility makes the cost of Far-UVC light worth the investment. The cart can be moved from room to room for active work, or left in a room where it may be necessary.



A *B*

Figure 10: Panel A shows a SolidWorks rendering with the general shape and external physical characteristics of the Mobile Light Cart. Panel B highlights the main features and components of the entire cart including the removable wand, wheels, and Far-UVC light on all sides.

5.Preliminary Design Evaluation

5.1 Design Matrix

Table 1: Far-UVC Device design matrix. The FULED was the highest-scoring design and therefore the winning design. Red areas represent the highest scores of each category. Lighter shaded red blocks indicate a tie in the rated category.

Far-UVC Device Designs							
Design Criteria	**Weight**	Mobile Light Cart - Easy Access		FULED Overhead Light		2-in-1 Air Purifier and Far-UVC Sanitation	
Efficacy*	25	4/5	20	5/5	25	4/5	20
Coverage	20	4/5	16	4/5	16	2/5	8
Safety	15	4/5	12	2/5	6	4/5	12
Ease of Fabrication	15	3/5	9	3/5	9	4/5	12
Cost	10	3/5	6	3/5	6	2/5	4
Energy Usage	5	4/5	4	3/5	3	2/5	2
Durability	5	4/5	4	5/5	5	2/5	2
Ease of Use	5	3/5	3	5/5	5	4/5	4
Total (100)	**100**		74		75		64

***Fractionated scores for each category are multiplied by the weight, giving a weighted score for each category. Scores are then added to give an overall score out of 100 possible points for each design.*

The design matrix above consists of eight criteria: efficacy, coverage, safety, ease of fabrication, cost, energy usage, durability, and ease-of-use. The efficacy rating is determined by the device's ability to effectively kill 99.9% of viruses within a reasonable timeframe (60 min or less) in a 10.20 m^3 room. This category has the highest weight of 25 in the design matrix because the main goal of as stated in our problem statement is to determine an effective method to inactivate viruses. The coverage criteria is how much area the product can effectively disinfect. The more area the design can cover, the more efficient and effective the design will be. The optimal coverage would be over 10.20 m^3. This goes hand-in-hand with our efficacy criteria as a greater coverage would increase the light's ability to disinfect 99.9% of viruses across the room in a timely manner. Thus, coverage is given the second highest weight with 20.

Another important goal is to limit the potential harm from exposure to light. Safety is an important criterion. Despite being believed to be safe for human exposure, the Far-UVC wavelength has not been tested thoroughly enough. As a result, these designs will be evaluated cautiously. While safety is an important subject, each of these devices can only cause harm if the light is in direct contact with human tissue, so all of these designs can be made safer by having them on only while people are absent. Thus, the weighted score of safety is 15, placed lower than efficacy and coverage. Ease of fabrication considers how much time and effort it will take to manufacture the product. If hospitals need access to these lights, manufacturing must be efficient to make the lights affordable and widely available. The weight of this category is the same as safety (15) as it is important but not as big of a concern as the performance attributes, efficacy and coverage.

The price of the materials and manufacturing is used to determine how we scored the cost criterion for each design. As the costs of Far-UVC light should decrease as manufacturing and production demands increase in the future, the cost criterion was not a major concern in our present situation, leading to its weight only being 10. Energy usage is the amount of energy required to operate the device. Durability relates to how long the device will last given the amount of time the customer uses the device and based on our goal of a 50,000 hour shelf-life. Lastly, ease of use relates to the accessibility and knowledge required to operate the light source. These three categories are all weighted at 5 because they are not the main focus of the project, but still, hold importance in the decision of which design would be best.

5.2 Design Matrix Evaluation

2-in-1 Air Purifier and Far-UVC Sanitation:

The 2-in-1 design shown in Figure 9 scored 64/100 overall. In considering efficacy, the 2-in-1 scored 20/25 because this unit would not only disinfect the air around it, it also provides a space for users to disinfect frequently used items. However, it would not be consistently effective in all areas of a room, so it cannot fully get rid of viruses like the FULED light. Thus, it did not receive the full 5/5 score. The coverage of the 2-in-1 is scored at 8/20. Although this design would ideally be placed in many areas, it is a single air purification system with minimal range that depends on the flow of air and the disinfecting box for personal items would only disinfect smaller items instead of the surrounding area. The 2-in-1 is rated at 4/5 for safety because the unit contains the Far-UVC light within it, limiting direct human exposure. We rated the 2-in-1 at the highest score of a 4/5 for ease of fabrication because a design like this is already on the market with regular UV light, so mimicking the design with the Far UVC light would not be difficult. Despite the 2-in-1 requiring many parts for the air purification and light system, once the parts are acquired it would not be disproportionately more difficult to assemble compared to other designs.

The cost is rated a 2/5 because the 2-in-1 is a larger, more complex unit than the other designs. Creating the air purification system would incur more costs and complexities because of the many components that would be required for different systems. In addition, replacing filters and installing this system could be costly. Energy usage received the lowest score of a 2/5 because this unit would remain on, requiring power to bring air in and push it out, in addition to the energy used by the light. For durability, the 2-in-1 also received the lowest score of a 2/5 because it is a large unit, and the air purification system would require many moving parts. If this unit is implemented on a large scale, it could be more difficult to maintain all units in working order. The 2-in-1 scored a 4/5 for ease of use because operating the unit would be simple. There would be controls for the intensity of the air-purifier and the box would require a user to simply place their items in for a specified amount of time. All in all, this design ranked the lowest because it is a more complex, inconvenient, and less effective design overall.

Mobile Light Cart - Easy Access:

The Mobile Cart design scored 74/100 with top scores in energy usage, coverage, safety, and cost. The mobile light cart would be effective because it can be moved to certain spots in a room that need to be disinfected, giving it lots of versatility. Additionally, the removable disinfecting wand can reach areas that are not accessible for the cart. Unfortunately, a large coverage and high efficacy are not guaranteed for this design. The removable wand only acts as a disinfectant when being used and the cart itself only offers variable times of disinfecting as it needs to be moved around often. This brings the possibility of the user not applying an effective dosage to a contaminated surface by moving away from the area too quickly. While this design seeks to reach every surface in the room, its overall coverage during a given time frame is not as large as the FULED. Thus, it would not deactivate as high of a percentage of viruses during that time frame. As a result, it received a 20/25 in efficacy (lower than the FULED) and a 20/25 in coverage. This design was deemed relatively safe because you can use the mobility of the product to keep it from pointing directly at people at a high intensity. However, patients and users would still be exposed to this light and as we do not have enough evidence to determine the long term effects of exposure to Far-UVC light, this design received a 12/15 safety score.

The mobile design received a relatively low score for ease of fabrication. Moving components, like the addition of the removable wand, may pose challenges to manufacturing. As a result, the cost of the mobile light cart would be more expensive. However, it would be more affordable for a healthcare facility to rotate several carts around the premises rather than purchasing and installing lights in every room. The energy usage of the mobile design would be relatively low since it would not be on all the time and could be used only as needed. Additionally, there would be less overall light being used for a few mobile carts as compared to the number of lights you would need for a whole room. The durability of the mobile light would be moderate considering the expected daily use and frequent transportation. Lastly, ease of use for the mobile light would be the lowest of the three design options because it requires someone to manually operate and maneuver the device.

FULED Overhead Light:

Our final design is the FULED. This design would be attached to the ceiling with the goal of illuminating large spaces and rooms while simultaneously disinfecting this area. Therefore, the FULED would have proper coverage, convenience, and high efficacy due to its constant usage and dosage output. The FULED design scored 75/100 in our design matrix evaluation. It received the highest scores in efficacy, coverage, durability, and ease of use. This overhead LED design would allow for the light source to span the length of a room while maintaining a proper intensity to effectively disinfect a room. Additionally, this design would operate through a traditional light switch which would increase the ease of use because the user only needs to flip the switch to begin operation. If the room does not need to be disinfected it can just as easily be shut off. The durability is also high in this design because the users would not have to directly handle the device besides installation so it avoids traditional wear and tear. The FULED is on the lower end in the ease of fabrication category because the combination of the Far-UVC light with the LED lights could pose a challenge during fabrication. Currently, Far-UVC LEDs are not readily available and are still being researched due to the difficulty in maintaining a proper output at such low light wavelengths.

In the design matrix, this design tied with the mobile cart in cost and ranked lower than the mobile design in energy usage because the device would likely be used a considerable amount of time. We would expect the cost of a Far-UVC LED to be comparable to the currently expensive Far-UVC lamp. But because LEDs have longer lifespans we anticipate the FULED design to be more cost-effective. Lastly, the FULED design received the lowest score in the safety category due to the lack of research, short and long term, on the effects on humans and the high intensity required to disinfect a full room with 99.9% effectiveness. Overall, this design received the highest score on the design matrix due to its high scores in the categories directly involved in addressing the problem statement.

5.3 Proposed Final Design

Our initial final design proposal included the best aspects of the proposed preliminary designs to achieve the most optimal product. As explained in the design matrix evaluation, efficacy, coverage, and safety are the top three criteria to create an optimal design. Therefore, we wanted our final design to include aspects of our preliminary designs that may improve certain criteria but base our ultimate design on the FULED because of its highest overall ranking and high rankings in the most important categories. The Far-UVC LED design would remain on the ceiling, but we wanted to also incorporate ways to adjust the light or improve the geometry in order to increase the coverage and make the device more versatile similar to the Mobile Light Cart.

We wanted to include an LED component in our design as opposed to a typical Far-UVC lamp in hopes of creating a more energy-efficient design with greater intensity, coverage, and efficacy. In addition, keeping the light attached to the ceiling and adjusting the lights to target specific parts of the room while keeping the lights on throughout the day would consistently keep the room clean and cover the full area of the enclosed space. This would thus allow for optimal efficacy.

To incorporate a selectivity aspect into our design, we wanted to make a separate set of switches that can control the movement of the lights on the ceiling. The idea is that you can angle the lights to direct it towards certain surfaces or lower/raise it to increase the intensity on respective surfaces. By incorporating the “mobile” aspect to our design, we can increase the level of safety and the overall coverage due to different angling and height variance for which the light is at. This allows certain areas to be specifically targeted for higher/lower exposure, such as an area where there is increased traffic.

We decided against using any aspects of the 2-in-1 design for our proposed final design because we felt that it was lacking in most of the criteria we had established, as well as the design did not fit all of the specific requirements set forth by our client. Although the 2-in-1 design incorporates features that we think are effective and can be useful in a future design, our client was hoping to use the Far-UVC light in a broader context where the design is used constantly whenever human traffic is present.

Ultimately, throughout the course of the design process, we made a couple final changes to our final design proposal as described above. In order to make the design more feasible, we had to use existing Far-UVC lamps instead of trying to fabricate our own Far-UVC light with an LED component. Our design also switched to having a light fixture with lights attached at various angles, including on the sides of the trapezoid, in order to increase the coverage so the full room can be reached efficiently and selectivity is not required. Incorporating a dimmer switch also allows the selectivity and efficacy to be adjusted instead of requiring our lights to move and is easier to implement in the design. Our final design, which will be described in the following sections, also considers other aspects such as geometry, materials, and efficacy in order to meet our clients criteria and make an optimal design.

6.Fabrication/Development Process

6.1 Materials

The aforementioned proposed final design was tentative, therefore throughout the course of the design process, we considered multiple materials that would work for the various ideas and modifications that came about. Ultimately, each material we decided on for our final design was chosen for a specific purpose.

In order to construct the base of the light fixture that the lamps would be attached to, we suggest using aluminum [26]. The reason for this material is because of its durability and affordability. In order to calculate the cost for the material that will be used as the base of the fixture, the total volume of material needed to be calculated. Assuming a thickness of ½ cm, the volume of material needed is approximately 11,343.66 cm^3 (see section 6.3 for details on dimensions). This was found by adding the volume of the base (230 x 62 x ½ cm) with the volume of the two trapezoids (708.66 cm^3 collectively), and the volume of the two dividers between the side and middle sections (3505 cm^3 collectively). After finding the required volume of the material, the density of the chosen metal and the price per unit was used to determine the cost in dollars. For the suggested material of aluminum, the density is 0.00595248 lb/cm^3 and the price per pound is $1.63 [27], totalling $110.06.

Because Far-UVC lights do not actually radiate light on the visible spectrum, we added visible white light LEDs to our design to illuminate the room. The cost for LED lights with a length of 238 cm is $24.50 [28]. Our final design uses seven LED lights with a length of 230 cm so the cost should be around $24.50 per light to give a total cost of $171.50 for the LED lamps. As for the Far-UVC light, we decided to incorporate a Far-UVC lamp that was already on the market, proven to work, and had optimal specifications (such as wattage, length, intensity, etc) for our design to be most effective and practical.

Ideally, we would have liked to incorporate some aspect of a Far-UVC LED into our design as our FULED preliminary proposal implied, however, it is more manageable to use a lamp that has already been created whereas an LED Far-UVC light has not been fabricated by any company. It is also more realistic if our design is to be implemented immediately. We decided to move forward with the Ushio lamp after comparing calculations with other lamps (see section 6.4 below). Our final design included 20 of the Ushio lamps at a price of $2,860/lamp or $57,200 total [29].

The addition of the fixture to the ceiling can be done with simple metal bolts of choice in the holes that are indicated in our final design. We did not include the price of the bolts in our total cost due to the fact that it is not directly part of the light fixture but rather is a part of the attachment system that the installer is responsible for. The total cost of our design would be

$57,481.56. The final materials, a cost table, and an outline of calculations can be found in Appendix 11.3.

We performed many calculations to ensure that our design not only met all of our clients criteria but also did so in the most effective way possible. In the results section, we created a graph depicting the number of lamps and their efficacy in order to rationalize how many lamps we would need for a timely inactivation rate without producing an unreasonable cost.

To ensure maximum output from the device, all of the excimer lamps must be wired in parallel, providing full voltage and amperage to each of them [23]. While this is more energy intensive, standard U.S. outlets generally provide up to 1800 watts of energy which is on the factor of 100 times what is required to power any of the excimer lamps we are considering and is well above the approximately 230 watts required for seven 220 centimeter visible LEDs that we will be incorporating into the design [22]. Additionally, two dimmer switches will be incorporated on the housing and integrated into the power cord that runs into the fixture. These dimmer switches will regulate the electrical input into the visible LEDs and excimer lamps independently allowing for variable output intensities [24].

Due to the fact that our design experiment was not completed in person we did not have a specified budget because we did not need to purchase anything. The ultimate list of hypothetical materials for the fixture includes the preferred material of the customer for the lights to be contained in (aluminum is suggested but not required), seven rows of visible white LEDs, and 20 Far-UVC lamps. The bolts for attachment, a power cord, electrical wiring, and dimmer switches would also be implemented by the installer.

6.2 Methods

The methods used in the development of our design project were limited to things that we could do virtually and experimentally. The reason for our hypothetical approach to the design experiment came from constraints such as a lack of access to facilities and resources due to Covid-19 regulations and an inability to purchase or create a Far-UVC light. Since our experimental design project was solely hypothetical, we were able to experiment with many virtual prototypes.

Our first final design prototype was a ceiling attachable light fixture consisting of Far-UVC LEDs. When we moved on to determining the hypothetical fabrication of this design, we found that Far-UVC emitting LED lights would have led to many complications. Problems arise with these particular LED lights because of a special semiconductor needed to produce light at the required 222 nm wavelength. This semiconductor is made of aluminum gallium nitride (AlGaN) and allows the electrons to transfer energy into light at the required wavelength. In order to construct this semiconductor to implement into LEDs, the growth of aluminum nitride crystals must allow for such crystals to be cut into very small pieces. These pieces often have small fractures that result in a high threading dislocation density. High threading dislocation blocks electrons from entering the band-gap without interference. This causes the LED to have low efficiency when transferring input energy to output energy. Aluminum gallium nitride is also hard to create in the form of p-type semiconductors. This is a problem as there will be much more electrons compared to holes, and often results in the electrons being lost, decreasing the energy efficiency [20]. Overall, using AlGaN semiconductors would allow for LEDs to produce Far-UVC light, but the efficiency is so low that it will take far too long to thoroughly disinfect a given area. As a result, our final design had to be modified to use Far-UVC light excimer lamps, opposed to Far-UVC LEDs.

After we established that Far-UVC LEDs were not plausible for our design, we decided to move forward with using existing excimer lamps for our final product instead. This was an easier and more realistic choice, as these lights are already commercially available, allowing our design to be implemented immediately. This meant that our final product was now going to be a light fixture consisting of existing Far-UVC lamps and illuminating LEDs that can be installed on the ceiling. After solidifying the design, we created hypothetical “prototypes", each using a different Far-UVC excimer lamp.

Using calculations and theoretical testing as our experimentation, we were able to evaluate the effectiveness of each available design. Originally, we were going to use a modeling software to create an image of the room with the lights in it, but we realized that it was not worth the cost to purchase a software when we could perform our own calculations via hypothetical models and formulas. The methods we used in order to experiment with our proposed final design “prototypes” included determining the minimum dosages required for 99.9% efficacy, establishing measurements for the typical room these lights would be in, and experimenting with various lamps, dosages, and intensities, through calculations. The testing methods that we used included finding the duration to reach a 99.9% disinfection rate of different coronaviruses, utilizing Beer-Lambert’s Law to determine absorbance, comparing different types of lamps and their respective disinfection rates, and analyzing how many lamps would generate optimal efficacy. For a more in-depth procedure, the calculations and testing document can be viewed in the Appendix, section 11.2.

After completing the experimental testing, we used computer generated images to construct our hypothetical design, ensuring that it will work well in the 10.20 m^3 clinical patient bathroom with regards to size. One main consideration taken into account when looking at size was the length of the light as the large amount of lamps utilized in the final design elongated the fixture substantially. The logic and reasoning behind our final design was enforced by our AutoCAD image, testing, calculations, and research.

6.3 Final Prototype

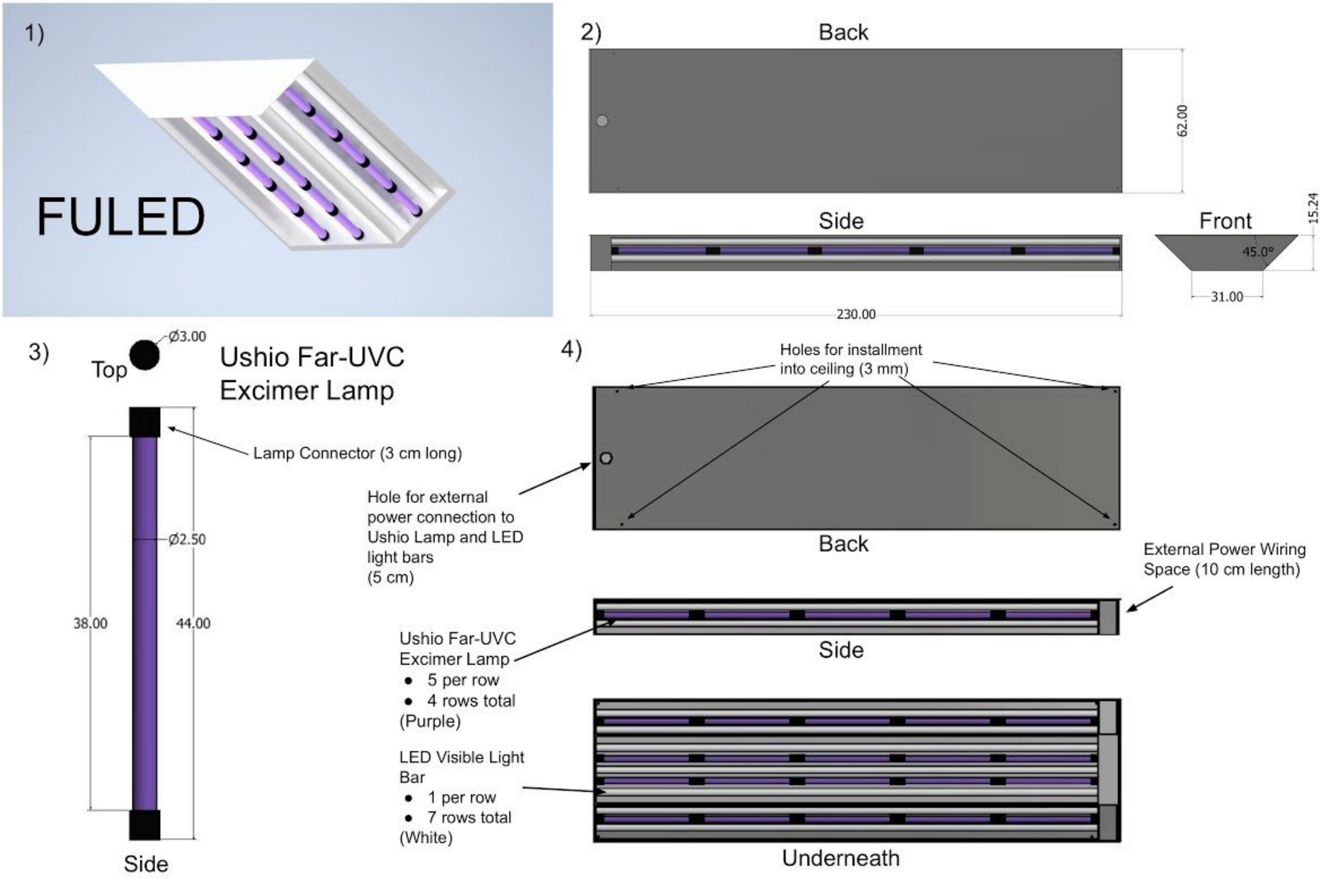


Figure 1)	Rendered image of software created model
Figure 2)	Back, side, and front view of software created model with dimensions (cm)
Figure 3)	Ushio Far-UVC Excimer Lamp software created model with dimensions (cm)
Figure 4)	Back, side, and underneath view of software created model with descriptions

Figure 11: Final Prototype of the FULED illustrating various views of the design to highlight specific features and components of the product.

6.4 Testing

First, the survival rate of HCoV-229E and HCov-OC43 and the dosages (D) required to kill them were found, as the calculations and testing could not be performed until target dosages were acquired. The virus survival rate ([S]) of HCoV-229E and HCov-OC43 is described by the first-order kinetics equation [14]:

$$\ln[S] = -k \times D$$

The k value is the UV inactivation rate constant or susceptibility factor (cm^2/mJ). For HCoV-229E and HCoV-OC43, the k values are 4.1 cm^2/mJ and 5.9 cm^2/mJ respectively [14]. The k value is not known for SARS-CoV-2, but we can determine the results of this strain based on the other two strains due to their biological similarities (see background section). In solving for 99.9% total disinfection, we set S = .001 and solved for the dosage. After the calculations, it was determined that the dosage for 99.9% effectiveness at inactivating HCoV-229E is 1.68 mJ/cm^2 while it is 1.17 mJ/cm^2 for HCov-OC43. We can then conclude that the dosage required for 99.9% effectiveness in killing the SARS-CoV-2 is between 1.17 and 1.68 mJ/cm^2.

According to the ICNIRP, the current regulatory exposure limit for Far-UVC radiation is a maximum dosage output rate of .05 mJ/cm^2 per minute. Over an eight-hour exposure period, the maximum dosage rate allowed is .047 mJ/cm^2 per minute [28]. Assuming a constant intensity and dosage were used to disinfect the viruses, we used these limits and the required dosages for 99.9% efficacy to calculate the approximate minimum duration required to reach a 99.9% disinfection rate for each of the coronaviruses of interest. *Table 2* displays the results of our calculations below. As these inactivation durations do not take into account intensity drop-off over distance, these calculated durations set up the basis for which the rest of our calculations and testing were founded on.

Table 2: An organization of the different durations to reach a 99.9% inactivation rate following differing standard limits for HCoV-OC43 and HCoV-229E.

Coronavirus	Standard Limit (mJ/cm^2)	Duration to Reach 99.9% Disinfection Rate (min)
HCoV-OC43 (beta)	0.05	23.4
HCoV-229E (alpha)	0.05	33.6
HCoV-OC43 (beta)	0.047	24.4
HCoV-229E (alpha)	0.047	35.1

In order to adhere to our client and the product design specifications, we determined that the dimensions for a typical clinical patient bathroom are 3.72 square meters with a ceiling height of 2.74 meters. As our light will be centrally located within the room, we determined that the furthest distance from a perfectly centrally located point is 3.04 meters (304 cm) using simple geometry calculations. These dimensions represent the distances for the rest of our calculations.

In order to determine how much the dosage would drop-off over 3.04 m distance, we used Beer-Lambert's law to determine how much Far-UVC light was absorbed over this distance. Beer-Lambert's Law is described by the following equation [30]:

$$A = \varepsilon * l * c$$

The ε value is the molar absorption coefficient with units 1/M(m), c represents molar Concentration with units of M, and l is the optical path length travelled by the light (3.04 m). As the major source of absorbance between the light and surfaces is air, we found the molar absorption coefficients at 222 nm and typical concentrations for each component of air and plugged them into the equation above, solving for absorbance. These values and calculations can be found in *Table 3* below.

Table 3: The absorption coefficients and concentrations for H_2O and CO_2 and their corresponding absorbance of Far-UVC light (222 nm).

Element	Absorption Coefficient 1/M*m [31]	Concentration (M)	Optical Path Length (m)	Absorbance
H_2O (g)	10^{-3}	.01904 [32]	3.04	3.32576e-5
CO_2 (g)	10^{-3}	.02272 [33]	3.04	6.90688e-5

Summing these absorbance values and plugging them into the equation, Absorbance = log(Transmittance) [30], we found that the transmittance of light through these elements is 1 (100%). These calculations prove that no light is absorbed over the distance from a centrally located light source to the corners of the room. As no light is absorbed, dosage and intensity will not be affected by absorption from water vapor and carbon dioxide. The absorption coefficients for N, N_2, O, and O_2 at 222 nm are so small that they cannot be measured precisely. Therefore, to determine the absorption, the penetration depth of Far-UVC light into each of these elements must be used. The penetration depth of Far-UVC light through each of these elements is about 110 km [34]. As the dimensions of our room are 3.72 m^2 room with a height of 2.7432 m, the absorption coefficient can be approximated as 0 because the light will not need to travel 110km.

Therefore, as the transmittance of Far-UVC light is not altered by H_2O and CO_2 and the penetration depth of Far-UVC light in N, N_2, O, and O_2 is not a concern based on the bathroom dimensions, the absorbance effects of air on Far-UVC are considered negligible. As air absorbance is not an issue, the intensity drop-off over distance and its effect on dosage will be our focus to determine efficacy.

The rest of our dosage, duration, and intensity calculations used the distance 3.04 m. This distance was used because it is the distance to the furthest point that our light will have to reach. If we determine that the light is 99.9% effective at this distance for a given intensity and duration, it will be 99.9% effective everywhere else in the room as these points are closer to the light and will experience a higher intensity. To determine how intensity is affected by distance (d), we used the point source inverse-square law [35]:

$$\text{Factor of Drop-off} = (1/[4(\text{pi})(d^2)])$$

This equation was used to find the corresponding drop-off over the 304 cm distance. After plugging in 304 cm for d, we found that intensity will decrease by a factor of 8.61e-7 by the time the light reaches the furthest point in the room. In order to determine how this intensity decrease will affect the time required to reach the optimal dosages, we used the dosage equation [35]:

$$\text{UV dose} = I \times t$$

"UV dose" represents the target dosage (1.68 mJ/cm^2 and 1.17 mJ/cm^2), "I" is the UV Irradiance/Intensity, and "t" represents the time of exposure. With the three commercially available Far-UVC lights (see background section), we calculated the intensity each light would output at 3.04 m and solved for the time required to reach the specified dosage. After determining the time it would take to reach each dosage, we added this delay to the original durations found in *Table 2*. By incorporating the delay into the times required to reach 1.68 mJ/cm^2 and 1.17 mJ/cm^2, we were able to determine the true duration required across the whole room, taking the intensity drop-off into account. To begin, we tested each light individually to determine which lamp was going to be most effective and thus the one we need to focus on for our subsequent tests. The four different lights and their intensity and time results at the dosage rates of .05 mJ/cm^2/min and .047 mJ/cm^2/min can be seen below in *Table 4 and Table 5* respectively.

Table 4: An organization of four commercially available Far-UVC excimer lamps with their respective intensities and durations required to reach a 99.9% inactivation rate following 0.05 mJ/cm^2/min standard limit for the set 10.20 m^3 bathroom dimensions for HCoV-OC43 and HCoV-229E.

Excimer Lamp	Duration Required for 99.9% Efficacy on HCoV-OC43 (min)	Duration Required for 99.9% Efficacy on HCoV-229E (min)
Ushio Lamp (5µW/cm2 from the source)	4,529,210	6,503,482
Sailon Lamp (35µW/cm2 at 100 cm)	647,033	929,074
Larson Excimer Lamp (80 µW/cm2 at 3.9878 cm)	283,093	406,493
Ushio Lamp (.2W/cm2 from the source)	136.7	196.2

Table 5: An organization of four commercially available Far-UVC excimer lamps with their respective intensities and durations required to reach a 99.9% inactivation rate following 0.047 mJ/cm^2/min standard limit for the set 10.20 m^3 bathroom dimensions for HCoV-OC43 and HCoV-229E.

Excimer Lamp	Duration Required for 99.9% Efficacy on HCoV-OC43 (min)	Duration Required for 99.9% Efficacy on HCoV-229E (min)
Ushio Lamp (5µW/cm2 from the source)	4,439,409	6386,199
Sailon Lamp (35µW/cm2 at 100 cm)	634,305	912,319
Larson Excimer Lamp (80 µW/cm2 at 3.9878 cm)	277,477	399,157
Ushio Lamp (.2W/cm2 from the source)	135.4	194.8

Based on the results seen in *Table 4 and Table 5*, we determined that the most efficient light to move forward with was the .2 Watt Ushio Lamp as this was the only lamp that produced an inactivation rate under 200 min with a single light. All of the other lights had a disinfection rate in the thousands which is considered not an applicable rate for our purposes. Therefore, based on the data and testing, we do not expect the Larson, Sailon, and 5μW Ushio lamps to be compatible with a design that requires a 99.9% efficacy rate at killing HCoV-OC4, HCoV-229E, and SARS-CoV-2 based on our room dimensions. Although the .2 Watt Ushio Lamp had the fastest disinfection rate, a rate of over two hours is still too long to be an effective design. In order to increase the time, we needed to increase the intensity of the lights. Thus, we performed our last set of tests on multiple lights in order to determine how many lights are required for an efficient time (under 60 min) as well as to compare how the rate is impacted over the course of multiple lights. Although we increased the intensity by adding more lights, we had to decrease the dosage output from each light in order to stay within the ICNIRP guidelines. Based on these tests, we expected to finalize our design by choosing an amount of lights that had a timely inactivation rate while still being material efficient. The results of these calculations can be seen in *Table 6 and Table 7* below.

Table 6: Durations required for an increasing number of Ushio Lamps (0.2W/cm^2) to reach 99.9% efficacy while adhering to the 0.05 mJ/cm^2/min limit

Number of Lamps - Ushio Lamp (.2W/cm2 Intensity)	Duration Required for 99.9% Efficacy on HCoV-OC43 (min)	Duration Required for 99.9% Efficacy on HCoV-229E (min)
1	136.7	196.2
2	80	114.9
3	61.1	87.7
10	34.7	49.9
16	30.5	43.7
20	29.06	41.7
25	27.93	40.1
32	26.94	38.68

Table 7: Durations required for an increasing number of Ushio Lamps (0.2W/cm^2) to reach 99.9% efficacy while adhering to the 0.047 mJ/cm^2/min limit

Number of Lamps - Ushio Lamp (.2W/cm2 Intensity)	Duration Required for 99.9% Efficacy on HCoV-OC43 (min)	Duration Required for 99.9% Efficacy on HCoV-229E (min)
1	135.4	194.8
2	79.8	114.8
3	61.4	88.3
10	35.5	51.1
16	31.3	45.1
20	29.95	43.1
25	28.84	41.49
32	27.87	40.1

The full set of calculations and testing can be found in section 11.2 of the Appendix.

7.Results

Tables 4 and *5* above display the time required for the individual lamps to reach a 99.9% inactivation rate for HCoV-OC43 and HCoV-229E adhering to the two different ICNIRP exposure limits. As seen in these tables, the Ushio lamp with an intensity of 0.5µW/cm^2 had inactivation rates of HCoV-OC43 in 4,529,210 and 4,439,409 min at dosage rates of 0.05 mJ/cm^2/min and 0.047 mJ/cm^2/min respectively. For HCoV-229E, this lamp had a deactivation rate of 6,503,482 min and 6,386,199 min for the two dosage outputs. Under the same exposure limit, due to the higher intensity of the Sailon lamp (35µW/cm2 at 100 cm), it managed to drop these times down for the same strains to 647,033, 634,305, 912,319, and 929,074 min respectively. The Larson excimer lamp had an intensity of 80 µW/cm2 at 3.9878 cm and thus was able to further decrease the total duration required for a 99.9% inactivation rate. This product had reached the benchmark in 283,093 and 277,477 min for HCoV-OC43 at a dosage of 0.05 mJ/cm^2/min and 0.047 mJ/cm^2/min respectively. It also had inactivation times of 406,493 min and 399,157 min for HCoV-229E under the same dosage limits. The Ushio lamp with an intensity of 0.2W/cm^2 had the highest 222 nm intensity output, allowing us to expect the fastest disinfection time. Our evidence backed this up as its respective durations were from the source, however, had durations of 136.7 and 135.4min for HCoV-OC43 and 196.2 and 194.8 min for HCoV-229E.

Based on this first set of testing, we concluded that the 0.5µW/cm^2 Ushio Lamp, Sailon Lamp, and Larson Lamp had too low of inactivation times. In order to be considered an efficient time, the rate has to be under an hour. Even though the data demonstrates that an increase in intensity leads to a higher disinfection rate, these lights are far too inefficient. Increasing the intensity by increasing the number of lights based on the lamps would require too many lights for our design and would lead to a very costly product as a result. Luckily, the .2 W/cm^2 output had an inactivation rate under 200 min, providing it was the most effective lamp. As the trend experienced from the data in *Table 4* and *Table 5* demonstrates that increasing intensity increases the inactivation rate, we determined that this lamp was close enough to our efficiency goal and that we could increase the intensity by adding more lights in order to reach rates under 60 min.

Table 6 and Table 7 above depict our tests on how increasing the lights impacted intensity and thus inactivation rate. These tables demonstrate the various rates of 99.9% efficacy for HCoV-OC43 and HCoV-229E corresponding to a certain number of 0.2 W/cm^2 Ushio lights. Under the 0.05 mJ/cm^2/min restraint, this Ushio lamp had disinfection durations of 136.7, 80, 61.1, 34.7, 30.5, and 29.06 minutes for 1, 2, 3, 10, 16, and 20 lamps respectively for HCoV-OC43. For the HCoV-229E strain with the 0.05 mJ/cm^2/min restriction, the 0.2W/cm^2 Ushio lamp had disinfection durations of 196.2, 114.9 87.7 49.9, 43.7, and 41.7 minutes for 1, 2,3, 10, 16, and 20 lamps respectively as well. With the 0.047 mJ/cm^2/min limit, the durations were 135.4, 79.8, 61.4, 35.5, 31.3, and 29.95 minutes for 1, 2, 3, 10, 16, and 20 lamps respectively for HCoV-OC43, while they were 194.8, 114.8, 88.3, 51.1, 45.1, and 43.1 minutes respectively for HCoV-229E.

Based on these results, we can conclude that increasing the number of lamps in our design exponentially increases the rate of inactivation and we see that the .2 W/cm^2 Ushio lamp will be able to provide a disinfection rate under an hour in a 10.20 m^3 bathroom. The testing proves that once ten lamps are implemented into our design, the product has an inactivation rate for both strains under an hour and thus meets our product design specifications. We continued to increase the number of lights in order to determine how much we could increase the disinfection rate within reason, as seen by our tests for 16 and 20 lights. We even found that 32 lights will correlate to a disinfection rate of HCoV-OC43 in 26.94 min at 0.05mJ/cm^2/min and 27.87 minutes at .047mJ/cm^2/min, while it is 38.68 min at 0.05mJ/cm^2/min and 40.1 minutes for HCoV-229E.

Figure 12 below gives a visual representation of how the number of 0.2W Ushio lamps impacts the inactivation rate of HCoV-OC43 and HCoV-229E under both of the ICNIRP exposure limits. The durations for each strain at the two standards are similar enough that the lines of best fit are the same, so only two lines appear on the graph. As concluded from the tables and our testing, the general trend of the inactivation rate as the number of lamps increase is negatively exponential. This means that the disinfection durations decrease and thus the inactivation rate increases exponentially as the amount of lamps increase.

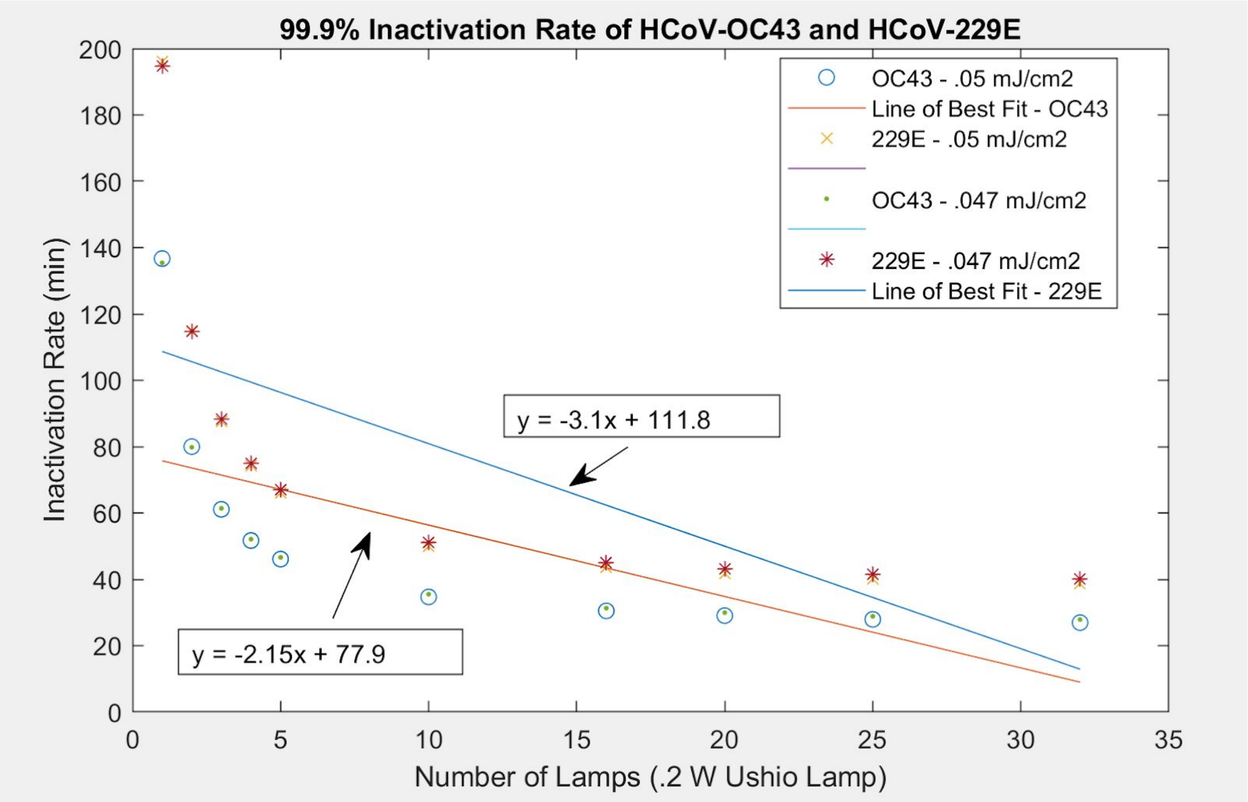


Figure 12: Inactivation Rate (min) vs Number of Lamps (0.2W USHIO Lamp) for HCoV-OC43 and HCoV-229E at 0.05mJ/cm^2/min and 0.047mJ/cm^2/min.

As the relationship between the number of lamps and the rate is exponential, our final goal was to determine the most effective amount of lights to implement in our design and compare it to our original plan of 20 lights. Although cost was not a major concern for our client, we wanted to make sure that all of the lamps used had a significant impact on the efficiency of the design and thus was worth the cost. As seen in *Figure 12*, once the design reached 20 lamps, the drop in disinfection time started to level out and was very minimal. At 16 lamps, the inactivation rate is 30.5 min for HCov-OC43 and 43.7 min for HCov-229E at .05 mJ/cm2. For .047 mJ/cm2, the rate is 31.3 min for HCov-OC43 and 45.1 min for HCov-229E. For 20 Ushio lamps, the disinfection rate is 29.06 min for HCov-OC43 and 41.7 min for HCov-229E at .05 mJ/cm2. For .047 mJ/cm2, the rate is 29.95 min for HCov-OC43 and 43.1 min for HCov-229E. The increase in disinfection rate from 16 lamps to 20 lamps for HCoV-OC43 is about 1.4 min and it is about 2 min for HCoV-229E. However, if we add 12 more lamps so our design has a total of 32 Ushio lamps, the rate only increases to 26.94 min for HCov-OC43 and 38.68 min for HCov-229E at .05 mJ/cm2. and 27.87 min for HCov-OC43 and 40.1 min for HCov-229E at .047 mJ/cm2. This is just over a 2 min increase for HCov-OC43 and about a 3 min increase for HCov-229E, despite adding 12 lamps. After adding 20 lamps to our design, any additional lamps added becomes highly inefficient in its decrease in time. The very minimal increase in disinfection rate is not worth the cost of these additional 12 lights, thus proving that our 20 Ushio lamp design is the most efficient and best possible design for our purposes.

Thus, based on the testing results above, our 20 Ushio light design will have a 99.9% inactivation rate of HCoV-OC43 in 29.06 min and of HCoV-229E in 41.7 min when the dosage is set to 0.05 mJ/cm^2/min. When the dosage is set to 0.047 mJ/cm^2/min, we expect a 99.9% inactivation rate of HCoV-OC43 in 29.95 min and of HCoV-229E in 43.1 min. For SARS-CoV-2, as the genomics are so similar to HCoV-OC4 and HCoV-229E (section 3.1.4 and 3.1.5), we can confidently expect a similar time frame of 29.06 - 41.7 minutes at 0.05mJ/cm^2/min and 29.95 - 43.1 minutes at .047mJ/cm^2/min to get 99.9% inactivation, with expectations that the rate would be closer to HCoV-OC43. Therefore, our design will provide an efficient disinfectant against HCoV-OC43, HCoV-229E, and SARS-CoV-2 for a clinical patient bathroom that can be run consistently with 99.9% effectiveness.

8.Discussion

8.1 Implications of Results

The results of our design experiment were found using hypothetical “prototypes” that we performed calculations and testing on. The results, as previously described, were the absorbance was negligible, and the optimal number of lamps to use was 20 because it would have an efficient 99.9% inactivation rate in 29-41 minutes. These results are relevant to the field of Far-UVC research because we have made relevant calculations that can be adjusted to match different needs. For instance, if the coverage of the light would need to be greater so that it could cover a larger room, there might need to be multiple light fixtures or more lamps but the calculations remain the same. Another way our calculations could be adjusted to apply to various circumstances is by varying the number of lamps to lower the 99.9% inactivation time. If cost is not an issue and someone wanted to rapidly disinfect a room, more lamps per square area could be used. Our calculations, testing, and results form the basis for future Far-UVC efficacy research. Researchers can look at these results to have a starting point for the results they will expect with our design and draw conclusions on how to alter their designs in order to meet desired inactivation rates based on room dimensions. In this field of research, some studies have been conducted to show that the product out on the market is effective at killing viruses and is safe, and our research supports these findings.

8.2 Ethical Considerations

Due to the fact that our research has been done experimentally through calculations rather than on samples in a lab, there were not any ethical considerations that we needed to include in the testing phase. In future work, however, prior to our light being used, there would be in-lab testing that would need to consider ethics. First, testing would need to be done on the viruses to verify the inactivation rate that we found in a setting similar to our design experiment. This will ensure that our results are correct and are not leading consumers astray. However, ethical considerations must be taken into account when considering the use of the light. Although Far-UVC light is considered safe to humans (see section 3.1.3), the long term effects have not been well documented. Even though studies regarding the safety of Far-UVC light on mice found no damage to skin cells [36], serious precautions need to be taken in order to ensure the safety of humans and that our product is not putting anyone at risk. We would need to perform physical tests and include experiment specifications to meet this ethical consideration. The latter criteria may be harder to ensure because long term exposure effects have yet to be studied.

8.3 Changes Made

The beginning of our project was focused on the safety and effectiveness of Far-UVC light as opposed to UV-light while under the assumption that we will be using Far-UVC LED lights. As stated in section 6.2, using Far-UVC LED lights would be possible, but highly inefficient and would not provide for reasonable times of disinfection. This steered us in the direction of using already existing Far-UVC emitting lights, with the use of LED lights as a visible light source. This allowed us to continue constructing a product that could be used immediately, with implications of discovering an effective method of creating Far-UVC emitting LED lights in the future.

Our design for the light fixture started off as a rectangular box that housed both Far-UVC and LED lights. However, we decided to switch our design to a trapezoidal shaped structure as it would allow for light to be dispersed at different angles. This increases coverage and allows for more disinfection in the corners and sides of the room compared to a rectangular fixture.

Another change to our design stemmed from concerns of not having enough Far-UVC emitting lights in the fixture for our design to meet the 99.9% efficacy required. We decided to increase the length of the fixture in order to add up to 5 lights per row, and added another row in the center, for a total of 20 Ushio Excimer lamps in the fixture. This reduced disinfection time from 61.4 minutes to 29.95 minutes, and from 88.3 minutes to 43.1 min, for HCoV-OC43 and HCoV-229E respectively.

8.4 Sources of Error

Sources of error would come anywhere from using calculations during hypothetical testing to reliance on already found data being inaccurate. Results of our testing came from using calculations used to determine the intensity of light at a given distance, and then using this intensity to estimate the total time needed to completely disinfect the area of the corresponding coronavirus strain. Being unable to perform physical experiments obtaining data specific to our design, we were forced to use light intensities and inactivation constants found through research and literature in order to obtain values for our testing results. Light intensity values for the Ushio Excimer Lamp [17] were found to have the most amount of UV-light output at 222 nm wavelength, which was .2W/cm^2. This value was recorded from a professional research facility with sufficient power input and light intensity data collectors that may not exactly replicate the scenario of a public bathroom. Any and all variables must be accounted for when determining light intensity from a distance to truly have an idea of how long it will take to disinfect the given area. Inactivation coefficients for the current strains of SARS-CoV-2 were also unattainable. To compensate for this, we used coefficients of HCoV-OC43 and HCoV-229E as they have very similar physical, chemical, and biological structures to current strain, SARS-CoV-2. This may result in some inaccuracies as the current strain will have a slightly different inactivation coefficient than the other two strains. On top of this, coronavirus strains are constantly mutating[38], making it impossible to obtain every coronavirus strain in order to find inactivation values for our product testing. It is safe to assume that the inactivation rate is just an estimate, but SARS-CoV-2 should not have a deactivation time significantly different from the values calculated in our testing.

9.Conclusion

9.1 Outcome

The goal of this research and design project was to design a light fixture and its configuration to provide maximum sterilization coverage and efficacy in a healthcare setting. Ultimately, we determined that a permanent ceiling fixture would provide sufficient coverage from preliminary research, a minimum of 99.9% sterilization efficacy is required, and our focus would be on single-occupancy patient restrooms. Additionally, we were tasked with clearly presenting the relationship between Far-UVC light exposure time, distance, intensity, and dosage to allow for more simple modification and future work.

Due to the situation and circumstances arising around the novel coronavirus (SARS-CoV-2) pandemic, we were unable to obtain any physical devices to aid in research and design, but a meta-analysis was used to perform a series of calculations as a proof of concept. Deactivation dosages of Far-UVC light for two strains of coronavirus comparable to the novel coronavirus were first obtained from published primary sources and used to determine the exposure time required for a constant emission intensity [14]. We then searched for excimer lamps with the highest irradiance outputs available to minimize the required exposure time, and found four possible options. To account for possible absorbance of Far-UVC light photons, Beer-Lambert's Law was used for the constituent molecules in air but the absorbance was found to be negligible. Using the point source inverse-square law, maximum intensity drop-off was calculated using the farthest distance in the room from the excimer light, approximating the lamp's power output as a point source. From these intensities, the time required to reach the minimum dosage for 99.9% sterilization was calculated for each lamp. However, the intensities of all four individual lamps did not provide deactivation dosages in a sufficient time frame (under 60 min), therefore, we expanded our design to include 20 total excimer bulbs. The 0.2 W/cm^2 Ushio lamp provides the greatest light intensity and thus the shortest minimum deactivation time at about 29 to 41 minutes with 20 lamps, while still remaining within ICNIRP standards, and was therefore selected for our design. From the requirement of 20 0.2 W/cm^2 Ushio lamps and the seven visible LED lights, we were able to design a housing (figure 11) and ensure standard U.S. power outlets provided a sufficient power supply of about 470W.

9.2 Future Work

While our current design proves the plausibility of Far-UVC light in small environments, more research still needs to be conducted to prove efficacy, improve efficiency and to optimize the device to make it marketable for a wider range of environments. This means experimentally testing the intensities of excimer lamps individually and in a multiple lamp design from various distances on our target coronavirus samples. Overall, increasing the intensity and consequently decreasing the time to reach deactivation dosages while producing a cost efficient design is the primary focus of future work. Additionally, the use of reflective materials in the housing to direct the lamp output towards target areas as opposed to being absorbed to improve efficiency is a point of further research. Far-UVC LEDs are a promising alternative to the current excimer lamps as they are generally more efficient and incorporate light focusing elements, however, their efficiencies in the Far-UVC spectrum are currently only a few percent [37]. Coverage may be improved in general by incorporating multiple independent fixtures and will also be a main focus of future research. Finally, research must be done on the long term effects of Far-UVC light on humans. This includes measuring the penetration of Far-UVC light in human skin cells.

While there should not be any harmful consequences of exposure in theory, this must be proved in practice and documented over time or there is little to no benefit of using Far-UVC devices over existing GUVC devices.

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Appendix

11.1 Product Design Specifications (PDS)

Far-UVC Light in Healthcare Design Specifications

Client: Dr. Ernesto Brauer

Project Name: Far-UVC Light in Healthcare

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Date: October 6, 2020

Function (a general statement of what the device is supposed to do): The PDS should begin with a brief, concise paragraph describing (in words) the overall function of the device. In the initial stages, this will be the problem statement, and will become more specific as you decide on a final design.

Germicidal ultraviolet light (254 nm), referred to as GUVC light, has been proven as an efficient source of killing pathogens with 99.9% effectiveness. Unfortunately, due to the nature of this longer wavelength, GUVC light can only be utilized in settings where no humans are present, as prolonged exposure to this light can cause temporary or permanent eye and skin damage. As an alternative, Far-UVC light (~220 nm) has been proposed to have little to no health risks due to less penetration into human skin from its shorter wavelength, while still maintaining the same effectiveness rate as GUVC light. As these results have only come from short term and limited empirical studies, our goal is to perform a meta-analysis to investigate the effectiveness of Far UVC light in preventing coronavirus strains HCoV-229E, HCov-OC43, and SARS-CoV-2 from existing on surfaces and in the air. We will determine its efficacy at different light dosages, distances, and durations by utilizing literature, probability models, and survival formulas. Based on our findings, we will design a product that will use Far-UVC light to kill airborne and surface adherent viruses in a fully furnished 10.20 m^3 clinical patient bathroom, with 99.9% effectiveness. By using probability equations and models (Beer-Lambert's Law), we will theoretically prove the product's efficacy.

Client requirements (itemize what you have learned from the client about his / her needs): Briefly describe, in bullet form, the client needs and responses to your questions.

- Design a Far-UVC product that can be implemented in a clinical setting and is able to safely disinfect objects/surfaces while people are present and exposed to this light.
- Perform a meta-analysis to prove that Far-UVC light is 99.9% effective in killing microorganisms in populated spaces using light.
- Determine dosage (exposure time), distance, and intensity of light required to kill viruses and that can disinfect a full 10.20 m^3 fully furnished patient bathroom

Design requirements: This device description should be followed by a list of all relevant constraints, with the following list serving as a guideline. (Note: include only those relevant to your project):

1. Physical and Operational Characteristics

a. **Performance requirements:** The performance demanded or likely to be demanded should be fully defined. Examples of items to be considered include: how often the device will be used; likely loading patterns; etc.

The product must be able to disinfect 99.9% of viruses in the air and on target surfaces. Ideally the light will be able to completely disinfect a 10.20 m^3 patient bathroom. It must not pose any safety risk to humans who could be exposed for any period of time. This light must also be able to be on constantly for periods of time on the scale of years. It must be prepared to be on 24 hours a day for 365 days a year over the course of 5.5 years. An efficient inactivation rate is considered to be at a time less than 60 min.

b. **Safety:** Understand any safety aspects, safety standards, and legislation covering the product type. This includes the need for labeling, safety warnings, etc. Consider various safety aspects relating to mechanical, chemical, electrical, thermal, etc.

Use this light in a way that won't cause cancer (melanoma), damage eyes (cataracts), or any other kind of harm to anyone that is exposed to the light for any period of time. Studies must also be done to make sure the light still keeps the "beneficial microorganisms" in our bodies intact. In theory, this will be done by ensuring that the light has wavelengths that are short enough so they cannot penetrate living human cells but is long enough to penetrate and damage the DNA in viruses, thus killing them.

c. **Accuracy and Reliability:** Establish limits for precision (repeatability) and accuracy (how close to the "true" value) and the range over which this is true of the device.

Accuracy includes ensuring that the light accurately targets the intended area(s) by covering 99% of the target area and killing, on average, 99.9% of the intended HCoV-OC43, HCoV-229E, and SARS-CoV-2 in the area.

d. **Life in Service:** Establish service requirements, including how short, how long, and against what criteria? (i.e. hours, days of operation, distance traveled, no.of revolutions, no. of cycles, etc.)

A life in service greater than other types of light sources is required so that it remains effective in its disinfectant properties. Light will be a normal excimer lamp light source (3.3 forward voltage and a 120V power supply) and the Far-UVC light should be expected to be on at all times (24/7).

e. **Shelf Life:** Establish environmental conditions while in storage, shelf-life of components such as batteries, etc.

The shelf life must be for 50,000 hours or about 5.5 years if the light is on 24 hours a day for 365 days. This is comparable to a normal excimer light.

f. **Operating Environment:** Establish the conditions that the device could be exposed to during operation (or at any other time, such as storage or idle time), including temperature range, pressure range, humidity, shock loading, dirt or dust, corrosion from fluids, noise levels, insects, vibration, persons who will use or handle, any unforeseen hazards, etc.

This device is meant for use in a fully furnished typical patient clinical setting, such as a 10.20 m^3 bathroom, in order to sterilize these high risk environments. It will exist at room temperature (20-22 ^oC), low and stable humidity (40-50% relative humidity), will not encounter significant shock loading, dirt or dust. Must be resistant to other sterilizing chemicals used in the area. The housing must maintain stability when being built into/used in the operating environment (likely metal housing similar to those used in other lighting fixtures such as aluminum).

g. **Ergonomics:** Establish restrictions on the interaction of the product with man (animal), including heights, reach, forces, acceptable operation torques, etc..

Far-UVC light emission is safe for contact on human skin and eyes. People should not touch or bend lights otherwise they may break, however, the light will be in close proximity to humans and specialized equipment so it should not emit heat that could be damaging. Significant amounts of water should not be in contact with the lights as they can potentially explode.

h. **Size:** Establish restrictions on the size of the product, including maximum size, portability, space available, access for maintenance, etc.

A strip light overhead design should have dimensions of about 230 cm length x 62 cm in width x 15.24 cm depth* to ensure variable placement in clinical environments while not being bothersome. As an overhead light, three sections of this trapezoidal housing will be exposed for emission to the rest of the room and access for maintenance.

i. **Weight:** Establish restrictions on maximum, minimum, and/or optimum weight; weight is important when it comes to handling the product by the user, by the distributor, handling on the shop floor, during installation, etc.

The weight of this product should be less than 10lbs* to ensure it can be easily installed with regard to installation hardware and wall supports.

j. **Materials:** Establish restrictions if certain materials should be used and if certain materials should NOT be used (for example ferrous materials in MRI machine).

Materials should be safe and consistent with other materials that would be considered safe and usable in a hospital setting, such as an aluminum frame, LED tubes, and Far-UVC excimer lamp tubes.

k. **Aesthetics, Appearance, and Finish:** Color, shape, form, texture of finish should be specified where possible (get opinions from as many sources as possible).

A clean, smooth, simplistic finish and uniform shape are required in clinical settings to not interfere with procedures and movements occurring below/around.

2. **Production Characteristics**

a. **Quantity:** number of units needed

There is a current issue with the rate of production. This design needs to be able to be mass produced for uses in clinical settings around the world.

b. **Target Product Cost:** manufacturing costs; costs as compared to existing or like products

Existing products range from about \$500 to multiple thousands of dollars depending on the design. Manufacturing costs for products such as ours will be on the stepper side of price due to the large amount of lights required. However, the expectation is that the cost for Far-UVC lights will decrease as production and demand increases, leading to a future product cost that should be around \$500.

3. **Miscellaneous**

a. **Standards and Specifications:** international and /or national standards, etc. (e.g., Is FDA approval required?)

FDA approval would be required. Once approved by the FDA, international standards would likely be met. As of March 2020, there is a specific document for “Sterilizers, Disinfectant devices, and Air Purifiers” during the Covid-19 Pandemic. There are also regulatory limits set by the International Commission of Non-Ionizing Radiation Protection (ICNIRP). The current regulatory exposure limit of 222 nm light to the public is ~3 mJ/cm^2/hour with a maximum regulatory limit of 23 mJ/cm^2 per 8-hour exposure

b. **Customer:** specific information on customer likes, dislikes, preferences, and prejudices should be understood and written down.

Customers prefer simple, efficient products and lights that are easy to install and control. The light would be able to sterilize the area within a reasonable time (under 60 min) and work consistently.

c. **Patient-related concerns:** If appropriate, consider issues that may be specific to patients or research subjects, such as: Will the device need to be sterilized between uses?; Is there any storage of patient data that must be safeguarded for confidentiality?

Those sensitive to light may experience discomfort when using Far-UVC. Those with other conditions that might be more sensitive to light such as:

- People who are pregnant
- The elderly
- People with cancer
- People with large open wounds
- Babies / toddlers
- Animals

d. **Competition:** Are there similar items that exist (perform comprehensive literature search and patents search)?

- Air filters with Far-UVC light
- Portable wand design
- Vertical light lamps
- Architectural sanitation lights
- Overhead doorway
- Medical equipment with built in lights on high contact areas
- Sanitation boxes
- Mounted track/swivel

11.2 Calculations and Testing

Far-UVC Team Calculations and Testing

Survival Rate of Coronavirus

The surviving fraction (S) of the virus was calculated by dividing the fraction PFU/ml at each UV dose (PFUuv) by the fraction at zero dose (PFUcontrols): S = PFUuv/PFUcontrols.

UV dose (D, mJ/cm^2)
The virus survival [S] was described by first-order kinetics according to:

$\ln[S] = -k \times D$
where k is the UV inactivation rate constant or susceptibility factor (cm^2/mJ).

$k = 4.1\ cm^2/mJ$ for alpha coronavirus HCoV-229E.

$k = 5.9\ cm^2/mJ$ for the beta coronavirus HCoV-OC43
(k values given in Brenner et al 2020)

Ex:
If you want 90% effectiveness

$$D90 = -\ln[1 - 0.90]/k$$

Results

$D99 = -\ln[1 - 0.999]/k$

Dosage for 99.9 percent effectiveness on HCoV-229E = 1.68 mJ/cm^2

Dosage for 99.9 percent effectiveness on HCov-OC43 = 1.17 mJ/cm^2

As SARS-CoV-2 has very similar genomics to both alpha and beta coronavirus, we can assume that the dosage required for 99.9 percent effectiveness in killing the virus should be around 1.17 - 1.68 mJ/cm^2. As this is well within the range of the ICNIRP safety standards, we could increase the dosage to ensure that the virus will be killed.

Applying 99.9% Effective Dosage Rate to ICNIRP Standards

ICNIRP Standards

- There is a current regulatory exposure limit of ~3 mJ/cm^2/hr - 30,000 mJ/m^2/hr (30J/m^2/hr)
- Limit of 23 mJ/cm^2 per 8-hour exposure - 230,000 mJ/m^2 (230J/m^2) per 8-hour exposure

Application

Bathroom = 3.72 m^2 with a height of 2.7432 m
Max dosage = (3.72 m^2)*(30,000 mJ/m^2/hr) = 111600 mJ/hr (111.6 J)
(3.72 m^2)*(230,000 mJ/m^2) = 855,600 mJ (855.6 J) per 8-hr exposure

- Maximum dosage allowed on a per hour basis
  - Within the 3 mJ/cm^2/hr = (3/60) = 0.05 mJ/cm^2/min → 500 mJ/m^2/min
  - 23 mJ/cm^2 per 8-hr exposure = (23/480) = 0.0479 mJ/cm^2 per minute → 479 mJ/m^2/min

- Minimum Dosages for 99.9% Effectiveness
  - Dosage for 99.9 percent effectiveness on HCov-OC43 = 1.17 mJ/cm^2 → 11,700 mJ/m^2
  - Dosage for 99.9 percent effectiveness on HCoV-229E = 1.68 mJ/cm^2 → 16,800 mJ/m^2

Duration to Reach Effective Dosages without any Delay

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- In 23.4 min, 99.9% of HCov-OC43 will be inactivated

- In 33.6 min, 99.9% of HCov-229E will be inactivated

At 0.0479 mJ/cm^2 (479 mJ/m^2) per minute

- In 24.4 min, 99.9% of HCov-OC43 will be inactivated

- In 35.1 min, 99.9% of HCov-229E will be inactivated

For SARS-CoV-2, we would expect a similar time frame of 23.4 - 33.6 min at 0.05mJ/cm^2 and 24.4 - 35.1 min at 0.0479mJ/cm^2 to get 99.9% inactivation

Applying Delay in Dosages at Corners of the Room

Assumptions for calculations:

- Same minimum effective dosages above for each strain
- Same bathroom dimensions as previously mentioned
- Using the time frames given to reach a certain intensity we can perform calculations for how much time it will take for the lamps to inactivate 99.9% of the respective viruses

Using Intensity = Pavg/r^2

Ushio Lamp is at an intensity of 5 μW/cm^2 extending a distance of 3.04 m in all directions

- It takes 15400 min to reach .05mJ/cm^2 → 15400/1 = 15400
- It takes 14506 min to reach .047mJ/cm^2 → 14506/1 = 14506
  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At .05 mJ/cm^2 (500 mJ/m^2) per minute

- 99.9% of HCov-OC43 will be inactivated in (15400 *23.4 min) + 23.4 min = 36059 min

- 99.9% of HCov-229E will be inactivated in (15400 *33.6 min) + 33.6 min = 517474 min

At .047 mJ/cm^2 (479 mJ/m^2) per minute

- 99.9% of HCov-OC43 will be inactivated in (14506 *24.4 min) + 24.4 min = 353971 min

- 99.9% of HCov-229E will be inactivated in (14506 *35.1 min) + 35.1 min = 509196 min

For SARS-CoV-2, we would expect a similar time frame of 36059 - 517474 min at .5mJ/cm^2 and 353971 - 509196 min at .047mJ/cm^2 to get 99.9% inactivation

With the Sailon Lamp at an intensity of 35 μW/cm^2 extending a distance of 3.04 m in all directions

- It takes 2205 min to reach .05mJ/cm^2 → 2205/1 = 2205
- It takes 2068 min to reach .047mJ/cm^2 → 2068/1 = 2068
  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (2205*23.4 min) + 23.4 min = 51620 min

- 99.9% of HCov-229E will be inactivated in (2205*33.6 min) + 33.6 min = 6922 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (2068*24.4 min) + 24.4 min = 50484 min

- 99.9% of HCov-229E will be inactivated in (2068*35.1 min) + 35.1 min= 72622 min

For SARS-CoV-2, we would expect a similar time frame of 51620 - 6922 minutes at 0.05mJ/cm^2/min and 50484 - 72622 minutes at .0479mJ/cm^2/min to get 99.9% inactivation

<u>Using Intensity = Pavg/(4*(pi)*(r^2)</u>

With the Sailon Lamp at an intensity of 35 μW/cm^2 extending a distance of 3.04 m in all directions

- It takes 27650 min to reach .05mJ/cm^2/min → 27650/1 = 27650
- It takes 25991 min to reach .047mJ/cm^2/min → 25991/1 = 25991

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (27650*23.4 min) + 23.4 min = 647033 min

- 99.9% of HCov-229E will be inactivated in (27650*33.6 min) + 33.6 min = 929074 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (25991*24.4 min) + 24.4 min = 634305 min

- 99.9% of HCov-229E will be inactivated in (25991*35.1 min) + 35.1 min = 912319 min

For SARS-CoV-2, we would expect a similar time frame of 647033 - 929074 minutes at 0.05mJ/cm^2/min and 634305 - 912319 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With the Larson Lamp at an intensity of 80 μW/cm^2 extending a distance of 3.04 m in all directions

- It takes 12097 min to reach .05mJ/cm^2/min → 12097/1 = 12097
- It takes 11371 min to reach .047mJ/cm^2/min → 11371/1 = 11371

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (12097*23.4 min) + 23.4 min = 283093 min

- 99.9% of HCov-229E will be inactivated in (12097*33.6 min) + 33.6 min = 406493 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (11371*24.4 min) + 24.4 min = 277477 min

- 99.9% of HCov-229E will be inactivated in (11371*35.1 min) + 35.1 min = 399157 min

For SARS-CoV-2, we would expect a similar time frame of 283093 - 406493 minutes at 0.05mJ/cm^2/min and 277477 - 399157 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With the .2 W Ushio Lamp extending a distance of 3.04 m in all directions

- It takes 4.84 min to reach .05mJ/cm^2/min → 4.84/1 = 4.84
- It takes 4.55 min to reach .047mJ/cm^2/min → 4.55/1 = 4.55
  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (4.84*23.4 min) + 23.4 min = 136.7 min

- 99.9% of HCov-229E will be inactivated in (4.84*33.6 min) + 33.6 min = 196.2 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (4.55*24.4 min) + 24.4 min = 135.4 min

- 99.9% of HCov-229E will be inactivated in (4.55*35.1 min) + 35.1 min = 194.8 min

For SARS-CoV-2, we would expect a similar time frame of 136.7 - 196.2 minutes at 0.05mJ/cm^2/min and 135.4 - 194.8 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

Using Intensity = Pavg/(4*(pi)*(r^2) with Multiple Lights

With 2 Larson Lamp lights at an intensity of 80 µW/cm^2 extending a distance of 3.04 m in all directions

- It takes 6049 min to reach .05mJ/cm^2/min → 6049/1 = 6049
    - Each lamp applies a dosage of .025 mJ/cm^2/min

- It takes 5686 min to reach .047mJ/cm^2/min → 5686/1 = 5686
  - Each lamp applies a dosage of .0235 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (6049*23.4 min) + 23.4 min = 141570 min

- 99.9% of HCov-229E will be inactivated in (6049*33.6 min) + 33.6 min = 203280 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (5686*24.4 min) + 24.4 min = 138763 min

- 99.9% of HCov-229E will be inactivated in (5686*35.1 min) + 35.1 min = 199614 min

For SARS-CoV-2, we would expect a similar time frame of 141570 - 203280 minutes at 0.05mJ/cm^2/min and 138763 - 199614 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 3 Larson Lamp lights at an intensity of 80 μW/cm^2 extending a distance of 3.04 m in all directions

- It takes 4032 min to reach .05mJ/cm^2/min → 4032/1 = 4032
  - Each lamp applies a dosage of .0167 mJ/cm^2/min
- It takes 3790 min to reach .047mJ/cm^2/min → 3790/1 = 3790
  - Each lamp applies a dosage of .0157 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (4032*23.4 min) + 23.4 min = 94349 min

- 99.9% of HCov-229E will be inactivated in (4032*33.6 min) + 33.6 min = 135509 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (3790*24.4 min) + 24.4 min = 92500 min

- 99.9% of HCov-229E will be inactivated in (3790*35.1 min) + 35.1 min = 133064 min

For SARS-CoV-2, we would expect a similar time frame of 94349 - 135509 minutes at 0.05mJ/cm^2/min and 92500 - 133064 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 4 Larson Lamp lights at an intensity of 80 µW/cm^2 extending a distance of 3.04 m in all directions

- It takes 3024 min to reach .05mJ/cm^2/min → 3024/1 = 3024
    - Each lamp applies a dosage of .0125 mJ/cm^2/min
- It takes 2843 min to reach .047mJ/cm^2/min → 2843 /1 = 2843
    - Each lamp applies a dosage of .01175 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (3024*23.4 min) + 23.4 min = 70785 min

- 99.9% of HCov-229E will be inactivated in (3024*33.6 min) + 33.6 min = 101640 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (2843 *24.4 min) + 24.4 min = 69394 min

- 99.9% of HCov-229E will be inactivated in (2843 *35.1 min) + 35.1 min = 99824 min

For SARS-CoV-2, we would expect a similar time frame of 70785 - 101640 minutes at 0.05mJ/cm^2/min and 69394 - 99824 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 5 Larson Lamp lights at an intensity of 80 µW/cm^2 extending a distance of 3.04 m in all directions

- It takes 2419 min to reach .05mJ/cm^2/min → 2419/1 = 2419
    - Each lamp applies a dosage of .01 mJ/cm^2/min

- It takes 2274 min to reach .047mJ/cm^2/min → 2274 /1 = 2274
  - Each lamp applies a dosage of .0094 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (2419*23.4 min) + 23.4 min = 56628 min

- 99.9% of HCov-229E will be inactivated in (2419*33.6 min) + 33.6 min = 81312 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (2274 *24.4 min) + 24.4 min = 55510 min

- 99.9% of HCov-229E will be inactivated in (2274 *35.1 min) + 35.1 min = 79853 min

For SARS-CoV-2, we would expect a similar time frame of 56628 - 81312 minutes at 0.05mJ/cm^2/min and 55510 - 79853 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 2 .2 W Ushio Lamps at an intensity of extending a distance of 3.04 m in all directions

- It takes 2.42 min to reach .05mJ/cm^2/min → 2.42/1 = 2.42
  - Each lamp applies a dosage of .025 mJ/cm^2/min
- It takes 2.27 min to reach .047mJ/cm^2/min → 2.27/1 = 2.27
  - Each lamp applies a dosage of .0235 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (2.42*23.4 min) + 23.4 min = 80 min

- 99.9% of HCov-229E will be inactivated in (2.42*33.6 min) + 33.6 min = 114.9 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (2.27*24.4 min) + 24.4 min = 79.8 min

- 99.9% of HCov-229E will be inactivated in (2.27*35.1 min) + 35.1 min = 114.8 min

For SARS-CoV-2, we would expect a similar time frame of 80 - 114.9 minutes at 0.05mJ/cm^2/min and 79.8 - 114.8 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 3 .2 W Ushio Lamps at an intensity of extending a distance of 3.04 m in all directions

- It takes 1.61 min to reach .05mJ/cm^2/min → 1.61/1 = 1.61
    - Each lamp applies a dosage of .0167 mJ/cm^2/min
- It takes 1.516 min to reach .047mJ/cm^2/min → 1.516/1 = 1.516
    - Each lamp applies a dosage of .0157 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (1.61*23.4 min) + 23.4 min = 61.1 min

- 99.9% of HCov-229E will be inactivated in (1.61*33.6 min) + 33.6 min =87.7 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (1.516*24.4 min) + 24.4 min = 61.4 min

- 99.9% of HCov-229E will be inactivated in (1.516*35.1 min) + 35.1 min = 88.3 min

For SARS-CoV-2, we would expect a similar time frame of 61.1 - 87.7 minutes at 0.05mJ/cm^2/min and 61.4 - 88.3 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 4 .2 W Ushio Lamps at an intensity of extending a distance of 3.04 m in all directions

- It takes 1.21 min to reach .05mJ/cm^2/min → 1.21/1 = 1.21
    - Each lamp applies a dosage of .0125 mJ/cm^2/min
- It takes 1.137 min to reach .047mJ/cm^2/min → 1.137/1 = 1.137
    - Each lamp applies a dosage of .01175 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 $mJ/cm^2/min$ (500 $mJ/m^2/min$)

- 99.9% of HCov-OC43 will be inactivated in (1.21*23.4 min) + 23.4 min = 51.7 min

- 99.9% of HCov-229E will be inactivated in (1.21*33.6 min) + 33.6 min = 74.3 min

At 0.0479 $mJ/cm^2/min$ (479 $mJ/m^2/min$)

- 99.9% of HCov-OC43 will be inactivated in (1.137 *24.4 min) + 24.4 min = 52.1min

- 99.9% of HCov-229E will be inactivated in (1.137 *35.1 min) + 35.1 min = 75 min

For SARS-CoV-2, we would expect a similar time frame of 51.7 - 74.3 minutes at 0.05$mJ/cm^2/min$ and 52.1 - 75 minutes at .047$mJ/cm^2/min$ to get 99.9% inactivation.

With 5 .2 W Ushio Lamps at an intensity of extending a distance of 3.04 m in all directions

- It takes .968 min to reach .05$mJ/cm^2/min$ → .968/1 = .968
  - Each lamp applies a dosage of .01 $mJ/cm^2/min$
- It takes .910 min to reach .047$mJ/cm^2/min$ → .910/1 = .910
  - Each lamp applies a dosage of .0094 $mJ/cm^2/min$

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 $mJ/cm^2/min$ (500 $mJ/m^2/min$)

- 99.9% of HCov-OC43 will be inactivated in (.968*23.4 min) + 23.4 min = 46.1 min

- 99.9% of HCov-229E will be inactivated in (.968*33.6 min) + 33.6 min = 66.1 min

At 0.0479 $mJ/cm^2/min$ (479 $mJ/m^2/min$)

- 99.9% of HCov-OC43 will be inactivated in (.910 *24.4 min) + 24.4 min = 46.6 min

- 99.9% of HCov-229E will be inactivated in (.910 *35.1 min) + 35.1 min = 67 min

For SARS-CoV-2, we would expect a similar time frame of 46.1 - 66.1 minutes at 0.05mJ/cm^2/min and 46.6 - 67 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 10 .2 W Ushio Lamps at an intensity of extending a distance of 3.04 m in all directions

- It takes .484 min to reach .05mJ/cm^2/min → .484/1 = .484
  - Each lamp applies a dosage of .005 mJ/cm^2/min
- It takes .455 min to reach .047mJ/cm^2/min → .455/1 = .455
  - Each lamp applies a dosage of .0047 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.484*23.4 min) + 23.4 min = 34.7 min

- 99.9% of HCov-229E will be inactivated in (.484*33.6 min) + 33.6 min = 49.9 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.455 *24.4 min) + 24.4 min = 35.5 min

- 99.9% of HCov-229E will be inactivated in (.455 *35.1 min) + 35.1 min = 51.1 min

For SARS-CoV-2, we would expect a similar time frame of 34.7 - 49.9 minutes at 0.05mJ/cm^2/min and 35.5 - 51.1 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 16 .2 W Ushio Lamps at an intensity of extending a distance of 3.04 m in all directions

- It takes .302 min to reach .05mJ/cm^2/min → .302/1 = .302
  - Each lamp applies a dosage of .03125 mJ/cm^2/min
- It takes .284 min to reach .047mJ/cm^2/min → .284/1 = .284
  - Each lamp applies a dosage of .00294 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.302*23.4 min) + 23.4 min = 30.5 min

- 99.9% of HCov-229E will be inactivated in (.302*33.6 min) + 33.6 min = 43.7 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.284 *24.4 min) + 24.4 min = 31.3 min

- 99.9% of HCov-229E will be inactivated in (.284 *35.1 min) + 35.1 min = 45.1 min

For SARS-CoV-2, we would expect a similar time frame of 30.5 - 43.7 minutes at 0.05mJ/cm^2/min and 31.3 - 45.1 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 20 .2 W Ushio Lamps at an intensity of extending a distance of 3.04 m in all directions

- It takes .242 min to reach .05mJ/cm^2/min → .242/1 = .242
    - Each lamp applies a dosage of .0025 mJ/cm^2/min
- It takes .227 min to reach .047mJ/cm^2/min → .227 /1 = .227
    - Each lamp applies a dosage of .00235 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.242*23.4 min) + 23.4 min = 29.06 min

- 99.9% of HCov-229E will be inactivated in (.242*33.6 min) + 33.6 min = 41.7 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.227 *24.4 min) + 24.4 min = 29.95 min

- 99.9% of HCov-229E will be inactivated in (.227 *35.1 min) + 35.1 min = 43.1 min

For SARS-CoV-2, we would expect a similar time frame of 29.06 - 41.7 minutes at 0.05mJ/cm^2/min and 29.95 - 43.1 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 25 .2 W Ushio Lamps at an intensity of extending a distance of 3.04 m in all directions

- It takes .194 min to reach .05mJ/cm^2/min → .194/1 = .194
    - Each lamp applies a dosage of .002 mJ/cm^2/min
- It takes .182 min to reach .047mJ/cm^2/min → .182/1 = .182
    - Each lamp applies a dosage of .00188 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.194*23.4 min) + 23.4 min = 27.93 min

- 99.9% of HCov-229E will be inactivated in (.194*33.6 min) + 33.6 min = 40.1 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.182 *24.4 min) + 24.4 min = 28.84 min

- 99.9% of HCov-229E will be inactivated in (.182*35.1 min) + 35.1 min = 41.49 min

For SARS-CoV-2, we would expect a similar time frame of 27.93 - 40.1 minutes at 0.05mJ/cm^2/min and 28.84 - 41.49 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

With 32 .2 W Ushio Lamps at an intensity of extending a distance of 3.04 m in all directions

- It takes .151 min to reach .05mJ/cm^2/min → .151/1 = .151
    - Each lamp applies a dosage of .00156 mJ/cm^2/min
- It takes .142 min to reach .047mJ/cm^2/min → .142/1 = .142
    - Each lamp applies a dosage of .00147 mJ/cm^2/min

  (See Dosage Equation section for calculations for durations)

Applying these delays to the current rates to reach 99.9% effectiveness at different strains

At 0.05 mJ/cm^2/min (500 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.151*23.4 min) + 23.4 min = 26.94 min

- 99.9% of HCov-229E will be inactivated in (.151*33.6 min) + 33.6 min = 38.68 min

At 0.0479 mJ/cm^2/min (479 mJ/m^2/min)

- 99.9% of HCov-OC43 will be inactivated in (.142 *24.4 min) + 24.4 min = 27.87 min

- 99.9% of HCov-229E will be inactivated in (.142*35.1 min) + 35.1 min = 40.1 min

For SARS-CoV-2, we would expect a similar time frame of 26.94 - 38.68 minutes at 0.05mJ/cm^2/min and 27.87 - 40.1 minutes at .047mJ/cm^2/min to get 99.9% inactivation.

Beer-Lambert Law

$$A = \log(I0/I) = \varepsilon lc$$

I0 = Incident Light - The light that falls on a subject - It can be from natural lighting, like the sun, or from an artificial source. Incident light can also be light that's reflecting off another surface, like a reflector

I = Transmitted Light (%)
A = Absorbance (unitless)
ε = Molar absorption coefficient 1/M(cm)
c = Molar Concentration (M)
l = optical path length (cm)

Beer's Law (Beer-Lambert Law): The amount of energy absorbed or transmitted by a solution is proportional to the solution's molar absorptivity and the concentration of solute. In simple terms, a more concentrated solution absorbs more light than a more dilute solution does

When a beam of radiation (light) passes through a substance or a solution, some of the light may be absorbed and the remainder transmitted through the sample. The ratio of the intensity of the light entering the sample (Io) to that exiting the sample (It) at a particular wavelength is defined as the transmittance (T). This is often expressed as the percent transmittance (%T), which is the transmittance multiplied by 100 and correlates to the percentage of light that can pass through a certain object. The absorbance (A) of a sample is the negative logarithm of the transmittance.

$$\% T = (Io / It) \times 100$$

$$A = -\log(T) \rightarrow (\text{not } \%T)$$

The absorbance of a sample at a given wavelength is proportional to the absorptivity of the substance (a constant at each wavelength), the path length (the distance the light travels through the sample) and, in many instances, the concentration of the absorbing substance. In these cases the Beer-Lambert Law holds:

$$A = \varepsilon * l * c$$

where
ε = Molar absorption coefficient 1/M(m)
c = Molar Concentration (M)
l = optical path length (m)

Results

1. For N2, O2, O, N
   1. Penetration depth of Far-UVC light through each of these elements is about 110 km
   2. In a 3.72 m^2 room with a height of 2.7432 m, the absorption coefficient can be approximated as 0 because it will not come near the 110km penetration depth value
   3. Absorbance of Far-UVC in N2, O2, O, N = 0
2. For Water Vapor and CO2
   1. Absorption Coefficient for both is anywhere between 0 and about 10^{-3}. Given this, we want to use the larger absorption coefficient possible to be sure that our calculations error on the more safe side.
   2. Length = 304 cm
   3. Concentration for Water Vapor = 10.94 mol/m^3 = 0.01094 M
   4. Concentration for CO2 = 1000ppm = 0.02272M
   5. Absorbance for Water Vapor = $(10^{-3})*(3.04\text{ m})*(0.01094\text{M}) = 0.0000332576$
   6. Absorbance for CO2 = $(10^{-3})*(3.04\text{ m})*(0.02272\text{M}) = 0.0000690688$

Standard for CO2 concentrations in a room is approximately 1,000 ppm: https://www.aivc.org/sites/default/files/members_area/medias/pdf/VIP/VIP%2033_CO2%20General.pdf

Conversion to molarity: https://www.omnicalculator.com/chemistry/ppm-to-molarity

The saturation of water vapor density (the largest amount of water vapor we can get) in the average room temperature of 70 degrees F is $197 g/m^3$ = 10.94mol/m^3
https://courses.lumenlearning.com/physics/chapter/13-6-humidity-evaporation-and-boiling/

Dosage Equation

$$\text{UV dose} = (I/UVT) \times t$$

Where:
I = UV Intensity
UVT = UV Transmissivity (a measure of how much UV light can penetrate through the water being treated)
t = time of UV exposure

UV Intensity measures the “amount” of UV energy actually penetrating through the water being treated. UV dose is the amount of UV energy penetrating the water, multiplied by the amount of time the water is exposed to this energy. It is the UV dose that determines the log reduction of a pathogen.

UV dose is considered the "average” dose, meaning that some of the water being treated will receive the prescribed dose, some will receive more than the prescribed dose, but some water will receive less than the prescribed dose.

I = Transmitted intensity in Beer's law

$$I_T = I_0 e^{-La}$$

I_T = Transmitted intensity
I_0 = Initial or incident intensity

Results

Using the Dosage equation and plugging in specific dosages with the given intensities, we were able to determine the duration required to reach this dosage

- Ushio Excimer Lamp - 5 $\mu W/cm^2$ intensity
    - Dosage of 1.68 mJ/cm^2 is reached at 336 seconds - 5 min and 36 seconds
    - Dosage of 1.17 mJ/cm^2 is reached at 234 seconds - 3 min and 54 seconds
    - Dosage of .05 mJ/cm^2 is reached at 10 seconds
    - Dosage of .047 mJ/cm^2 is reached at 9.4 seconds

- Sailon Excimer Lamp - 35 μWatts/cm^2 at 100 cm
    - Dosage of 1.68 mJ/cm^2/min is reached at 48 seconds
    - Dosage of 1.17 mJ/cm^2/min is reached at 33.4 seconds
    - Dosage of .05 mJ/cm^2/min is reached at 1.40 seconds
    - Dosage of .047 mJ/cm^2/min is reached at 1.34 seconds

In a 3.72 square meter room with a ceiling height of 2.7432 m with a perfectly centrally located point, the distance to the furthest point in the room = 3.04 m (304 cm)

Simple Intensity vs. Distance Drop-off (Using cm for Calculations)

Intensity will decrease by a factor of 1.081e-5 by the time the light reaches this spot as intensity decreases by 1/d^2 (d is distance). As a result, the intensity will become 5.40e-11 Watts/cm^2 from the Ushio lamp and 3.78e-10 Watts/cm^2 from the Sailon lamp when it reaches each crevice of the room.

Ushio Lamp (5 μW/cm^2 Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	518300
1.17	361000
.05	15400
.047	14506

Sailon Lamp (35 μWatts/cm^2 at 100 cm Intensity)

Dosage(mJ/cm^2)	Time(min)
1.68	73900
1.17	51600
.05	2205
.047	2068

Intensity vs. Distance Drop-off from a Point Source (Using cm for Calculations)

In a 3.72 square meter room with a ceiling height of 2.7432 m with a perfectly centrally located point, the distance to the furthest point in the room = 3.04 m (304 cm)

Intensity will decrease by a factor of 8.61e-7 by the time the light reaches this spot as intensity decreases by 1/[4(pi)(d^2)] (d is distance). As a result, the intensity will become 4.31e-12 Watts/cm^2 from the Ushio lamp and 3.014e-11 Watts/cm^2 from the Sailon lamp when it reaches each crevice of the room.

Ushio Lamp (5 µW/cm^2 Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	6503500
1.17	4529200
.05	193555
.047	181942

Ushio Lamp (.2 W)

Using 304 cm for Inverse Law

Intensity will decrease by a factor of 8.61e-7 1/cm2 by the time the light reaches this spot as intensity decreases by 1/[4(pi)(d^2)] (d is distance). As a result, the intensity will become .172 µWatts/cm^2 from the Ushio lamp when it reaches each crevice of the room.

Dosage to time = Dosage / Intensity = Time

Dosage(mJ/cm^2/min)	Time(min)
1.68	162.6
1.17	113.2
.05	4.84
.047	4.55

Sailon Lamp (35 µWatts/cm^2 at 100 cm Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	929066
1.17	647028
.05	27650
.047	25991

Larson Excimer Lamp (80 µWatts/cm^2 at 1.57" Intensity)

Dimensions = 17.32"-L x 1.22"-H x 0.984"-OD

Intensity will decrease by a factor of 8.61e-7 1/cm2 by the time the light reaches this spot as intensity decreases by 1/[4(pi)(d^2)] (d is distance). As a result, the intensity will become 6.89e-11Watts/cm^2 from the Larson Lamp when it reaches each crevice of the room.

Larson Lamp (80 µWatts/cm^2 at 1.57" Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	406467
1.17	283075
.05	12097

.047	11371

Dosage Output and Time with Multiple Lights

We will use the Larson Excimer Lamp for these calculations as it has the highest intensity output for the above lamps except for the .2 W Ushio Lamp and thus disinfects the room the fastest.

For 2 lights

The intensity drop off will still be 6.89e-11 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will double = 1.378e-10 Watts/cm^2. The dosage rate for each light will have to drop to half of the dosages below to adhere to the ICNIRP standards, but as we can just add the dosage and intensity totals together, we can still perform our calculations using the full dosages below as the total dosage output by the lights will still be .047, .05, 1.17, or 1.68 mJ/cm^2/min.

Larson Lamp (80 µWatts/cm^2 at 1.57" Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	203233
1.17	141538
.05	6049
.047	5686

For 3 lights

The intensity drop off will still be 6.89e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will triple = 2.067e-10 Watts/cm^2.

Larson Lamp (80 µWatts/cm^2 at 1.57" Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	135489
1.17	94358
.05	4032
.047	3790

For 4 lights

The intensity drop off will still be 6.89e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will quadruple = 2.755e-10 Watts/cm^2.

Larson Lamp (80 µWatts/cm^2 at 1.57” Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	101617
1.17	70769
.05	3024
.047	2843

For 5 lights

The intensity drop off will still be 6.89e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will quintuple= 3.44e-10 Watts/cm^2 .

Larson Lamp (80 µWatts/cm^2 at 1.57” Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	81293
1.17	56615
.05	2419
.047	2274

We will use the .2W/cm^2 Ushio Excimer Lamp for these calculations as it now has the highest intensity output and thus disinfects the room the fastest.

For 2 lights

The intensity drop off will still be 1.722e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will double = 3.444e-7 Watts/cm^2 . The dosage rate for each light will have to drop to half of the dosages below in order to still adhere to the ICNIRP standards, but as we can just add the dosage and intensity totals together, we can still perform our calculations using the full dosages below as the total dosage output by the lights will still be .047, .05, 1.17, or 1.68 mJ/cm^2/min.

Ushio Lamp (.2 Watts/cm^2 at 1.57” Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	81.30
1.17	56.62
.05	2.42
.047	2.27

For 3 lights

The intensity drop off will still be 1.722e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will triple = 5.166e-7 Watts/cm^2.

Ushio Lamp (.2 Watts/cm^2 at 1.57" Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	54.20
1.17	37.74
.05	1.61
.047	1.516

For 4 lights

The intensity drop off will still be 1.722e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will quadruple = 6.89e-7 Watts/cm^2.

Ushio Lamp (.2 Watts/cm^2 at 1.57" Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	40.65
1.17	28.31
.05	1.21
.047	1.137

For 5 lights

The intensity drop off will still be 1.722e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will quintuple= 8.61e-7 Watts/cm^2.

Ushio Lamp (.2 Watts/cm^2 at 1.57" Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	32.52
1.17	22.65
.05	.968
.047	.910

For 10 lights

The intensity drop off will still be 1.722e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will decuple = 1.722 e-6 Watts/cm^2 .

Ushio Lamp (.2 Watts/cm^2 at 1.57" Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	16.26
1.17	11.32
.05	.484
.047	.455

For 16 lights

The intensity drop off will still be 1.722e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will be multiplied by 16 = 2.76e-6 Watts/cm^2 .

Ushio Lamp (.2 Watts/cm^2 at 1.57" Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	10.2
1.17	7.077
.05	.302
.047	.284

For 20 lights

The intensity drop off will still be 1.722e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will be multiplied by 20 = 3.44 e-6 Watts/cm^2 .

Ushio Lamp (.2 Watts/cm^2 at 1.57" Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	8.129
1.17	5.662
.05	.242
.047	.227

For 25 lights

The intensity drop off will still be 1.722e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will be multiplied by 25 = 4.304 e-6 Watts/cm^2 .

Ushio Lamp (.2 Watts/cm^2 at 1.57” Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	6.50
1.17	4.529
.05	.194
.047	.182

For 32 lights

The intensity drop off will still be 1.722e-7 Watts/cm^2 from the Larson Lamp according to the point source inverse law when this intensity reaches each crevice of the room. However, as there are two lamps now, the intensity will be multiplied by 32 = 5.51 e-6 Watts/cm^2 .

Ushio Lamp (.2 Watts/cm^2 at 1.57” Intensity)

Dosage(mJ/cm^2/min)	Time(min)
1.68	5.08
1.17	3.543
.05	.151
.047	.142

UV Decay equations

Microbes exposed to UV irradiation are subject to an exposure dose (fluence) that is a function of the irradiance multiplied by the exposure time, as follows:

$$D = E_t \cdot I_R$$

where

D = UV exposure dose (fluence), J/m^2

E_t = exposure time, sec

I_R = Irradiance, W/m^2

Single Stage Decay

The primary model used to evaluate the survival of microorganisms subject to UV exposure is the classical exponential decay model. This is a first-order decay rate model and is generally adequate for most UVGI design purposes provided the UV dose is within first order parameters.

This is because disinfection rates of 90–99% can generally be achieved in the first stage of decay, and this is adequate for most design purposes. With few exceptions, a D90 value defines the first stage of decay for bacteria and viruses. The D90 value typically remains accurate up to a D99 or even higher, but extrapolation beyond this point is not always valid.

The single stage decay equation for microbes exposed to UV irradiation is:

$$S = e^{-kD}$$

where

S = Survival, fractional

k = UV rate constant, m^2/J

Two Stage Decay

It is commonly observed in most methods of disinfection that a tiny fraction of the microbial population exhibits a higher level of resistance, and the same is true in UV disinfection. When the exposure dose is sufficient to cause several logs of reduction (i.e. 99% disinfection or higher) in the microbial population, the surviving population is often an order of magnitude more resistant to UV. This effect will only be apparent if the disinfection rate is very high, sometimes as much as six logs of disinfection. In effect, most microbial populations behave as if two separate populations were present – one relatively susceptible and one relatively resistant.
The survival of the two populations is simply the sum of each decay rate computed per each contribution, as follows.

$$S = (1-f)e^{-k_1 D} + fe^{-k_2 D}$$

where

f = UV resistant fraction (slow decay)

k 1 = first stage rate constant, m^2/J

k 2 = second stage rate constant, m^2/J

Shoulder Curves

The exponential decay of a microbial population in response to biocidal factors like UV is often subject to a slight delay called a shoulder because of the shape. Shoulder curves start out with a horizontal slope before developing into full exponential decay. The lag in response to the stimulus implies that either a threshold dose is necessary before measurable effects occur or that repair mechanisms actively deal with low-level damage at low doses. Once the threshold is passed the exponential decay curve becomes fully developed.

The multihit target model can be written as follows:

$$S(t) = 1 - \left(1 - e^{-kD}\right)^{n}$$

where

n = multitarget exponent

11.3 Materials and Cost

Far-UVC Team Materials and Cost for Light Fixture

Budget: N/A because our design was strictly hypothetical. Our client, however, mentioned that had we made a product like this, cost would not be an important criteria because safety and efficacy hold greater importance and cost will lower as the light becomes more readily available.

Aluminum:

The density of aluminum is 2.7 g/cm^3

Converting this to pounds we get 0.00595248 lb/cm^3

The price of aluminum per pound according to https://agmetalminer.com/metal-prices/aluminum/

Is \$1.63/lb

In order to determine how many pounds we have we need to multiply by the volume of aluminum that we will need in cm^3.

Assuming that the metal will be about a ½ centimeter thick, we can find the volume by multiplying the other dimensions of our design.

The top section that is attached to the ceiling has dimensions of 230 x 62 cm which gives 14260x(½) = 7130 cm^3.

The other section that will have aluminum is the trapezoids which have an area of 708.66cm^2 so multiplying by a thickness of (½) cm and multiplying by 2 because there are trapezoids on both sides of the fixture we get 708.66 cm^3.

Lastly there is also aluminum separating the side sections from the middle section that is of 15.24x230x(1/2) and would have a volume of 1752.6 cm^3 . Since there are 2 of these we multiply by 2 to get 3505 cm^3.

Adding together the individual pieces we get 7130+708.66+3505 = 11,343.66 cm^3

Multiplying 11,343.66 cm^3 by 0.00595248 lb/cm^3 we get that we would need 67.523 pounds of aluminum.

Since the price per pound is $1.63 we would get that the total price to be 67.523*$1.63 = $110.06.

Ushio Lamps:

The price of the Ushio lamps were found on following site:
https://english.kyodonews.net/news/2020/09/a897375a08d4-ushio-launches-worlds-1st-uv-lamp-safely-killing-coronavirus.html#:~:text=A%20recent%20third%2Dparty%20study,of%20300%2C000%20yen%20(%242%2C860).
The price given on the website is $2860

Since we are going to be using 20 Ushio Lamps we can multiply the price by 20 to get the total price of the lamps to be: $57,200

LED Lights

According to the following website:
https://www.grainger.com/product/53UG85?gclid=CjwKCAiAwrf-BRA9EiwAUWwKXgGIJ6OcMI_bzpOUF_2fGvAOZydqyOoUQOnKc7VztwnWFJyiuxE8FRoCN6kQAvD_BwE&cm_mmc=PPC:+Google+PLA&ef_id=CjwKCAiAwrf-BRA9EiwAUWwKXgGIJ6OcMI_bzpOUF_2fGvAOZydqyOoUQOnKc7VztwnWFJyiuxE8FRoCN6kQAvD_BwE:G:s&s_kwcid=AL!2966!3!281698275504!!!g!472075813898!&gucid=N:N:PS:Paid:GGL:CSM-2295:4P7A1P:20501231
A light of approximately 238.125 cm costs $24.50.
Using this information we can confirm that the cost of our LED lights will not be more than $24.50.
Due to the fact that our design calls for 7 of these LED lights we can multiply $24.50 by 7 to get $171.50 total.

Bolts and Attachment pieces:

A price for these will not be included in the cost table due to the fact that this is not directly part of our fixture and is rather separate and would be up to the installers for what they choose to use.

Table 8: Materials and Cost Table for the final design light fixture. Final total is in US dollars.

Far-UVC Light Fixture Materials and Cost Table			
	Amount	**Price per Amount**	**Total Price**
Ushio Lamps	20 lamps	$2,860.00/lamp	$57,200.00
Aluminum	11,343.66 cm^3→ 67.523lbs	$1.63/lb	$110.06
LED Lights	7 lamps	$24.50	$171.50
Total			**$57,481.56**