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# Developing A Self-Sanitizing Mask to Combat the Spread of Infectious Disease

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# DEVELOPING A SELF-SANITIZING MASK TO COMBAT THE SPREAD OF INFECTIOUS DISEASE

by

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# ABSTRACT

Masks have become an important part of everyday life, protecting both the wearer and individuals nearby from the spread of infectious diseases, most notably severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the coronavirus that causes coronavirus disease 2019 (COVID-19). However, these masks are easily contaminated, whether through continued use or by the wearer touching the mask fabric with contaminated hands, therefore reducing the efficacy and exposing the user to these contagions. When the mask becomes contaminated, it can be discarded, which produces large amounts of waste that will end up in a landfill, or it can be washed, which is costly, wasteful, and time consuming. Our solution to this problem is a mask apparatus that can sanitize itself quickly on demand. The user wears the shell, which contains the fully retracted mask, on a string like they would a necklace. When the mask is required, it is easily pulled out of the shell and can be worn for as long as the user needs it. When it is safe to remove the mask, the user simply pushes a button and the mask retracts back into the shell, where it is then sanitized for the next use. The design of the apparatus features a retractable cloth mask that is sanitized using ultraviolet-C (UVC) radiation while confined safely within an outer shell, minimizing unwanted exposure to the wearer. UVC radiation at wavelength 222 nm has been shown to destroy the outer shell of coronaviruses similar to SARS-CoV-2, inactivating 99.9% of the virus when exposed at a dosage of 2 $mJ/cm^2$. The 28 light-emitting diode (LED) lamps used in this prototype produce this specified wavelength UVC and are separated into 4 strips located in different locations within the shell. Glass rods were used within the shell to guide the mask fabric into a zig-zag shape when fully retracted to maximize exposure to the UVC. To further reduce waste, two lithium-ion rechargeable batteries were used as the power

supply for the lamps. The efficacy of this design for inactivating the SARS-CoV-2 coronavirus on the mask was determined indirectly using nano membrane UV sensors placed on the mask fabric, showing that the specified wavelength of UVC radiation can be applied for the required time on all surfaces of the mask. This mask apparatus can directly benefit both front-line healthcare workers as well as individuals going about their daily lives by eliminating pathogens present on their masks, therefore reducing the spread of deadly infectious diseases.

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# CHAPTER ONE: INTRODUCTION

Since being first reported in December 2019, coronavirus disease 2019 (COVID-19) has continued to spread worldwide with more than 120 million confirmed cases and 2.6 million related deaths as of March 17, 2021.[1] Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is the beta coronavirus which causes COVID-19, and is able to be spread via multiple modes of transmission, including direct contact and through airborne particulates.[2] As a result, the importance of methods to reduce the spread between individuals, such as mask mandates and social distancing, have been emphasized. While mask wearing as a mitigation technique has been effective, it has also revealed the shortcomings of current mask technologies.

Previous studies have shown masks to be effective at blocking the release of respiratory particles into the nearby environment of the wearer, while also acting as a filter that can reduce the wearer's exposure to these infectious droplets.[3,4] However, the ability of a mask to protect the wearer is reduced when it is not used properly. One of the most common faults in the use of a protective face covering is contamination. Improper handling and storage of a mask when not in use, as well as prolonged use without sanitization, and physical touching of the mask material with infected hands can all contribute to the contamination of the face covering and the exposure of the wearer to these pathogens.

Current mask technology is limited to two broad categories of face coverings: disposable and reusable. Both types have unique advantages and disadvantages, allowing for significant room for improvement. Disposable masks are designed for single-use and can easily be thrown away and replaced when contaminated, making them useful in clinical settings. However, the

United Nations reported in July 2020 that an estimated 75% of the waste from disposable masks will end up in landfills or in the oceans.[5] A September 2020 study estimated that 16,659 tons of medical waste is produced daily solely in Asia.[6] Reusable masks significantly reduce the amount of plastic waste produced, however the repeated use of a single face covering can lead to the accumulation of harmful viruses and bacteria on the protective material. In order to maintain the function of reusable face coverings, they must be constantly washed, resulting in the expenditure of large amounts of water and electricity, while also taking extended periods of time for the sanitization process to be completed, making them expensive and impractical in clinical settings.

When considering alternative methods to sanitize a face covering, few options match effectiveness with practicality. Antiseptic solutions such as a bleach are primarily used to disinfect hard surfaces and can only be used on porous materials when added to the wash. Autoclaves are commonly used to sterilize laboratory materials; however, these machines are expensive and impractical for use in clinical settings and by the public. One method that does combine efficiency and functionality is the use of concentrated ultraviolet radiation to sanitize surfaces.[7,8] Buonanno, et. al. showed the effectiveness of using ultraviolet C (UVC) radiation at wavelength 222 nm to destroy the outer shell of coronaviruses similar to SARS-CoV-2.[8] It was found that an energy dosage of 2 $mJ/cm^2$ successfully inactivated 99.9% of the alpha coronavirus HCoV-229E and 99.99% of the beta coronavirus HCoV-OC43.[8] Germicidal UV light has long been proven useful in disinfecting surfaces to reduce the spread of other viruses and bacteria such as Mycobacterium tuberculosis.[7]

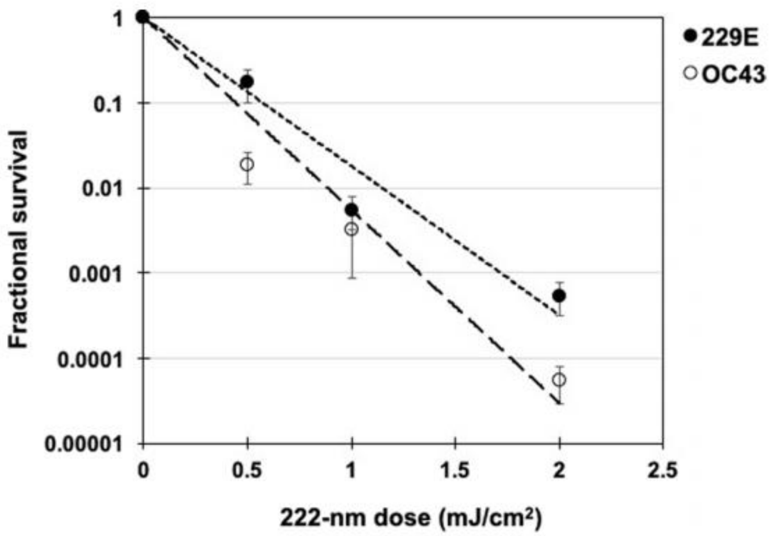


**Figure 1 Coronavirus Survival as a Function of Far-UVC Energy Dosage[8]**

Given the importance of facial coverings in order to reduce the transmission of COVID-19 between individuals, there is a lack of attention given to improving the function and sustainability of current mask designs. There is a need for a mask that is more easily sanitized and can still be easily put on and removed, while still promoting healthy mask wearing when necessary. As a result, we have developed the Auto-sanitizing Retractable Mask Optimized for Reusability (ARMOR), to further combat the spread of COVID-19 and other infectious diseases and reduce unnecessary waste.

# CHAPTER TWO: PROTOTYPE DESIGN

The idea behind our ARMOR is simple: use ultraviolet C radiation to kill bacteria and viruses on the face covering. However, there was much that had to be considered in the design. First, in order to provide maximum UVC exposure to the mask and limited exposure to the wearer, the light-emitting diode (LED) lamps must be contained within a case with the face covering at the time of sterilization. To achieve this, a case was designed to be worn around the wearer's neck, with the mask contained inside while not being used. When the user requires use of the face covering, it can be easily extracted from the case and worn for as long as necessary. If the face covering becomes contaminated, it can be retracted back into the case with a simple press of a button where it is then disinfected.

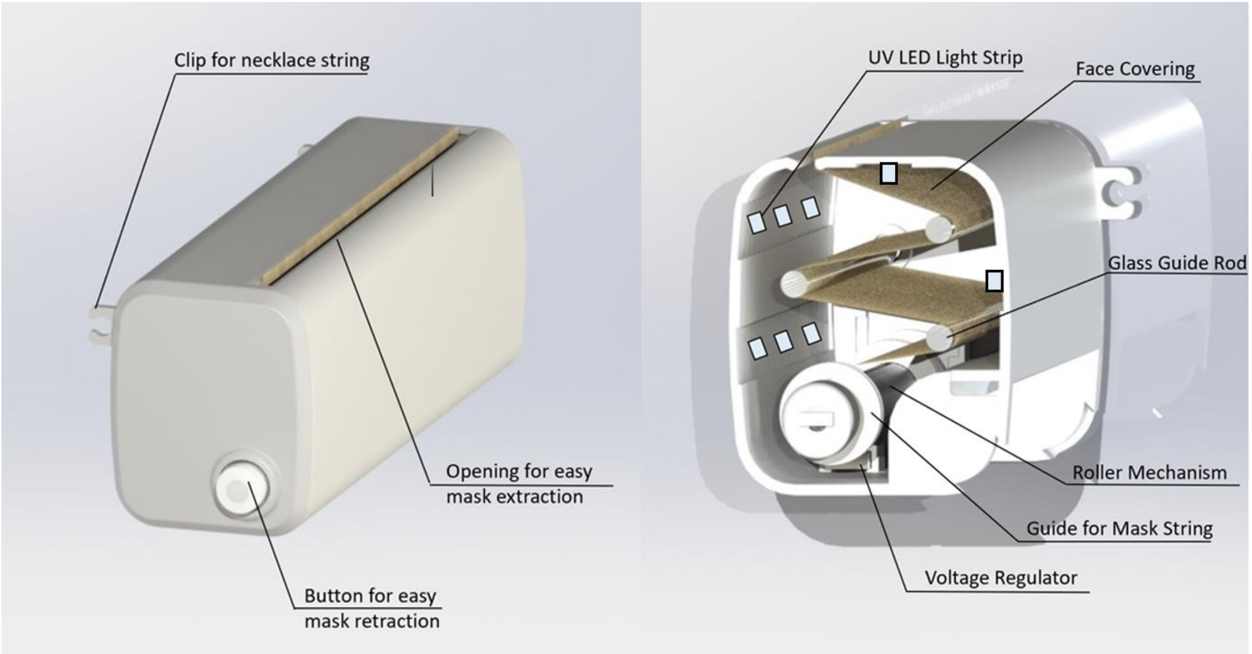


**Figure 2 ARMOR Exterior and Interior Components**

The interior of ARMOR was designed to promote ease of use and maximal UVC exposure to all parts of the face covering. In this initial prototype, a cotton cloth was used as a sample face covering. Rods were used to define the track the mask follows when inside the case, creating a zig-zag pattern that prevents the material from folding in on itself and blocking areas from the LEDs. Glass was the selected material for these rods because it is permeable to UVC, allowing the germicidal radiation to reach the areas of the mask in direct contact with the rods. A roller mechanism was employed to retract and deploy the face covering. One side of the roller contains an anchor which attaches to the left end cap, and the other side of the roller contains a ratchet mechanism which slips when the mask is being extracted. As the mask is pulled from the case, two strings attached to the bottom of the mask cause the roller to rotate, adding tension to a spring inside the roller. Upon complete extraction, the ratchet mechanism holds the spring tension until the retractor button is pressed, causing the clutch to disengage, allowing the spring tension to be released, which pulls the mask back into the case. The guides surrounding the roller act as a spool for the incoming string.

Four strips of 7 270 nm UVC-producing LEDs (28 lamps total) (cleanUV™, Waveform Lighting, Vancouver, WA) were placed in different locations around the interior of the case to provide exposure to all surfaces of the face covering. Two rechargeable 3.7V lithium-ion batteries (lithium-ion cylindrical battery, Adafruit, New York City, NY) serve as the power source for ARMOR. The LEDs require a 12V power source, so the batteries separately run through two isolated step-up voltage regulators (step-up regulator, Pololu Robotics and Electronics, Las Vegas, NV) to account for the increase to 12V. The batteries are confined in a separate space from the mask in ARMOR and can easily be accessed and removed for recharging with the removal of the rear battery cover. A push-button switch (Push-button switch 1A, CW Industries, Southampton, PA) allows for the LEDs to be turned on and off. Later iterations will feature a micro-USB port for recharging the batteries to provide increased ease of use.

**Figure 3 User Wearing ARMOR**

# CHAPTER THREE: EXPERIMENTAL METHODS

Current CDC recommendations for experimentation using cultures of SARS-CoV-2 is that it must be conduced in a Biosafety Level 3 laboratory.[9] As a result, it is not feasible to test ARMOR directly using virus samples. However, as previous research has established that a UVC energy dosage of 2.0 $mJ/cm^2$ inactivates more than 99.9% of tested coronaviruses, an indirect method of testing the effectiveness of ARMOR can be used.[8]

Waveform Lighting provides specific details on their website on the irradiance (intensity) of a single 270 nm UVC-producing LED lamp at 1 in (2.54 cm) intervals up to 11 in.[10] A ZnO-based UV sensor developed at the University of Central Florida was used in the experiment to measure light intensity as the inverse of electrical resistance.[11] In order to obtain measurements of UVC light intensity inside ARMOR, a standard curve of intensity versus inverse resistance was first generated. To create the standard curve, the UV sensor was placed at fixed distances 1 in, 2 in, 3 in, and 4 in away from a single LED lamp, and electrical resistance values at each distance were recorded and compared to the irradiance data from the LED manufacturer.

After the standard curve was generated, 9 sensor locations on both sides of the mask were selected in a 3X3 grid to measure UV light intensity inside the case. Using an adjustable clamp, the sensor was lowered into one of the selected locations on the face covering where it was held in place with the LED lamps turned on while electrical resistance was measured using a multimeter. This step was carried out for all 18 designated locations on the mask, and then the resistance values were compared to the standard curve to obtain the UV intensity data.

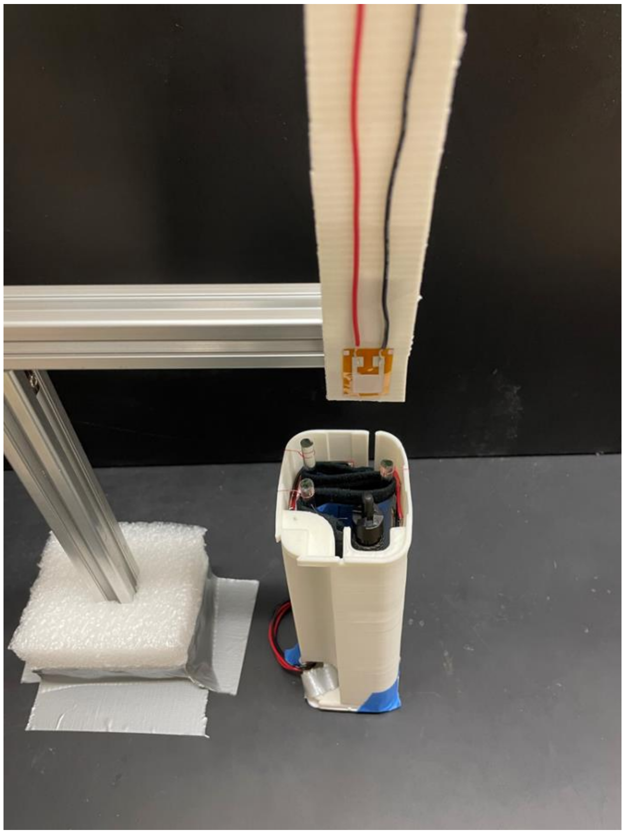

**Figure 4 Experimental Setup Using ZnO-Based UV Sensor**

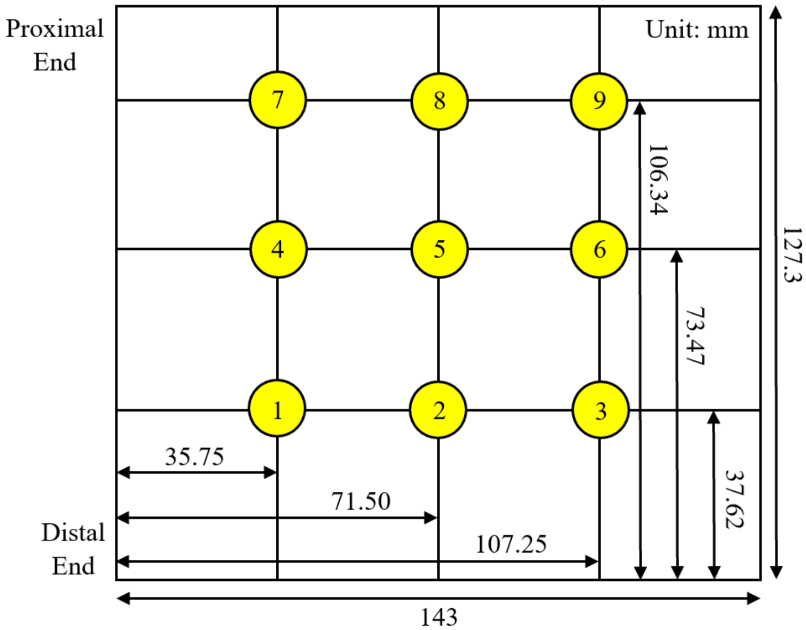


**Figure 5 Locations of UV Sensor Placement on the Face Covering**

# CHAPTER FOUR: RESULTS

| Distance (in) | Intensity (µW/cm$^2$) | Measured Resistance (MΩ) | 1/$R_m$ |
|---|---|---|---|
| 1.00 | 118.4 | 0.1955 | 5.115 |
| 2.00 | 78.2 | 0.72 | 1.389 |
| 3.00 | 61.5 | 1.52 | 0.658 |
| 4.00 | 48.6 | 3.30 | 0.303 |

**Table 1 Given Intensity and Measured Resistance of a Single LED Lamp**

After measuring the electrical resistance of the UV sensor when exposed to a single LED lamp at set distances, the irradiance data provided by Waveform Lighting could be used to create a standard curve of intensity over inverse resistance. The equation of the curve is $y=70.536x^{0.3159}$ and will be used to calculate the experimental intensity at each sensor location.

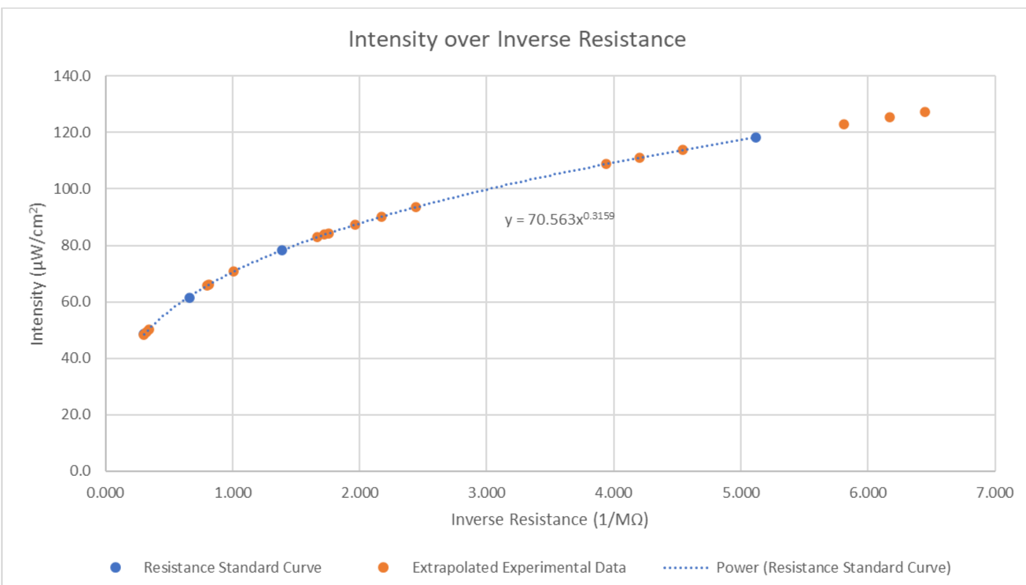


**Figure 6 Intensity over Inverse Resistance Standard Curve and Experimental Values**

| Front Side Location | Sensor Position | Experimental Resistance (MΩ) | $1/R_e$ |
|---|---|---|---|
| Bottom | 1 | 0.57 | 1.754 |
| | 2 | 0.58 | 1.724 |
| | 3 | 0.60 | 1.667 |
| Middle | 4 | 0.162 | 6.173 |
| | 5 | 0.155 | 6.452 |
| | 6 | 0.220 | 4.545 |
| Top | 7 | 0.51 | 1.961 |
| | 8 | 0.46 | 2.174 |
| | 9 | 0.41 | 2.439 |

**Table 2 Mask Front Side Experimental Resistance Values**

| Back Side Location | Sensor Position | Experimental Resistance (MΩ) | $1/R_e$ |
|---|---|---|---|
| Bottom | 1 | 1.25 | 0.800 |
| | 2 | 1.23 | 0.813 |
| | 3 | 0.99 | 1.010 |
| Middle | 4 | 3.30 | 0.303 |
| | 5 | 2.92 | 0.342 |
| | 6 | 3.09 | 0.324 |
| Top | 7 | 0.172 | 5.814 |
| | 8 | 0.238 | 4.202 |
| | 9 | 0.254 | 3.937 |

**Table 3 Mask Back Side Experimental Resistance Values**

Once the experimental resistance values of the 18 different sensor locations on the mask inside the case were measured, the intensity of each location can be calculated using the standard curve. The y axis of the curve is intensity, and the x axis is inverse resistance; therefore when 1/Experimental Resistance is substituted for x in the equation $y=70.536x^{0.3159}$, y is the intensity of the UVC at that specific location in μW/cm$^2$. After a unit conversion to mW/cm$^2$, the required energy dosage of 2.0 mJ/cm$^2$ provided by Buonanno et. al. can be divided by the calculated intensity in order to determine required exposure time to kill coronaviruses in each location on the face covering. This exposure time was recalculated using $E=hc/\lambda$ (E=light energy, h=Planck's constant, c=speed of light, λ=wavelength) to account for the difference in light energy between the referenced 222 nm UVC and the 270 nm UVC used in ARMOR. Linear forecasting was used to extrapolate the intensity data to the edges of the face covering, and after calculation, the required exposure time at the area of least intensity is 83.69 seconds. Analysis of the experimental UVC intensity data revealed areas of the face covering with high exposure, and areas with less exposure. The contour plots of intensity reveal that the locations with the highest UV exposure are the center (y=40-100 mm) and top (y=110-127 mm) of the front side, and the top (y=95-127 mm) of the back side of the face covering.

| Front Sensor Position | Calculated Intensity ($\mu W/cm^2$) | Calculated Intensity ($mW/cm^2$) | Reqired Energy Dosage ($mJ/cm^2$) | Required Exposure Time (s) | Recalculated Exposure Time (s) |
|---|---|---|---|---|---|
| 1 | 84.274 | 0.08427 | 2.0 | 23.732 | 28.863 |
| 2 | 83.813 | 0.08381 | 2.0 | 23.863 | 29.022 |
| 3 | 82.920 | 0.08292 | 2.0 | 24.120 | 29.335 |
| 4 | 125.398 | 0.12540 | 2.0 | 15.949 | 19.398 |
| 5 | 127.160 | 0.12716 | 2.0 | 15.728 | 19.129 |
| 6 | 113.843 | 0.11384 | 2.0 | 17.568 | 21.367 |
| 7 | 87.288 | 0.08729 | 2.0 | 22.913 | 27.867 |
| 8 | 90.180 | 0.09018 | 2.0 | 22.178 | 26.973 |
| 9 | 93.519 | 0.09352 | 2.0 | 21.386 | 26.010 |

**Table 4 Mask Front Side Calculated Intensity and Exposure Time Values**

| Back Sensor Position | Calculated Intensity ($\mu W/cm^2$) | Calculated Intensity ($mW/cm^2$) | Reqired Energy Dosage ($mJ/cm^2$) | Required Exposure Time (s) | Recalculated Exposure Time (s) |
|---|---|---|---|---|---|
| 1 | 65.760 | 0.06576 | 2.0 | 30.414 | 36.989 |
| 2 | 66.096 | 0.06610 | 2.0 | 30.259 | 36.801 |
| 3 | 70.787 | 0.07079 | 2.0 | 28.254 | 34.363 |
| 4 | 48.393 | 0.04839 | 2.0 | 41.329 | 50.265 |
| 5 | 50.299 | 0.05030 | 2.0 | 39.762 | 48.359 |
| 6 | 49.408 | 0.04941 | 2.0 | 40.479 | 49.231 |
| 7 | 123.048 | 0.12305 | 2.0 | 16.254 | 19.768 |
| 8 | 111.049 | 0.11105 | 2.0 | 18.010 | 21.904 |
| 9 | 108.790 | 0.10879 | 2.0 | 18.384 | 22.359 |

**Table 5 Mask Back Side Calculated Intensity and Exposure Time Values**

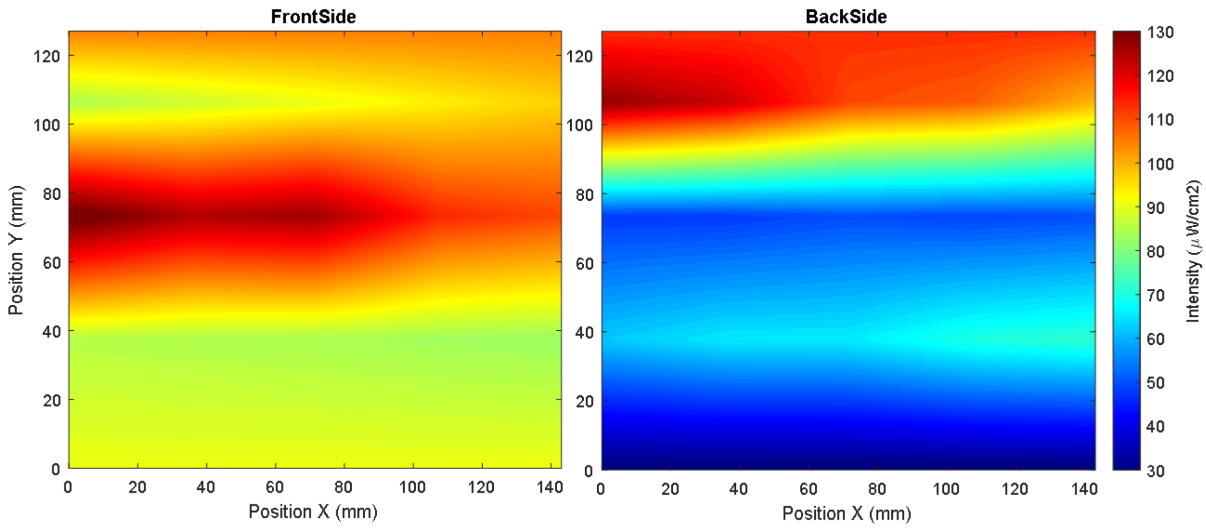


**Figure 7 Contour Plots of UVC Intensity Across Front and Back Sides of the Mask**

# CHAPTER FIVE: CONCLUSION

The ARMOR was designed to be an effective and elegant solution for minimizing face covering contamination and disposable mask waste. Using existing knowledge on the ability of ultraviolet C radiation to inactivate coronaviruses related to SARS-CoV-2, the effectiveness of our design in sanitizing a reusable mask could be tested indirectly. The “front” side of the mask is designated as the surface that faces away from the wearer and is exposed the most to the environment. Therefore, it is advantageous that this side receives the highest intensity of the germicidal UVC light because it is likely the most easily contaminated. The “back” side of the mask faces the wearer, and it is important that this surface receives sufficient exposure during sanitization as well. The upper half of the back side is in contact with the nose and mouth of the user, so it is significant that this area receives a UV intensity greater than 70 $\mu W/cm^2$. The bottom of the back side of the face covering is in contact with the wearer’s chin and neck area, which means that it likely receives the least amount of contamination. As a result, it is reasonable that this area receives a lesser intensity of the germicidal radiation.

It is important to note that regardless of the intensity in each location on the face covering, all areas on both sides are exposed to the UVC light. This means that even the areas of least intensity can reach the required energy dosage of 2.0 $mJ/cm^2$ to be sanitized if the exposure time is sufficient. The exposure time was initially calculated by dividing the required energy dosage by the light intensity. This number was then recalculated by dividing by the percentage of light energy produced by the 270 nm LED lamps used in ARMOR compared to the 222 nm light used by Buonanno et. al.[8] Limited research has been performed directly showing the ability of ultraviolet C radiation to inactivate SARS-CoV-2 and related coronaviruses, therefore it is unknown if longer wavelength, lower energy 270 nm light would take longer to have the same germicidal effects as the higher energy 222 nm light. However, use of UVC radiation at 270 nm is a proven bactericidal and virucidal method.[7] The recalculated exposure times therefore reflect the worst-case ability for the ARMOR prototype to inactivate more than 99.9% of coronaviruses HCoV-229E and HCoV-OC43. The longest recalculated exposure time was determined to be at the bottom of the back side of the face covering, taking 84 seconds for this area to be sanitized. The 84 seconds is also the time ARMOR takes to sanitize all areas of the mask from these coronaviruses. Some viruses such as H1N1 Influenza require a higher energy dosage to reach the same level of lethality. As a result, the exposure time can be extended accordingly to achieve broad-spectrum sterilization.

Overall, the high observed light intensity on both sides of the face covering and the relatively short time required to disinfect when compared to traditional washing methods indicates that we were successful in achieving our objective. The ARMOR prototype presents benefits to front-line healthcare workers by eliminating pathogens present on their masks, therefore reducing the spread of deadly infectious diseases. In between visiting patients, the mask can be removed and sanitized in just a couple minutes, reducing the accumulation of bacteria and viruses on the face covering. Use of ARMOR instead of traditional disposable masks can also significantly reduce the amount of medical waste that ends up in landfills.

There are some limitations to the current design of ARMOR, though these can be addressed with future development of the design. The current version of the prototype has increased weight due to a large number of LED lamps and multiple batteries. However, both the size and weight can be reduced in future iterations with additional optimization. Given the short amount of time currently required to sanitize the face covering, the number of LED lamps can be reduced, eliminating the need for two batteries, and reducing the size and weight of ARMOR while still keeping the exposure time to a few minutes. Additionally, a cotton face covering was used in this version, which can allow infected water droplets to settle into the material. This could result in reduced exposure of pathogens to the UVC and decreased germicidal effects on the mask. A solution to this issue is the use of a synthetic fabric that wicks moisture in future iterations. Our design of an Auto-sanitizing Retractable Mask Optimized for Reusability is effective at providing a lethal dose of ultraviolet-C radiation to the pathogens on the surface of a face covering, therefore protecting the wearer from infection and reducing unnecessary waste, while still leaving room for additional design improvement.

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