# Mail Cleaner

Commissioned by Phil Black for Presco Inc.

Developed by Peter Sauer

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## Table of Contents

# 1.0 Introduction

### 1.1 Product Summary

The purpose of this project is to design and build a device that can feed through assorted mail to disinfect it without ruining the contents. To achieve this goal, the design incorporates two UV-C bulbs that are capable of providing enough UV light to disinfect all of the surfaces of the mail item.

1-log performance (10x reduction in virus load) is achieved at a dosage of about 3,000 μJ/cm$^2$ for the typical Corona virus such as influenza.  Log-performance is linear with dosage.  This means that 3-log performance (99.9% kill rate) is achieved at 10 mJ/cm$^2$.[1] By comparison, antiseptic wipes and sprays are only about 99% effective, even if they are actually used in the proper way.  The goal of this project is to reach 3-log performance.

### 1.2 Constraints

The constraints given for this project are as follows:

- The cleaner should be capable of reaching at least 3-log performance
- The cleaner should be able to accept objects up to a minimum thickness of ¼” with it preferably accepting up to ½”
- The cleaner should be small enough to operate on a desk
- The cleaner should be able to clean objects at a reasonably fast rate

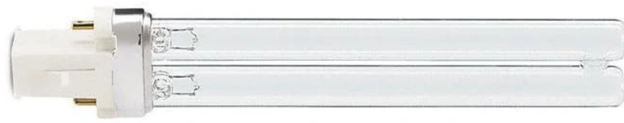
# 2.0 Product Design

### 2.1 Design of Light Fixtures

Originally, with the idea that the bulb would be one singular bulb, similar to the ones found in fluorescent light fixtures, the light fixture was designed for this project as a parabolic shape with a mirror finish that placed the light at its focus. This directs all of the light possible down towards the surface of the mail.
[1]

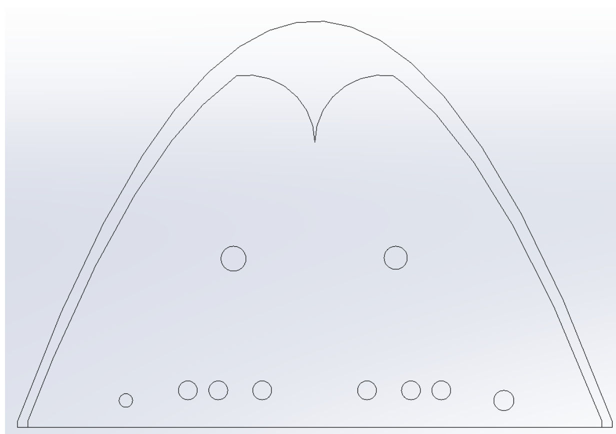
After some research, however, it was discovered that the bulb most suitable for this application actually consisted of two parallel bulbs. The bulb is the Philips TUV PL-L 24W/4P UNP/50 which sells for $9.71/bulb. It provides 7.1 W of UV-C and takes 24W of power.

[1] “Signify's UV-C Light Inactivates COVID-19 Virus.” *Signify*, www.signify.com/en-us/our-company/news/press-releases/2020/20200616-signify-boston-university-validate-effectiveness-signify-uvc-light-sources-on-inactivating-virus-that-causes-covid19.



**[FIG 1]** The Phillips UV-C bulb

In order to accommodate for this change, two additional parabolas were added at the top of the initial parabola, reflecting each bulbs light out, away from the center intersection of the two bulbs.

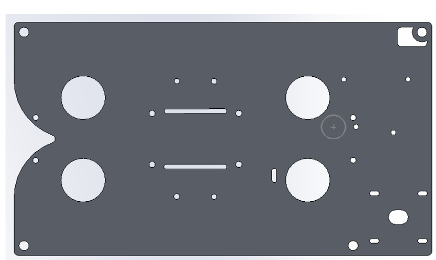


**[FIG 2]** A cross section of the final shade design

This design finally culminated in a fully contained assembly that both held the bulb, and was capable of directing most of its energy downward towards the mail object.

## 2.2 Design of Structural Components

This prototype was designed with cost and machinability in mind. To that end, the main structure of the prototype contains only two identical aluminum plates and 4 threaded rod/aluminum tube combinations.

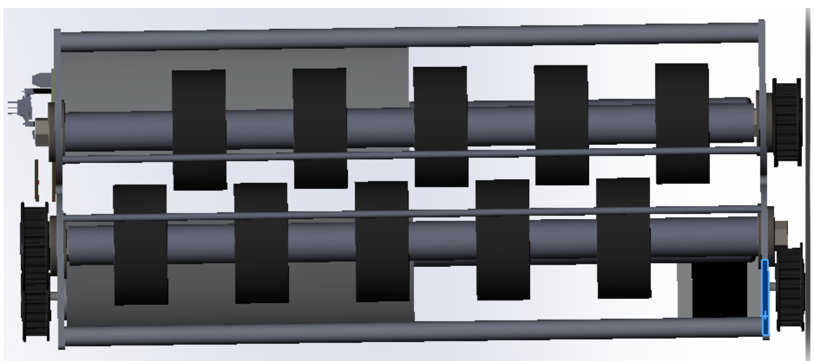


**[FIG 3]** The main structural component of this prototype

This plate contains holes for bearings, slots for power wires, mounting holes for the arduino and motor controllers and for the stepper motors used for movement.

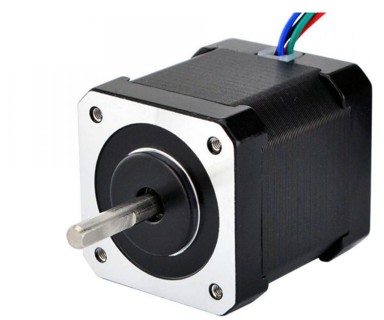
### 2.3 Design of Motion Components

In order to move the envelopes and magazines through this mechanism, foam wheels mounted on spring loaded shafts were originally planned as a way to grip the paper objects. However, because of cost and reliability reasons, this design was scrapped. Instead, a method used by many printers was adopted instead. Staggered, overlapping wheels were used to provide grip to the mail objects while also allowing space for the objects to flex. Traditionally in printers, these wheels are completely solid, but in this case, flexible intake wheels were used to provide the higher degree of height variance (0-½”) that was specified in the design constraints.



**[FIG 4]** A front view of the overlapping wheel intake system

In order to drive this system, a belt drive was used. This was chosen because of its reliability and the low amount of noise that it produces while being driven. These belts are driven by two NEMA 17 stepper motors. The belts used were ordered from SDP-SI with the part numbers A36R55M107090 and A36R55M120090.

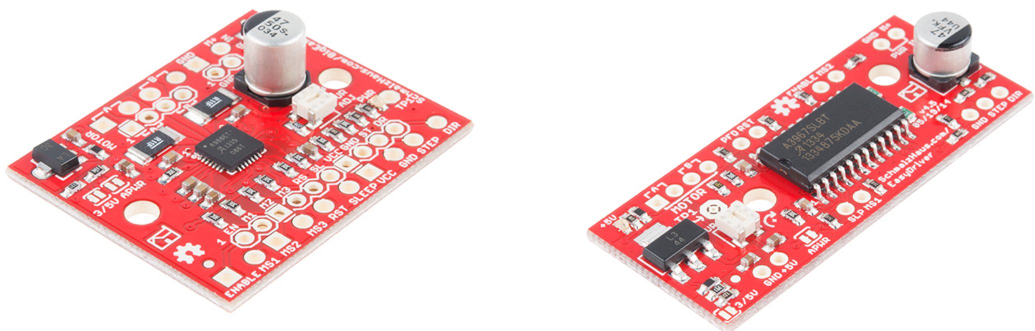


**[FIG 5]** The stepper motors

The stepper motors used in this prototype are Stepper Online 17HS19-2004S1 motors and provide 84 oz-in of torque. Two of these motors are used, running belts in opposite directions to provide counter-rotating shafts on the top and bottom of whatever mail is being fed in.

## 2.4 Electronics

The stepper motors referenced above were being driven by two Big Easy Stepper Drivers which were ordered from SparkFun. Initially, two Easy Stepper Drivers were used, but these did not provide enough amperage to the motors to reach the desired torque. Eventually it was discovered that the Big Easy Driver also did not provide enough torque, and was unreliable.

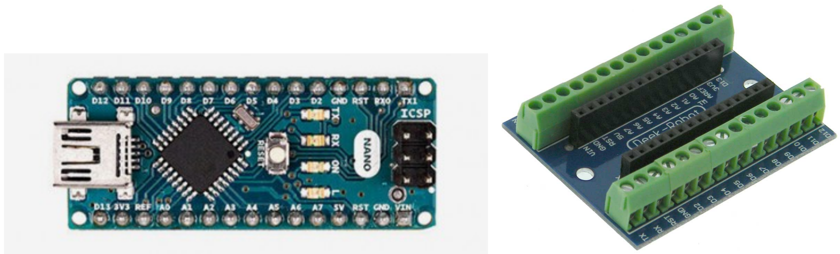


**[FIG 6-7]** Big Easy Driver, Easy Driver

After this discovery, the MakeBlock 2H Stepper Driver was used instead. One of these was initially used to drive both steppers, however if a bigger arduino is used, two could be driven. The current arduino nano only provides enough current for one controller to be used.

**[FIG 8]** MakeBlock 2H Stepper Driver

The logic for these motor controllers takes place on an arduino nano. The arduino nano provides an apt amount of computing power in a relatively small package. This makes it ideal for this task. For ease of mounting and prototyping, the nano is mounted on a specially designed screw terminal extension board.



**[FIG 8-9]** Arduino Nano, Screw terminal expansion board

## 3.0 Arduino Firmware

The following code is used to run the motors for a desired duration at a desired speed in inches per second.

```
#include "MeOrion.h"

int dirPin = 2;//the direction pin connected to pin 2 on the arduino
int stpPin = 3;//the Step pin connected to pin 3 on the arduino


void setup()
{
  pinMode(dirPin, OUTPUT); //set both pins as outputs
  pinMode(stpPin, OUTPUT);
}

void step(int spd,int steps) //the step function (speed in in/s, stepper motor steps)
{
  float circum = 2.25*PI; //the circumference of the intake wheels
  int stepsPerRev = 200;  // the number of steps per revolution of the motor

  float convertedSpeed = 1000*circum/(spd*2*stepsPerRev); //the speed converted to ms
of wait time between steps

  digitalWrite(dirPin,LOW); //pull the direction pin low

  delay(50);

  for(int i=0;i<steps;i++) //toggle the step pin high and low at the frequency
specified by the speed
  {
    digitalWrite(stpPin, HIGH);
    delayMicroseconds(convertedSpeed*1000);
    digitalWrite(stpPin, LOW);
```

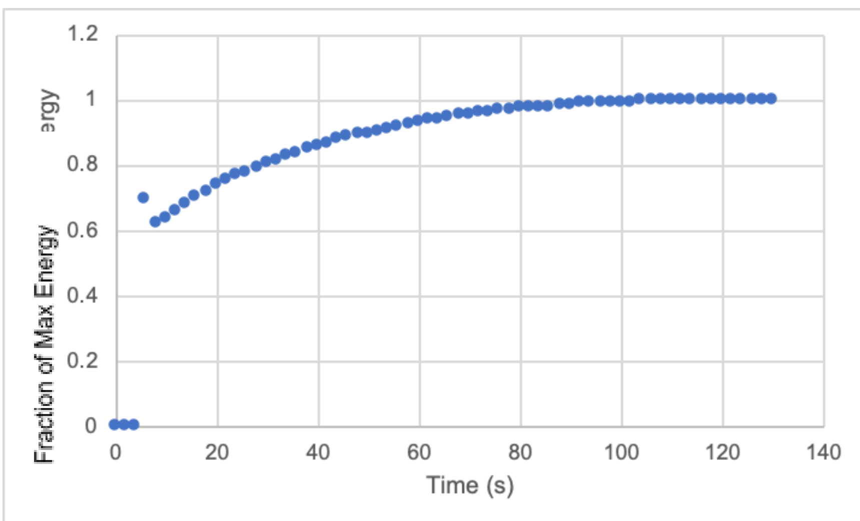
```
    delayMicroseconds(convertedSpeed*1000);
  }
}


void loop()
{
  step(4,10000); //run 10000 steps
}
```

## 4.0 UVC Testing

### 4.1 UVC Ramp Up Over Time

The first test performed on the Phillips UVC bulbs used for this prototype was to see how long it would take for them to reach their maximum brightness (or energy dispersal) level. Using the ballast previously selected, a UV meter was placed under the bulb as it was allowed to turn on and slowly climb to its full brightness. The following graph was logged by the meter.

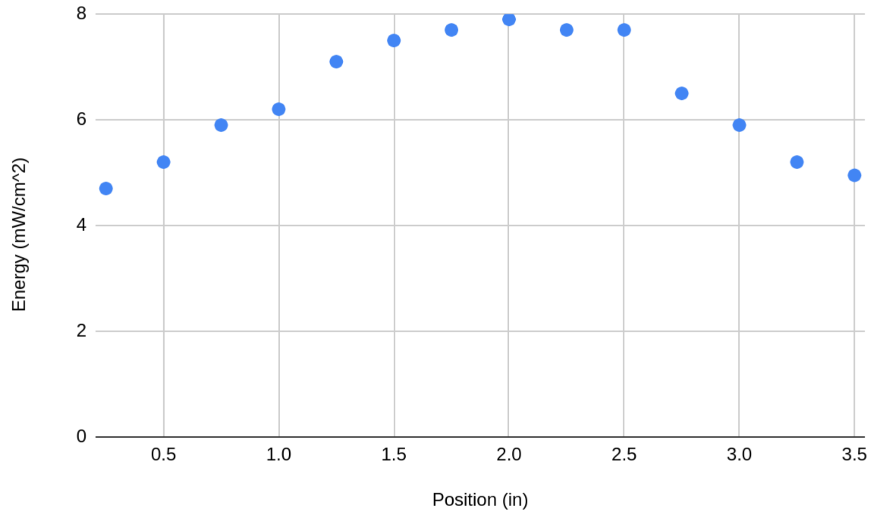



**[FIG 10]** The increase of bulb energy over time as a percentage of its maximum.

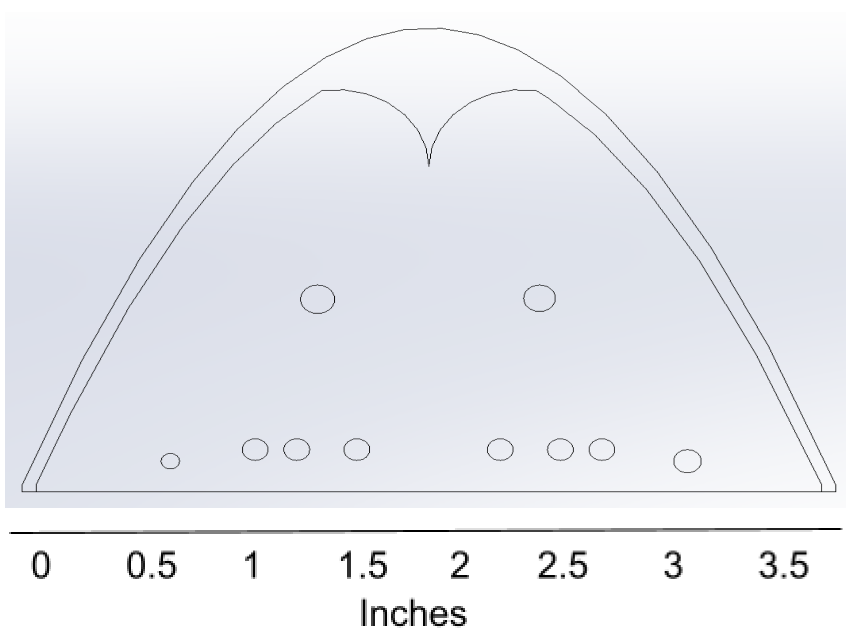
The ramp up over this time period is not quite as fast as would be optimal, so other ballasts are being explored that allow the bulb to heat up in less time.

### 4.2 Vertical Position and Energy Dispersal

The second test performed on the bulbs found the amount of energy that was dispersed under different positions along the width of the bulb, so that a more accurate representation of the total energy that would be absorbed by the mail could be found.




**[FIG 11]** The energy dispersed at 16 different positions along the width of the bulb.



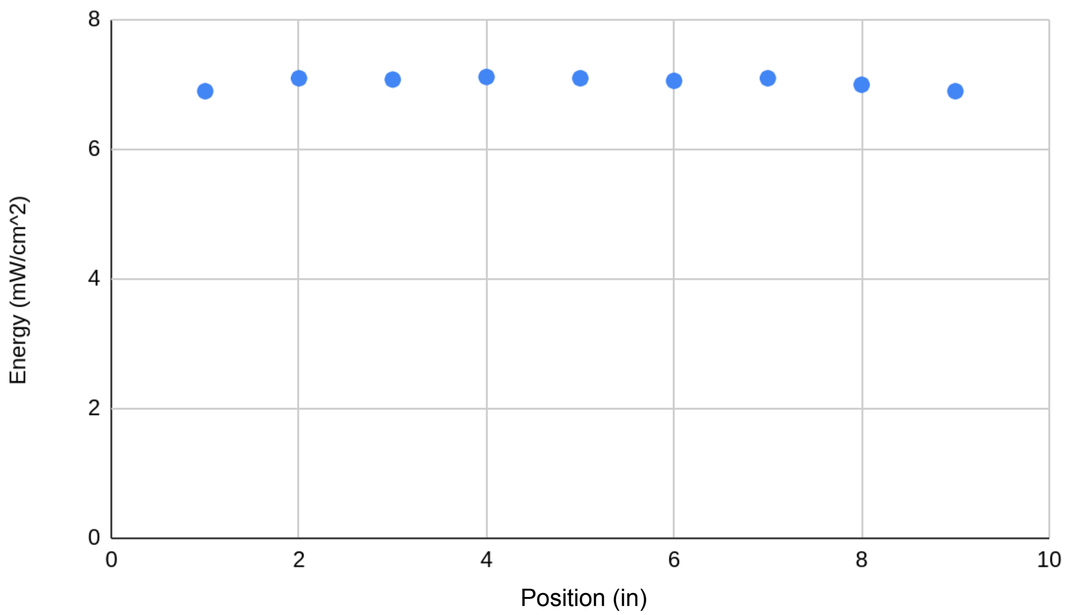

**[FIG 12]** The shape of the shade along which the UV Energy was measured

Using this data, the average energy dispersed at the side and middle locations was calculated. The middle location provided an average of 6.38 $mW/cm^2$. Since the lower number is the side measurement (as expected), that will be used for our calculations moving forward.

It is known based upon a paper by Boston University that 5 mJ/cm$^2$ is required for 2-log decontamination and 22 mJ/cm$^2$ is required for 5-log. Based upon those numbers, the mail will have to be under the light for 0.783 seconds to get 2-log and 3.45 seconds for 5-log.

### 4.3 Horizontal Position and Energy Dispersal

This test was used to determine how much the position along the length of the bulb affects the energy dispersed at that location. 9 different locations one inch apart were measured from the tip of the bulb (position 1) to the socket (position 9).




**[FIG 13]** The energy dispersed at 9 different positions along the length of the bulb.

This shows that there is a drop off on positions 1 and 9, however most of the other positions are relatively similar in terms of strength. Only the extreme right and left positions will be different (and those are already being used in the calculations for part 4.2. Measurements were taken in the same plane that the paper runs through the machine at.

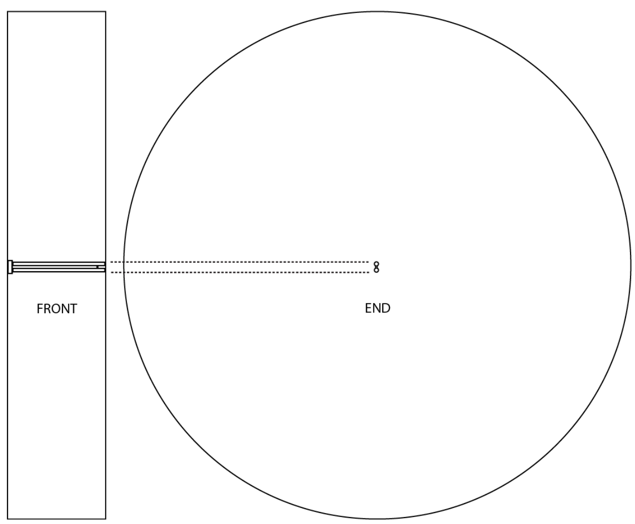
### 4.4 Creating a Legend for UV Label Testing

UV-C Labels were bought that change color based upon UV-C exposure. Unfortunately these labels did not come with a color code, so one had to be created in order to accurately identify the different colors. 5 different levels of UV-C exposure were tested by measuring the UV exposure directly next to a label using the UV meter which was used for the above experiments. The following legend was created.

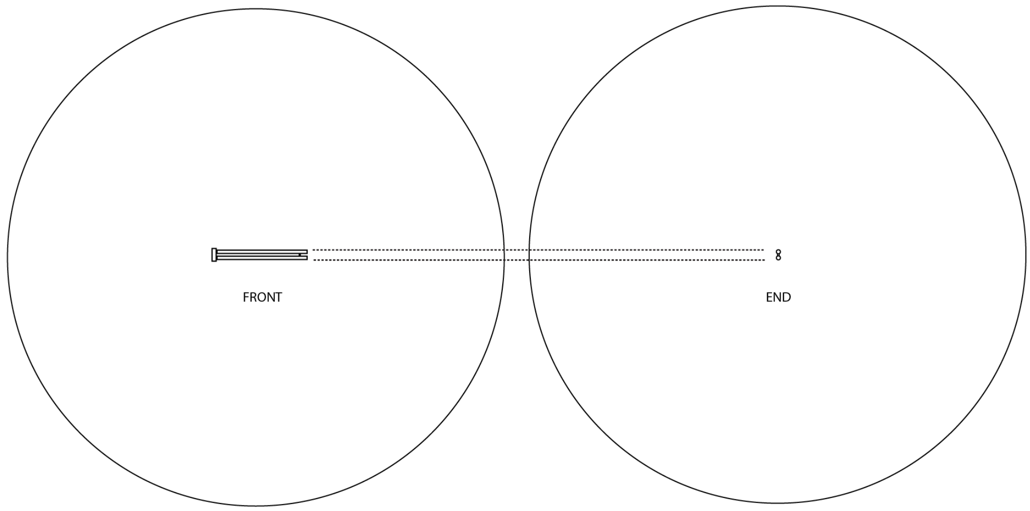

**[FIG 14]** The different colors of label based upon exposure.

### 4.5 Approximating the Shape of Light

Two different shapes were considered to model the way the light spreads out from the UV-C bulb. These two shapes were a cylinder, capped on each end where the bulb ends (the socket end and the end opposite that), and a sphere, considering the bulb to be a point at its center. After doing multiple tests using the UV-C sensor, measuring the UV-C at 1 meter from the bulb, it was determined that a spherical shape more accurately depicts the way the light spreads from the bulb.




**[FIG 15]** A depiction of the cylindrical shape




**[FIG 16]** A depiction of the spherical shape

The preferred shape was calculated by dividing the full UV-C wattage available from the bulb (7.1W) by the surface area of the shape and then taking different measurements from places around the bulb using the UV-C meter to determine if the $mW/cm^2$ it read matched more closely with that model. Using this technique, the spherical measurements should equal 0.055 $mW/cm^2$ at each point on the sphere (1m away from the center of the bulb). This number was obtained by dividing the total UV-C output of the bulb (7.1 W) by the surface area of a 1 meter (radius) sphere. At a point measured directly in front of the bulb (perpendicular in the middle) a reading of 0.063 was taken. At a point 1 meter away, and 45 degrees away from perpendicular to the center of the bulb, a reading of 0.054 was taken.

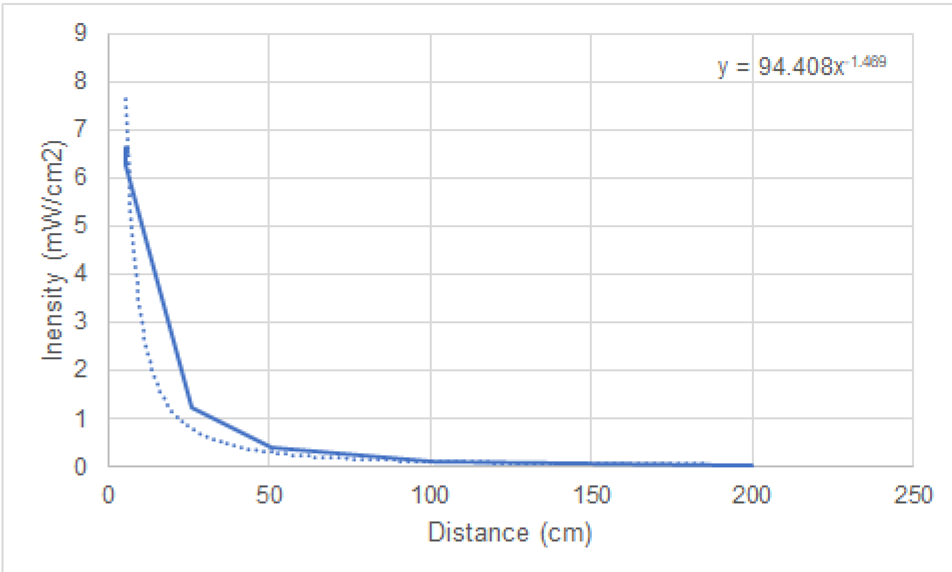
At a closer scale, a difference of up to 3x the expected dosage is lost. The above calculations were done to verify the effectiveness of the UV-C meter. One reason for this loss of energy could be complications due to the two cylinder shape of the bulb.

Calculations were also done to show that the reflective shade on top of the bulb was effective. Measurements were taken in the same plane as the paper would be relative to the bulb/bulb-reflector assembly, and and 3.1X the power was transmitted to the sensor with the reflector attached.

Condensing the sphere down to a size that makes more sense on the scale with which the light hits the paper, we are left with a sphere of radius ~10cm. Because the radius of this sphere is 10X smaller than the radius of our initial testing sphere, the energy distributed over its surface area should be 100X larger, or 5.5 $mW/cm^2$. In fact, it was found to be 2.4 mW/cm^2 without a shade, or a little less than half the expected. The sphere approximation, however, assumes a point source and as we move closer to the bulb it becomes a linear source with infinite length so the approximation does not hold.

**4.6 Intensity over Distance**

The intensity of the light coming from the bulb was measured as a function of distance from the bulb at which the UV-C meter was placed. The following graph was produced which shows this correlation.




**[FIG 17]** Intensity of UV-C vs. Distance of Meter

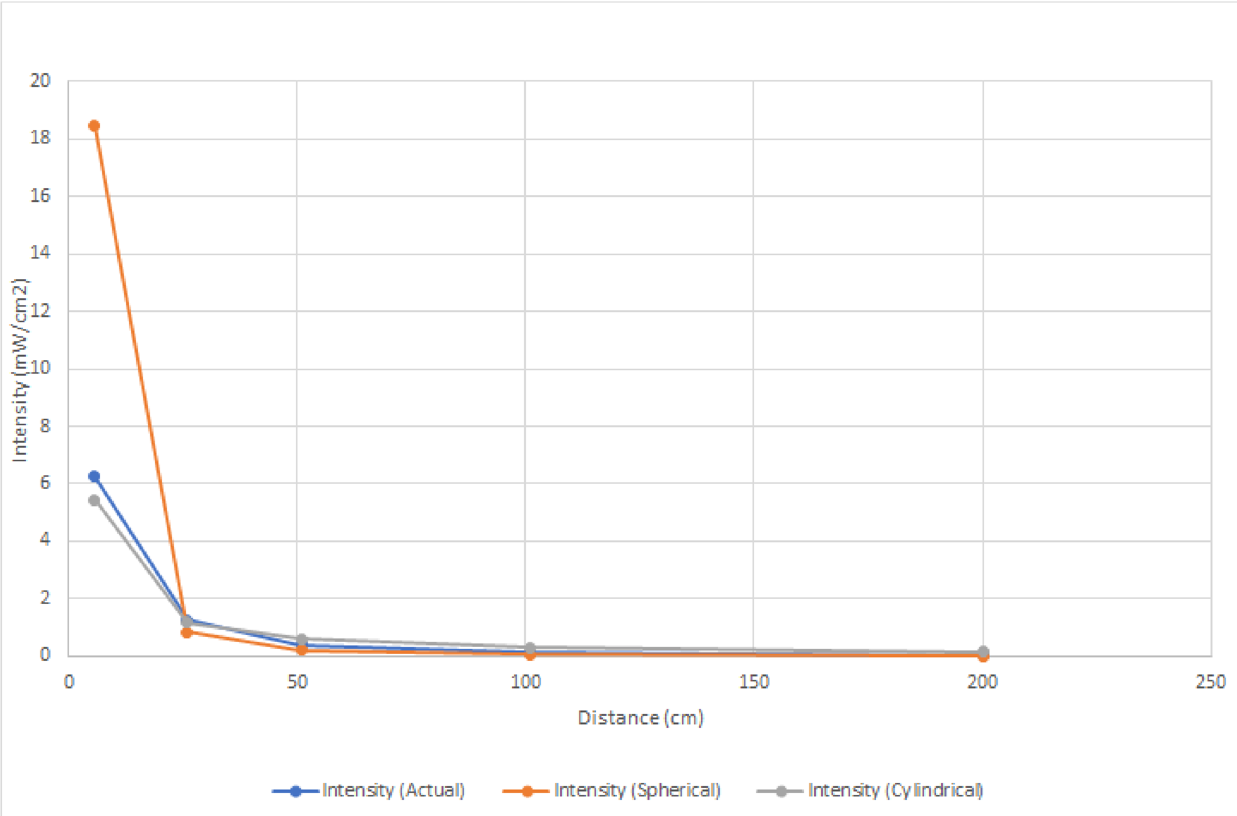
The correlation seen in the graph above seems to follow an inverse square trendline, meaning that the intensity of the bulb as seen by the meter will decrease as a function of the inverse square of the distance. The surface area of the assumed spherical shape of the emitted light would be equal to the radius (distance) squared multiplied by 4 PI. In this case, because the intensity is equal to the total UV-C energy emitted by the light divided by the total surface area of the sphere at the radius which the measurement is being taken. In this case, we end up with the formula:

$$Intensity\ = \frac{7\,W}{4\Pi r^2} = \frac{7}{4\Pi} r^{-2}$$

This shows that the UV-C energy emitted by the bulb acts between a sphere and a cylinder, because the equation for the intensity of light emitted if a cylinder were to be used would be:

$$Intensity\ = \frac{7\,W}{4\Pi r L} = \frac{7}{4\Pi L} r^{-1}$$

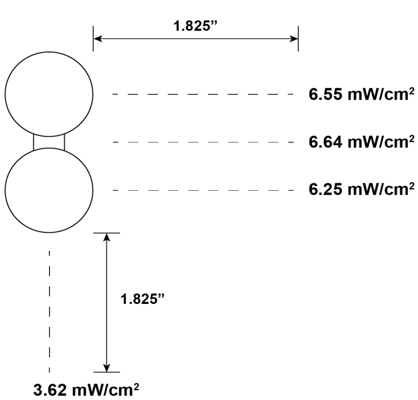
Therefore, the equation of the line of fit for the above plot shows that the distribution of intensity falls somewhere between the cylindrical and spherical spheres because with it follows an equation where the radius is held to the -1.5 power, directly in between the -2 power of a sphere and -1 power of a cylinder.




**[FIG 18]** Intensity at models vs actual

This is further shown in the above figure, which shows that the actual intensity of the bulb falls between the calculated spherical intensity and cylindrical intensity at all distances, and as the radius increases, it goes from being closer to the cylindrical model to closer to the spherical model. The first point on this figure shows the distance between the bulb and a sheet of paper running through the machine.

### 4.7 Short Distance Intensities



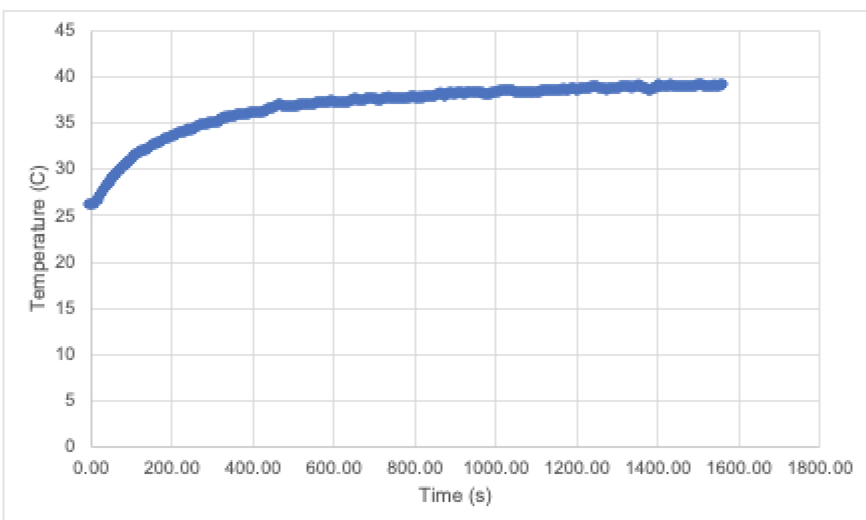

Tests were also done to see how effective the two-bulb system would be at close ranges. The diagram on the left shows the results of these tests. It seems that while perpendicular to the plane running through both bulbs (numbers on the right), the interference between the two bulbs is minimal, with numbers only ranging from 6.25 to 6.64. However, on the plane of the bulbs (the lower number) the result drops to about half of the others. Luckily, the paper runs in the area with lower variation, so it receives a more uniform dose of UVC as it runs through the machine.

**[FIG 19]** Intensities at close range

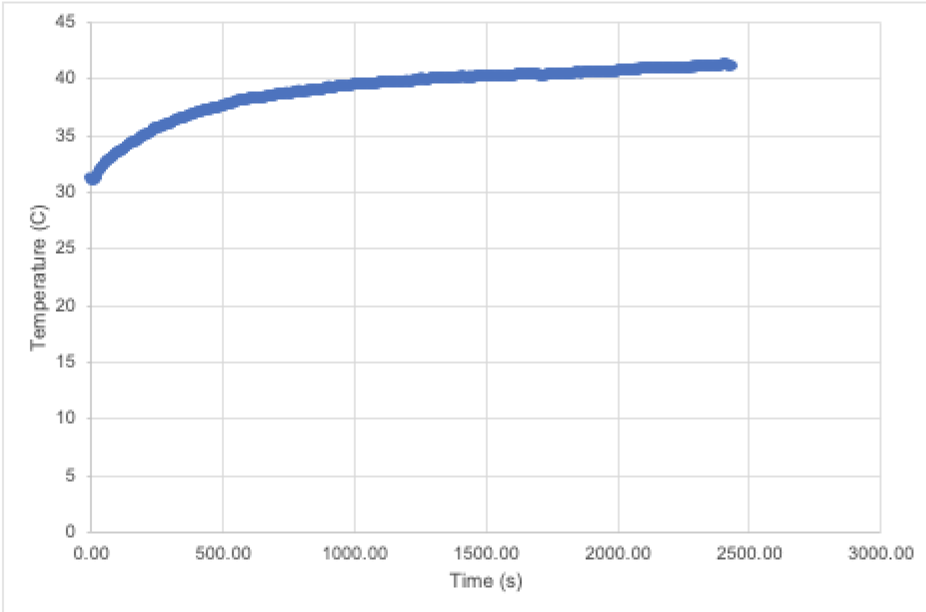
To further verify these short-distance intensities, calculations were done to determine the expected intensity, and those were compared with the results to gauge how effective the UV-C meter was. In order to evaluate the meter more effectively, the results from the position in line with the two bulbs were used (3.62 $mW/cm^2$). A number was calculated using the energy density at the surface of the bulb, 22.03 $mW/cm^2$. The sum of the distance from the surface of the bulb to the measurement device (1.825" or 4.6 cm) and the radius of the bulb (0.9 cm) was then divided by the radius of the (single) bulb (0.9 cm) to get a scaling factor. The energy density at the surface of the bulb was multiplied by this scaling factor. With these numbers, the calculated value of the energy density at 1.825" from the surface of the bulb should be 3.6 $mW/cm^2$ , which is remarkably close to the measured value of 3.62 $mW/cm^2$.

### 4.8 Temperature Testing

Another potential issue with these bulbs is that over time they will increase the temperature inside the assembly by a large amount, thus causing the whole device to overheat. Testing was done to ensure that the bulbs did not cause too much heat. Below are two plots taken using a type K thermocouple and the same UV-C/temperature meter in two different locations. Both of these locations were shielded from radiation by some aluminum foil. One testing location was between the reflector and the bulb and the other was in the same plane as the paper would be as it goes through the assembly.




**[FIG 20]** Temperature measured on the plane of the paper over time.




**[FIG 21]** Temperature measured between the bulb and reflector over time.

## Conclusions

Over the development of this prototype, and through its testing we have demonstrated that the device has the potential to clean the mail with an exposure of 3.45 seconds under the 3.5” path length. At that rate it will be capable of a 5-log reduction in COVID-19. If the user wanted a faster rate, the mail could be run through at a rate as fast as 0.8 seconds per 3.5” long piece, which retains a 2-log COVID-19 reduction. These rates translate to overall rates of 4.4 in/sec and 1.02 in/sec for 2-log and 5-log reductions, respectively.

| **Mail Type** | **Travel Length** | **2-log Reduction** | **5-log Reduction** |
|---|---|---|---|
| Flat Envelope | 11.5” | 1377 pieces/hour | 319 pieces/hour |
| Standard #10 Envelope | 4.125” | 3840 pieces/hour | 890 pieces/hour |

**[Table 1]** Travel time results for different sizes of mail in pieces/hour[1]