FOOD SANITATION DEVICE FOR USE IN MICROGRAVITY

Temple University Engineering Senior Design Document **Addendum**

Team 34: X-Hab Sanitation Device
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Abstract

This project served as an engineering senior design project at Temple University, and as part of NASA's eXploration and Habitation (X-Hab) 2018 Academic Innovation Challenge. The goal of the project was to design, construct, and test a device which would be used in microgravity to sanitize produce. This is part of a NASA's effort to grow and sanitize fresh produce on the International Space Station (ISS), in order to provide more nutritious meal options to the astronauts. Our team designed a 3-D printed spherical device with UV-C LEDs lining the interior. The designed device consists of an 8" spherical chamber, 10 UV-C LEDs, and a touchscreen user interface to control the device. Our design meets the project requirements by offering several features: a simple user interface, minimal crew time to operate, no waste produced, and the ability to sanitize multiple types of produce. The main reductions in Salmonella bacteria and Aspergillus Flavus mold were not verified. However, the aerobic plate count requirement was greatly exceeded and validated. Testing of the device resulted in visual results confirming significant decrease in E. coli activity with increased UV-C exposure, as well as quantitative results confirming significant reduction in CFU/g for the aerobic plate count. These reductions achieved from 1.464×10^7 to 2×10^4 CFU/g (2.86 log reduction) after 5 minutes, were significantly more than the requirements given by NASA (<20,000 CFU/g) for the aerobic plate count. This allows the team to conclude that the device can successfully reduce E. coli counts to safe levels on smooth surfaces. Heat, time, waste, and some of the sanitation requirements were achieved and validated in testing. In order to continue this research and also validate Salmonella bacteria and Aspergillus Flavus mold reductions, more testing will need to be performed. Also, testing on multiple surfaces, as well as in microgravity is needed to confirm that the system is viable in its intended setting.

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Design Overview

Project Context

The eXploration Systems and Habitation (X-Hab) 2018 Academic Innovation Challenge is a competition designed to develop strategic partnerships and collaborations with universities. It is sponsored by NASA and the National Space Grant Foundation. Groups of students from different universities submit proposals to be chosen to work on specific projects. This gives senior level university students the opportunity to work with professional organizations.

Our team was tasked with developing a prototype fresh food sanitation system that effectively manages microbial levels of fresh grown produce to suitable safety levels dictated by the NASA Human Research Program. Our final system should function in microgravity, and exhibit a high degree of sustainability, minimize crew time, and not foul fresh food in any way that would discourage astronauts from using the sanitation system.

Product Concept

We used *SolidWorks 2016*, provided by Temple University, to create a 3D model of the device. This allowed us to take a swift prototyping approach (i.e. 3D printing) for fabricating some of the necessary parts using a 3D printer for our prototypes and for additional tests. Acrylonitrile butadiene styrene (ABS) was selected to manufacture our device due to its relatively inexpensive cost and also due to the ease of printing the material. This plastic weighs 2 kg according to SolidWorks design. The device would be designed as a small orb, allowing for the food to sit in the middle of this sphere and the UV lights would surround the interior circumference of the sphere. The sphere was decided to be the best shape to use as this as we surrounded the chamber with a reflective coating. The sphere design gives a better angle of refraction for light to bounce off the surface and back toward the produce than other shapes such as a box. The top hemisphere would also have a lip overlapping the bottom to prevent UV light escaping the system and causing damage to skin through contact.

Product Components

The interior of our design will have a reflective coating, which will be a thin layer of aluminum (Mylar) to reflect the UV light. This coating allows for 98% of the light, which hits the surface to be reflected, focusing the radiation on the produce inside of our chamber.

The produce would be contained inside our chamber using a thin metal wire web. This web would prevent the produce from floating inside the chamber in microgravity and give a reference point on where to focus the UV radiation. The support web was made of an antimicrobial material, allowing the surface of the produce not being irradiated to still be sterilized.

The touchscreen and Raspberry Pi 3 microcontroller were mounted to the front of the device. The touch screen acts as the main control for user input for our food sanitation device. A cooling fan would also be placed behind the microcontroller to prevent it from overheating during use. A fan would also be placed inside the chamber, since there are no forces of gravity at the earth's surface this would make a heat sink redundant as they work using convection. The fan would be used to agitate the air, forcing the hot air out of the chamber and reducing the chances of our produce being fouled due to overheating.
Mounting brackets were attached to the feet of the design to keep the device grounded in microgravity.

For our design, we used a touch screen display to control all inputs into the system. The benefit of using a touchscreen display is that it helps us operate the device faster. Using the touch screen reduced the overall size of the device as the data entry method is combined using the display. This enabled us to keep the device portable and compact.

On the touchscreen, the options for each type of produce to be selected would be displayed. Since different produce demanded different light intensities as well as differing exposure time, this selection had preset light intensities for each produce, enabling the user to simply select which produce they want to disinfect from the screen, without having to perform calculations or having to manually select an intensity themselves.

As well as each produce having a predetermined light intensity level when selected on the touchscreen, the produce would also have a set time to be exposed to the UV light. This time would be calculated by our group and preset in the settings as well.

When the produce is free of contaminants and ready for consumption, the system would then automatically unlock after preset time.

Functional Requirements and Design Constraints

Functional Design Requirements and Objectives

Per the X-HAB Challenge Solicitation – 2018, the expected product is to:

> "develop a prototype fresh food sanitation system that effectively manages microbial levels of fresh grown produce to levels deemed safe by the NASA Human Research Program. System should function in microgravity, and exhibit a high degree of sustainability, minimize crew time, and not foul fresh food in a way that would discourage astronauts from using the sanitation system." (X-Hab, 2017).

From this description the minimally-acceptable design requirements, which will be quantified in the following section for clarity, can be obtained:

1. The system must reduce specific, as well as general microbial counts to those deemed safe by NASA.
2. The system must function in microgravity.
3. The system must be highly sustainable.
4. The system must complete disinfection in a practical amount of time and repair time should also be minimized.
5. Food should not be fouled. The taste and composition should remain agreeable to astronauts. (Douglas, 2016)

Furthermore, an additional minimally-acceptable requirement for the safety of the user:

6. The device must not expose the user to any UV radiation during treatment and must not exceed safe operation parameters, including operating temperature and electrical power.

In addition to the minimally-acceptable requirements, the additional desired requirements are:

7. Provide a touch-screen user interface so that the user can select a kind of produce and the system automatically selects the parameters to achieve the reduction.
8. Device will use a reflective coating to optimize the treatment.
9. The material that will maintain the produce centered in the device will have antimicrobial properties.

Now that a layman's explanation of the requirements has been given, each specific requirement can be quantified:

The specific reduction in microbial counts required by NASA are less than 20,000 CFU/g for the general aerobic plate count. In addition to this, the bacteria Salmonella Enterobacteriaceae and the mold Aspergillus Flavus will have to be specifically reduced to less than 1000 CFU/g each. However, no previous literature exists for long term reduction of these microbes using the chosen method of reduction (UV-C light), in contrast to the previous literature for the current method of using SANS wipes (Massa, 2015). For this reason, previous literature by Adhikari et. al. on Escherichia Coli is used as a basis and will be experimentally verified for the chosen microbes. An additional requirement to obtain the desired reduction based on this previous literature is that the UV-C dose is approximately 0.15 KJ/m^2, which resulted in a 1.2 and 2.4 log reduction on smooth fruit surfaces.

In order to work in microgravity, the device must use forced convection to dissipate heat, since there is no natural convection due to the lack of gravity and therefore no pressure gradients in the air. In order to achieve this, two fans will be used. One to cool the microcontroller, and another to cool the LEDs. Each LED will also have a heat sink so that the fan can dissipate the heat more efficiently.

Using UV-C LEDs for disinfection is already a highly sustainable method of reduction since there is no physical quantity to run out of, as is the case with disinfecting wipes. If there is power available, then the device will be able to function. Furthermore, since the device uses multiple sources of UV light, any single damaged source can be replaced without disabling the whole device, which makes UV LEDs more sustainable than mercury UV lamps (Kim, 2016).

Calculations based on Adhikari et. al. (Adhikari, 2015) illustrate that a 2-minute irradiation time using the chosen LEDs may achieve the required UV dose of 0.15 KJ/m^2, which is a practical amount of time per each produce, since the device can be left running while it reduces the counts. Furthermore, the 3D printing of the shell of the device means any damage to it can quickly be solved by 3D printing a replacement.

The fouling of the produce, meaning an undesired change to its taste and composition, is difficult to quantify. Observation of the produce color, taste, and smell will be used.

The device will be equipped with a contact sensor that will turn off the device if opened. This will prevent UV exposure to the user during irradiation. Also, the use of fans for forced convection will prevent unsafe operating temperatures.

Design Constraints

A general explanation of the primary design constraints placed by NASA for an ideal system were:

1. Low physical footprint.
2. Low mass.
3. Low power consumption.

These constraints were not quantified by NASA, so assumptions on these quantities, based on research, were made.

However, the main design constraint for the system is the low output power each LED provides (25 – 30 mW). This constraint led to other limitations on design parameters. The required input power and number of LEDs required to achieve a certain UV dose increased, so that placed a limit on the selected UV dose for irradiation and the number of LEDs, in order to have a low power consumption. Also, since the UV dose is a function of distance from LED and irradiation time, the distance, and therefore the device diameter, and the irradiation time were also constrained. This lead to the following secondary constraints:

4. Lower UV dose selected for irradiation to maintain practical power consumption, but enough to achieve microbial reduction.
5. Higher number of LEDs required to obtain UV dose, but lower number required to maintain practical power consumption.
6. Lower device diameter to obtain UV dose, but high enough to fit produce.
7. Higher irradiation time to obtain UV dose, but low enough to be practical to user.

Although these secondary constraints were a result of the low LED output power, they themselves are important since they are not values which are maximized or minimized, but must be optimized to obtain a balance between desired characteristics.

Now that the design constraints have been listed, they can be quantified:

The current method of produce sanitation in space using wipes has a high physical footprint since the wipes can only be used once and become waste after use. In contrast, the low volume of the device (8-inch diameter) in respect to the ISS internal pressurized volume of 32,333 cubic feet (Garcia, 2016) and lack of waste means that the low physical footprint is achieved.

The mass of all components, plus the low density of the 3D material leads to a total mass of less than 10 lbm. When this is compared to the average mass of a human at 137 lbm (Walpole, 2012), it only accounts for approximately 7.3% of that value. This illustrates a relatively low mass.

The power requirement for 10 LEDs and two fans is approximately 30 W. The ISS, where the device would initially be used, has a power output of 70 to 90 kW (Garcia, 2016). The power requirement of the device is only 0.5% of the total power input, which is relatively low.

The selected UV dose of 0.15 KJ/m^2 is practical since it still results in a 1.2 and 2.4 log reduction in smooth fruits (Adhikari, 2015), and along with the 2 minutes irradiation time results in a low power requirement, as mentioned before.

The 8 required LEDs is also practical due to the unit price of $, which, with 10 actual used LEDs, results in 25% of the total budget.

Verification and Performance

Design Verification

Housing

To design the housing for a sanitation system the objective was simple: create a platform that compliments the light emitted by the LEDs while maximizing the sterilization of pathogens. It was determined that a spherical shaped enclosure with the lights on the outer surface and the produce in the center would help achieve this goal due to its symmetrical shape when compared with other geometry. Preliminary models were drawn in SolidWorks not only to confirm component arrangement, but to have parts that could be 3D printed later project for easier assembly. Multiple iterations for the housing were considered with changes in the overall size of the system and the arrangement of the electrical layout as well which can be seen in Appendix C.1 Figures 1-3. The original diameter size of 12 inches was deemed too large for this application because of the produce required by NASA (small tomatoes, peppers, root vegetables and leaf lettuce) so it was changed to 8 inches. This not only increased the surface intensity of the UV light, but lowered the cost of the printing significantly by decreasing the required material.

LEDs

The sanitation method of choice ended up utilizing ultraviolet light concentrated at a wavelength of 265 nm, which was deemed ideal for pathogen reduction. With UV light emitting devices there are two choices available, LED or standard bulb lights. The team decided that not only do the mercury bulbs are considerably larger in size, the LED's use far less power. After the type selection, the number and strength of the LED's in question was determined. Finding a manufacturer from a recommendation, the team decided to select Klaran LED's and after talking directly with their sales department a 25 mW from their Crystal IS series was found to work for this application. Using that output value and the reduction requirement stated in the design constraint section (0.15 KJ/m^2) it was calculated that when combined with 9 others to provide enough irradiation for the reduction.

Thermal Management

In discussion with our advisors at NASA, this device required not only to destroy pathogens, but the total process must not foul the produce samples. Fouling encompasses any act which effects the taste or physical structure of the produce. This could be caused by too much irradiation of the surface or by excess heat in the housing. The team determined that the temperature in the device

should not exceed 5°F from room temperature. To combat this a cooling fan was placed in the exterior of the device to evacuate heat from the system which will work with heat sinks on the LED's to make sure they do not burn out.

Circuity
For the design of the electrical system, a few components required validation before parts could be ordered. The LED's required a minimum of 5 volts to turn on and the selected microcontroller only produces 3.3 volts in each GPIO pin. To combat this, the team decided that the design required an external power supply to run the lights. This was designed to power all LED's making for consistent power. Calculations were done to power the touchscreen and fans for the device as well.

Graphical User Interface (GUI)
To design the GUI, the team wanted the final product to be highly user friendly and easy to use. Instead of simply just having a dial with varying time values, design a touchscreen interface with images of select produce. These options have predetermined values for the length of time each sample must remain in the system.

In-Fabrication Tests

3D Printing
As the 3D printed parts were received from Temple University, all were examined for defects and to make certain they were within tolerance (± 0.005 inches). A dry fit of all components was conducted to ensure they would fit together with adhesive and all seams would be flush to their adjacent components.

LEDs
When the LEDs were first received from the manufacturer, the team found that soldering wire leads would be nearly impossible due to the small size (3.5 mm x 3.5 mm). After a discussion with Klaran, the LED's were returned and had small aluminum plates attached (12mm x 12mm) which could both attach solder and the heat sinks to the LEDs. Solder was used to connect 22 gage wire to the plate leads which were heavily inspected for quality and strength so they would not fail during use. Individual testing of the LED's was completed by connecting the leads to power supply in a Temple electrical lab to confirm they could power on.

Thermal Management
Once the LED's were received, soldered, and tested a thermal analysis was conducted to determine the temperature reached on the surface of the chip during simulated use. In Appendix C.2.1 an LED was powered on, attached to a heat sink, and let to run for 10 minutes with the team taking surface temperature readings every 30 seconds. After the analysis was run, a linear trend was seen which produced a maximum temperature of 83.3°F on the surface. While this is above the 5°F room temperature constraint, the cooling fan installed will evacuate the remaining heat leaving unspoiled produce.

Ultraviolet Intensity
To validate the calculations used to determine the quantity of LED's, an analysis of the actual intensity was required. It was seen that 1.25 W/m^2 was the minimum theoretical surface intensity needed to sanitize a sample. The team wanted to confirm if the actual LED intensity would match the theoretical intensity, so a simple experiment was conducted. Much like the thermal analysis, a single LED was powered on and using a UVC meter, values of intensity were recorded at various

lengths. Appendix C.2.2 compares UV intensity with distance. The operating distance for the LEDs will be maximized at 4 inches, which equals an intensity of 0.225 W/m^2 which was multiplied by 10 lights due to the symmetrical layout producing a surface intensity of 2.25 W/m^2 confirming the initial calculations and selection.

Performance Validation

To obtain data corresponding to the aerobic plate count functional requirement, the team, with the help of Dr. Avner Ronen and a lab assistant, created an experiment. With multiple options for pathogens, E. coli was selected as the test sample to give a good understanding of how the device worked. A small petri dish with a sample was placed inside the device for varying exposure time. The solution of E. coli was then diluted into six samples with varying strengths which can be found in Appendix C.3.5. Of the 4.5 ml samples in each dilution, 0.5 ml was taken and placed onto agar coated petri dishes for culturing. The dishes were placed into an incubator at 37°C for 24 hours for the cultures to grow. A small amount of sample was also taken for direct imaging with a microscope to see any instant results from the exposure.

Two tests were run to validate the performance of the prototype. The first was completed using the above describe procedure with sample intervals of 3, 6, and 9 minutes of exposure. Imaging was then completed which can be found in Appendix C.3.1-3.4 which show the control as well as the three samples. These images clearly show a drastic reduction of the E. coli population but due to an incubator issue, a colony forming unit count could not be completed. A second test was run with the same bacteria using 5 and 10-minute intervals due to a material shortage. During this second test, a CFU count was completed which can be found in Appendix C.3.5 showing very successful results which will be reviewed in the summary section below.

The reductions of Salmonella bacteria and Aspergillus Flavus bacteria were not validated due to time constraints. However, the similarity between E. coli and Salmonella bacteria's internal mechanisms, should at least provide a trend as to the expected results when testing Salmonella. However, no trends can be deduced for Aspergillus Flavus mold due to the difference in internal mechanisms.

Fabrication

3-D Printing and Prototyping

For the device construction to be as replaceable as possible, it was seen that 3D printing the housing and mount points would be the best option. Using SolidWorks or another 3D CAD software, the device can be created to the desired dimensions and material. Taking this CAD model, it can be converted to a format compatible with 3D printing software to interface with the printer. One major obstacle that needed to be overcome was the fact that when printing free standing curved structure, the main material needs to be supported by waste structural material to ensure the final product dries into the correct dimensions. To minimize the total cost of printing material, the device design required sectioning to shorten the dimensions of free standing curved lengths. Each half sphere was sectioned into 4 equal quarters and the handle, hinges, feet, and electrical component mounts were printed separately and attached once the printing was complete using cyanoacrylate. Once the printing was accomplished, the reflecting was attached to the interior of the device. Taking the reflective sheet and carefully adhering it, using adhesive, to the surface taking special care to remove all air pockets and creases. Following the reflective coating, 40-gauge copper wires were

strung along the top and bottom portions of the device to act as a net to encapsulate the produce sample while remaining sterile through its antimicrobial properties.

Electrical Hardware

The UV-C LEDs selected for this project are Klaran general disinfection LEDs manufactured by Crystal IS. We selected the KL265-35R-SM-GD product, which are their most powerful general disinfection LEDs: operating at an optical power output in the range of 25-30 mW. The LEDs are 3.5mm x 3.5mm and are mounted onto 12mm x 12mm printed circuit boards (PCBs). The manufacturer supplied LEDs which were already mounted on the board by reflow soldering. The wiring and heat sinks were then attached to the boards according to the wiring diagram. This was done by hand soldering 22 gauge wire onto the anode and cathode of each pads of the PCB. The heat sinks selected had an adhesive backing, but to supplement this thermal paste and super glue were used to reinforce the connection between the thermal pad of the PCB and the heat sink.

The manufacturer provided an Electrical Characteristics graph for the LEDs shows that at a typical operating current of 350 mA, the LEDs require 8.45 volts DC. The Raspberry Pi 3 GPIO pins are only capable of outputting 3.3 volts DC, so a 6 amp 12 volt DC power supply was selected to power the LEDs. The RS-75-12 Mean Well power supply manufactured by Jameco Electronics was selected because of its 6 amps capacity and 12 volt output, more than enough to handle a significant quantity of LEDs. This power supply will be plugged into a standard 120 volt AC receptacle. 10 LEDs were used in the construction of the device, creating a load of 3.5 amps because each LED draws 350 mA. The LEDs were wired in parallel, and a GPIO pin on the Raspberry Pi 3 was used to control an N-channel power MOSFET, allowing current from the power supply to reach the LEDs when the GPIO pin was set to a high voltage (3.3 V). This was done by placing the MOSFET on the negative side of the LEDs, and attaching the gate of the transistor to the Raspberry Pi GPIO pin. When the pin is at a voltage of 0, the MOSFET does not allow current to flow through it, and therefore cuts off the LEDs. When the GPIO pin is set to a high voltage of 3.3 V the MOSFET allows current to flow again, turning on the LEDs. All LEDs are therefore controlled simultaneously by one GPIO pin on the Raspberry Pi 3, which is acting as an electronic switch. The circuit diagram for this is available in Figure D.3 of the Appendix. The wiring to individual LEDs was wired with 22 gauge wire, which is rated for up to 7 amps for chassis wiring. These sections only carry 0.350 amps, making the wiring sufficient for the load. 16 gauge wiring was selected for the connections to the power supply, buck converter, and MOSFET, because these portions of the circuit carry the full 3.50 amps. 16 gauge wire is rated for up to 3.7 amps for power transmission, making it sufficient for the load.

The 5 V mini cooling fans are manufactured by Adafruit, and are designed to be connected directly to the 5 V power pins on the Raspberry Pi 3. Therefore, the fans run on independent circuits, allowing them to run longer than the LEDs do. This allows for cooling of the sanitation chamber, LEDs, and MOSFET during and after sanitation cycles. The PiTFT Plus 480x320 3.5” TFT+Touchscreen is also manufactured by Adafruit specifically for the Raspberry Pi 3. This connects directly to the board via a ribbon cable. The screen physically mounts directly to the back of the board as well. Lastly, the Raspberry Pi 3 is powered by a power adapter plugged into a standard 120 volt AC receptacle.

Software

The object-oriented language Python was used to program and implement the graphical user interface (GUI). This language was selected because it provides a large standard library which includes string operation and operating user interface, and it is open source. Also, Python has a list of built in user friendly data structures, which can be used to construct fast runtime data structures. This provides the option of dynamic high-level data typing which reduces the length of support code that is needed.

The items to be added to the GUI (known as widgets), were programmed into the touchscreen using the code provided in Appendix B. The widgets implemented into the touchscreen are the text widgets (which displays the produce name), PushButton widget (used to create a button and call on a function when the button is pushed), slider widget (which lets the user pick between a range of produce) and the picture widget (which displays the picture of the produce on the push button in GIF format).

The LED exposure time and light intensity were programmed into the design for each different type of produce. Timers and interrupts were also implemented in the code to control the time and duration the fan would be in use during operation of the system.

Operation Validation, Summary and Conclusions

Operational Validation

The thermal management system of the entire device was tested using a digital thermometer in the sanitation chamber over a 10 minute cycle. This was performed with heat sinks as the only management system because they proved to be sufficient on their own. The results of this test are seen in Figure C.3.7 of the appendix. This system proved to be more than adequate, as the chamber only increased by 4.9°F over 10 minutes, which was proven to be sufficient time for sanitation. This increase in temperature would not be enough to foul any produce, and therefore meets the needs of the project. The team recognizes that airflow is critical in microgravity because of the lack of convection. Therefore, in future testing and iterations of the device fans would certainly be implemented on the sanitation chamber and outside the device.

The operation of our device, in respect to the aerobic plate count functional requirement, was validated by two methods, as described in the performance validation section. Analysis by the microscope, as shown in Figures C.3.1-C.3.4 of the Appendix demonstrate the effects of UV-C exposure on the activity of E. coli. Taking images with an exposure time of 6.5 seconds allowed to see movement of bacteria, and revealed the effects of UV-C exposure on bacteria activity. A clear correlation was observed between increased exposure to UV-C and decreased activity of E. coli. While this was a useful visual representation of the success of our experiment, it cannot be legitimately quantified. Simply observing inactivity of a bacteria does not ensure it is dead, nor does observing movement from bacteria guarantee it will be able to form colonies. Being as the project goals are in terms of reduction of CFUs, the microscope images are insufficient to draw hard conclusions about the operation of the device.

Plating the E.coli bacteria on agar proved a more effective method of obtaining quantitative results. By diluting the solution into numerous concentrations, plating it, and allowing it to grow for 24 hours in an incubator; the team was able to obtain accurate counts of the number of CFUs

remaining per gram or mL. The results, shown in Figure C.3.6 of the appendix, reveal that after 5 minutes more than 99.86% of E. coli was eliminated. These results reveal that significant reduction was achieved. The goals of reducing general aerobic plate count to less than 20,000 CFU/g was greatly exceeded (2×10^4 CFU/g) after 5 minutes, and an even greater reduction of 100% elimination was achieved after 10 minutes. Neither the team nor NASA deem it to be an issue that the time required to achieve these results was longer than the initial estimate of 2 minutes. The main priorities are to have a system which takes little time from the crew, and is able to produce sanitary produce. The device requires no attention from the user while in operation, and therefore NASA communicated that requiring several minutes to achieve quality results is acceptable.

The main issue with the testing is that it was performed only on petri dishes, which are flat, transparent surfaces. Tests were performed, which confirmed that no UV-C light passed through the plate itself, so the results are accurate in that the sample was exposed to light from only the upper half of the device. Furthermore, another issue is that testing was only performed on a smooth surface, and was not done on each type of produce to be sanitized. This was due to time and material constraints; it requires many plates of agar, and significant time to perform a round of testing for one surface. Therefore, the team was able to only receive one set of significant data for analysis. The next several weeks may provide opportunity for testing on more types of surfaces to verify that successful sanitation can be achieved on all produce required by NASA. However, the results received from the initial testing are very promising, and were able to easily surpass the NASA standards for aerobic plate count. The team expects that time may vary to achieve acceptable results depending on the surface, and that the device can be programmed to operate at varying lengths of time depending on the produce inserted.

Summary & Conclusions

The system's operation was able to meet some of the standards required. It is simple to operate, takes very little time from the crew, and can eliminate nearly all E. coli bacteria present. However, the Salmonella bacteria and Aspergillus Flavus mold reduction was not tested or validated due to time constraints. The thermal management system was also able to ensure that the chamber temperature did not heat up significantly, and therefore prevents fouling of the produce. These were all key requirements set by NASA, and most have been validated through testing. However, before the device could be implemented on the ISS, it would be vital to test it with more types of surfaces, and to implement more methods of airflow about the device. The heat sinks proved to be more than enough in a gravity environment. However, with a lack of natural convection in microgravity it would be important to agitate the air about the device to dissipate the heat. This could be done both by implementing fans pushing air out of the sanitation chamber, and by blowing air over the entire device to create airflow over the heat sinks. With these final concerns addressed, the device very well may be a viable candidate as a system to sanitize produce grown in microgravity. It is well suited for this purpose, and this purpose alone. While the device has been proven to function properly in a gravity environment, it is too expensive and more complicated than necessary to market for both commercial or consumer use. Sanitation can be achieved more simply and cheaper with running water, sanitizers, and soap. However, in a microgravity environment, this specialized solution provides an easy to use and zero waste solution for NASA's needs. The team hopes that NASA will be satisfied with the results and use this research to continue work on this subject.

Appendices

Appendix A

A.1

The eXploration Systems and Habitation (X-Hab) 2018 Academic Innovation Challenge is a university level challenge with the intent of developing partnerships with universities. NASA's main goal for this challenge is to develop innovative design solutions for deep space exploration systems. This competition connects senior level design curricula, as well as graduate level curricula, highlighting hands-on design, research, development and manufacturing of functional subsystems for use in NASA space habitats and for deep-space missions.

The X-Hab Academic Innovation Challenge allows the student teams to experience the critical thinking and development, which goes into creating a product or new technology, with the aid of NASA researchers. Throughout the competition, the student teams undergo several NASA assessments. These assessments are as follows; the System Definition Review (SDR), the Preliminary Design Review (PDR), and the Critical Design Review (CDR).

The SDR assesses the projected system design and flow down of the requirements for the functional elements of the system. The main objectives of the SDR is to confirm a review of the team as well as reviewing the processes and products meet the criteria for a successful project.

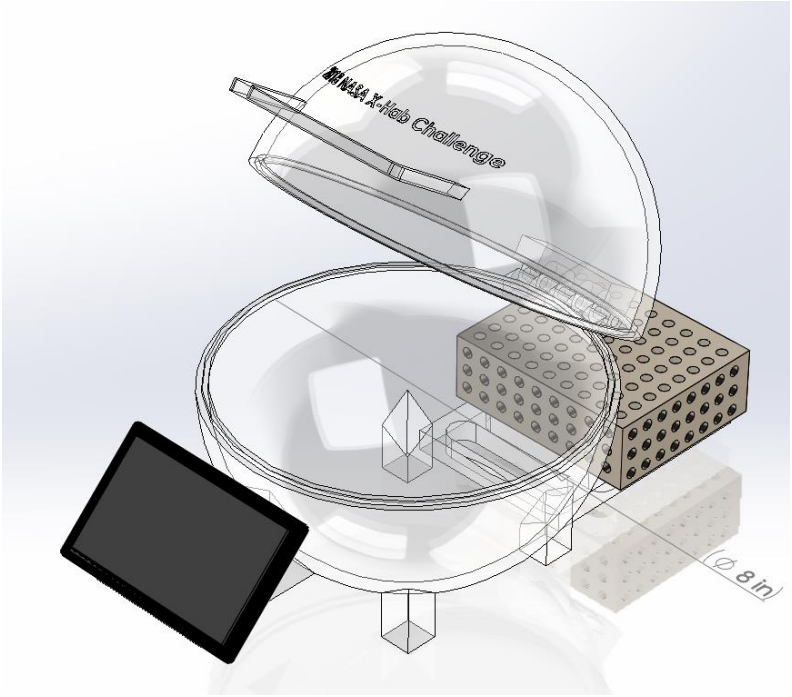
The PDR determines a preliminary design solution that meets the project objectives. During this stage, scheduling and cost estimates for the project were to be detailed. During the PDR, changes to the design from the first assessment (SDR) were also to be documented.

During the CDR, the design was to be finalized, reflecting all changes from the first two reviews, without repeating earlier content. At the completion of the CDR the design work should also have been concluded and the main focus was to be placed on testing, building and assembling the final system.

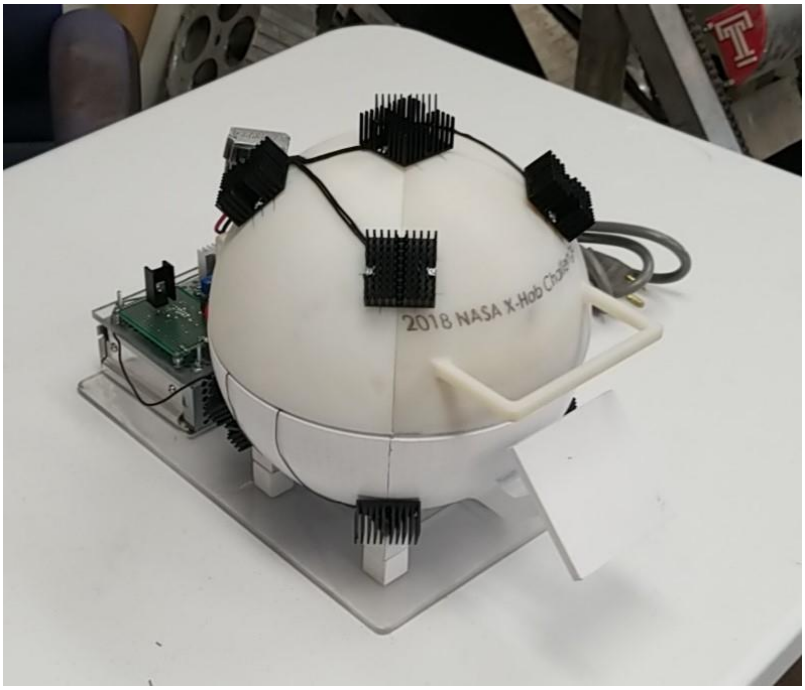
Finally, all proposals were to be accepted from faculty who are U.S. citizens and currently teach an Accreditation Board for Engineering and Technology (ABET), accredited engineering senior or graduate design at a university affiliated with the National Space Grant College and Fellowship Program, or other US accredited university. According to the Criteria for Accredited Engineering

Programs, Temple University falls under this umbrella, as the structure of the curriculum provides both depth and breadth across the range of engineering topics implied by the titles of each program (ABET, 2017). The competition also encourages collaborations with different departments and disciplines within engineering.

A.2



A.2.1 CAD model of conceptual design of device



A.2.2 Closed device without touchscreen

A.2.3 Open device without touchscreen

Appendix B

B.1 Design Requirements

Table 1
Average logarithmic reduction levels of *Escherichia coli* O157:H7 on selected organic fruit surfaces (N = 3).

Time (s)	Average UV-C dose (kJ/m^2)	*Escherichia coli* O157:H7 (log N/N_o)	
		Apple	Pear
0	0	0^{A}	0^{A}
10	0.15	-2.1 ± 0.4^{MN}	-1.2 ± 0.2^{GHIJ}
20	0.31	-2.2 ± 0.4^{MN}	-1.3 ± 0.2^{HIJ}
30	0.49	-2.4 ± 0.4^{NO}	-1.5 ± 0.2^{IJK}
40	0.63	-2.5 ± 0.3^{OP}	-1.5 ± 0.2^{JK}
50	0.78	-2.7 ± 0.3^{PQ}	-1.9 ± 0.2^{LM}
60	0.92	-2.9 ± 0.2^{Q}	-2.1 ± 0.1^{MN}
120	1.89		
240	3.66		
360	5.21		
480	7.17		
600	8.56		
720	10.5		

Table B.1.1 UV Dose Table (Adhikari, 2015)

Table 1, from Adhikari et al, illustrates the different UV doses and irradiation times used during their research, along with the E. Coli reduction on Apple and Pear. A UV dose of 0.15 kJ/m^2 was selected from this table (highlighted). It resulted in a 2.1 and 1.2 log reduction on Apple and Pear during their research.

Escherichia coli O157:H7 on selected organic fruit surfaces (Adhikari et. Al.)						
time (s)	time (min)	UV-C dose (kj/m^2)	UV-C Intensity (W/m^2)	radiant flux (Power at source)	# of LEDs Required	Total Power Dissipation at 350 mA at Ts 35 C
Source			UV Dose/time	UV Density * Surface Area	Total UV Power/Power per LED	Heat Dissipation per LED * # LEDs
120	2.0	0.15	1.25	0.162	8	28.4
20	0.3	0.31	15.5	2.011	101	351.9
30	0.5	0.49	16.33	2.119	106	370.8
40	0.7	0.63	15.75	2.043	102	357.5
50	0.8	0.78	15.6	2.024	101	354.1
60	1	0.92	15.33	1.989	99	348.1
120	2	1.89	15.75	2.043	102	357.5
240	4	3.66	15.25	1.978	99	346.2
360	6	5.21	14.47	1.877	94	328.5
480	8	7.17	14.94	1.938	97	339.1
600	10	8.56	14.27	1.851	93	323.9
720	12	10.5	14.58	1.892	95	331.0
max radius (in to m)	surface area (m^2)	output power per LED (W)	voltage (V)	current (mA)	input power per LED (W)	
0.1016	0.1297	0.02	10	350	3.5	
*4 in						

Table B.1.2 UV Dose Calculations Table (Adhikari, 2015)

This Table illustrates Adhikari's use of UV dose. However, the irradiation time was changed from 10 to 120 seconds to minimize the required UV intensity. Furthermore, these values were used, along with the maximum

distance from the LEDs (4 in) to calculate the required UV output power, the required number of LEDs and the power dissipation at a surface temperature of 35 C.

B.2 Design Constraints

Number of Components	Unit Current	Total Current	Operating Voltage	Power Consumption
10 LEDs	350 mA	3.50 A	8.45 V	29.58 W
2 fans	200 mA	0.40 A	5.00 V	2.00 W
	Total Current:	**3.90 A**	**Total Power:**	**31.58 W**

B.2.1 Device Power Calculations

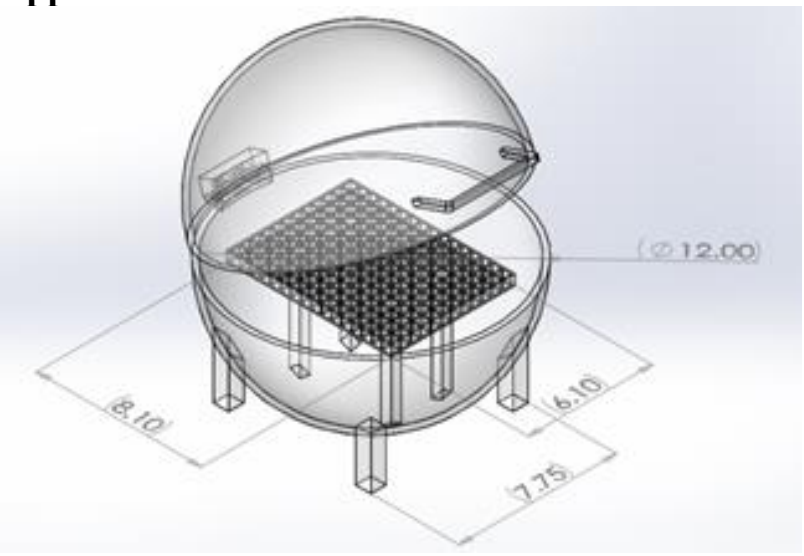
This table shows the power calculations for the fans and the LEDs. These are the primary source of power consumption, and therefore show the estimated power in watts at peak usage.

```
>> V = 8.45;
>> A = 0.35;
>> P = V*A

P =

    2.9575
```

B.2.2 Power of One LED

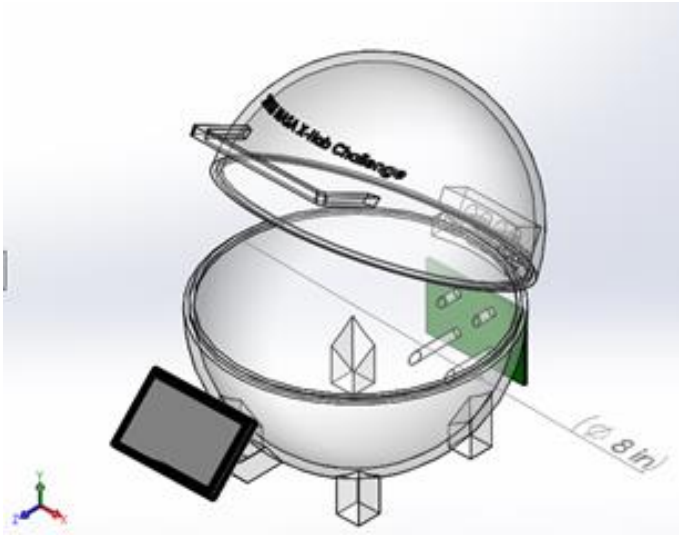
The above Matlab code shows the calculation of the power through one LED. This was used to determine what size heat sink to select. With each LED operating at approximately 2.96 watts, a heat sink rated for 7 watts was selected. This value was intentionally much higher than needed because the effectiveness of heat sinks is minimized in microgravity due to the lack of convection.

Appendix C



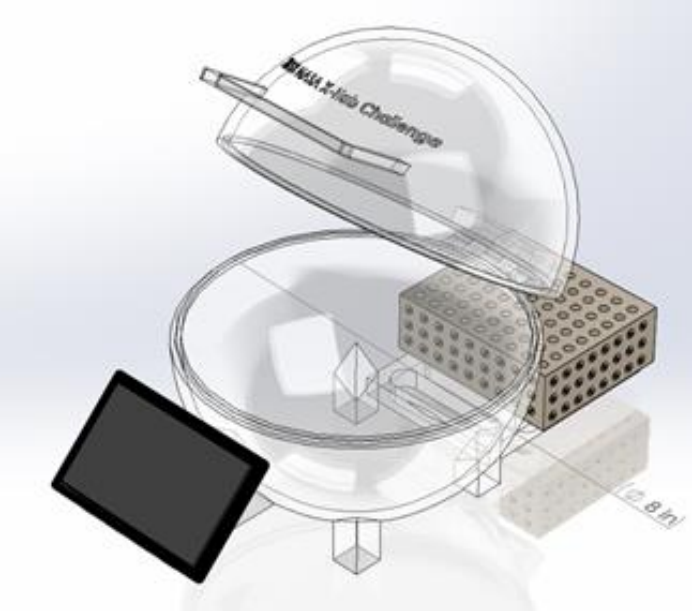
C.1.1 First Iteration Design

The initial design consisted of a 12-inch sphere in a clam shell configuration with a handle on the top portion for opening. A platform was designed for the produce to lay upon during exposure made from clear plastic to allow light to pass through. At this stage of the design process it was not known which microprocessor was to be used nor which electrical components, so the drawing is very bare.



C.1.2 Second Iteration Design

There were three main changes between the first and second iteration: the overall size, the platform, and the components. It was decided that a 12-inch diameter device was overkill for this application due to the small size of the produce in question, so it was lowered to 8-inches. In microgravity, the produce would not remain stationary on a flat platform, so it was scraped to be replaced with mesh net to encapsulate the sample in antimicrobial material. Electrical components were placed on the device with the touchscreen in the front and the Raspberry Pi in the back.



C.1.3 Third Iteration Design

The final design iteration remained relatively the same as the second with only minor changes. It was determined that an external power supply would be necessary for the device which needed to be added which can be seen in the back. The processor then needed to be moved which is now mounted directly underneath the touchscreen in the front of the device. The diameter remained 8 inches and the layout of the feet, handle, and device thickness remain unchanged.

Solarmeter Specifications	
Radiometer	
Model	8.0
Irradiation Range	0-1999 µW/cm² UVC
Response	246-262 nm UVC
Resolution	1 µW/cm²
Conversion Rate	3.0 Readings / Sec
Display	3.5 Digit LCD
Digit Size	0.4" / 10.2 mm
Operational Temperature	+32°-100°F / 0°-37.8°C
Operational Humidity	5% to 90% RH
Accuracy	±10% Ref. Nist
Dimensions	4.2L x 2.4W x 0.9D in / 106.7L x 61W x 22.9D mm
Weight	4.5 oz / 128 g Including Battery
Power Source	9-Volt DC Battery
Lens	UV Glass
Diffuser	None
Detector	SIC Photodiode w/IF
Agency Approval	CE Mark

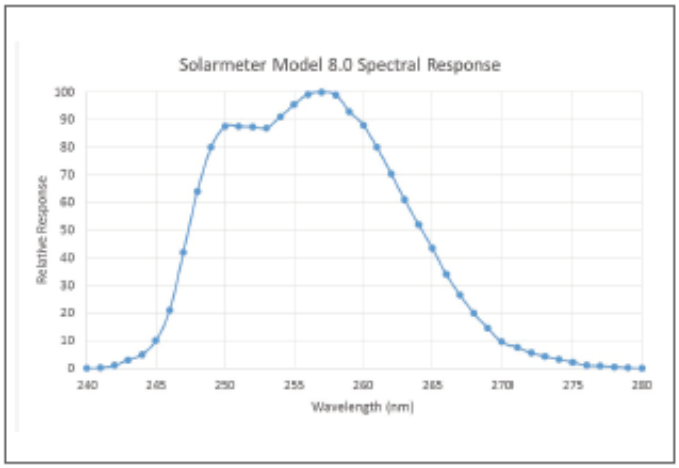
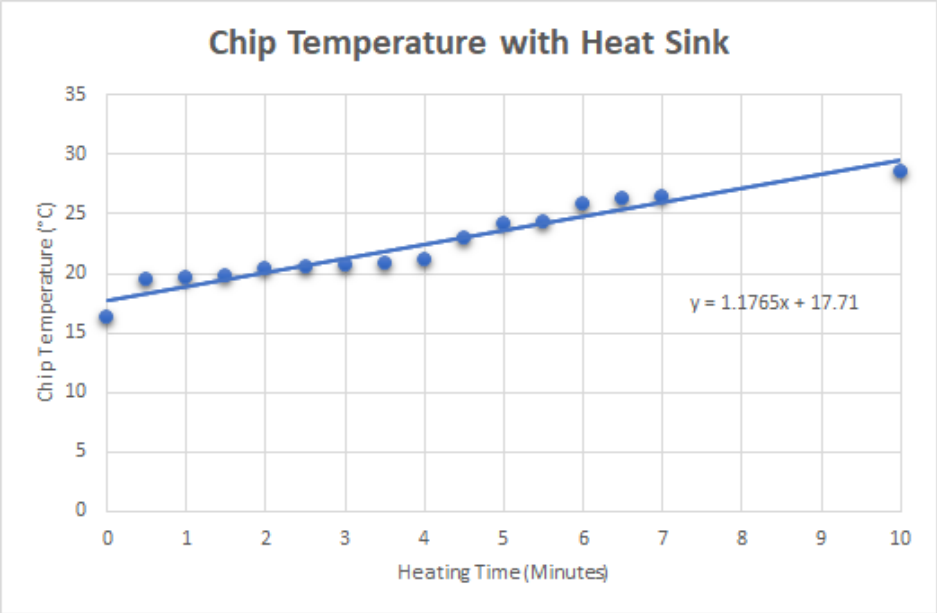


Fig. 1. Model 8.0 Spectral Response

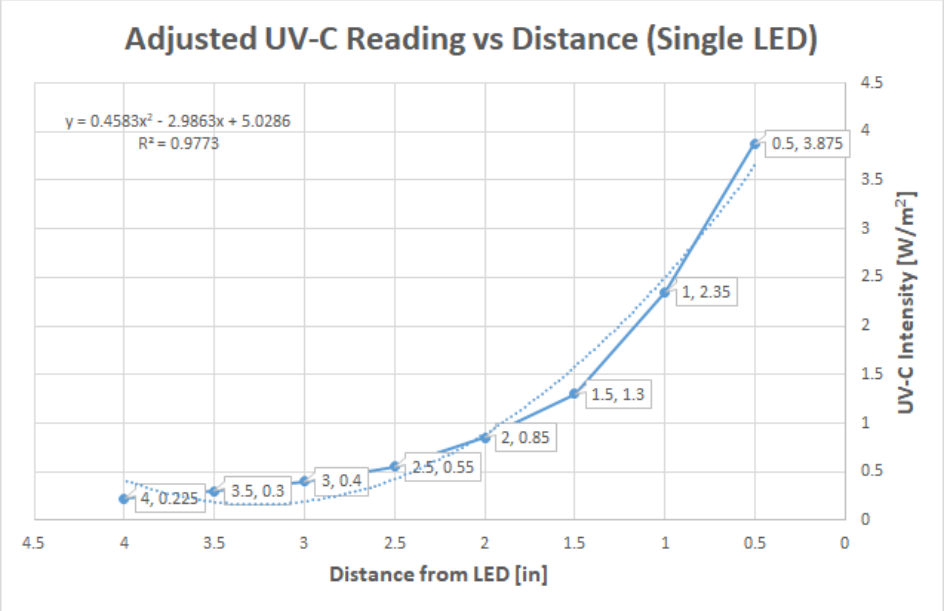
Table C.2.1 UV meter specifications

This is the manufacturer provided data sheet for the UV meter used to take readings from our hardware. Notice from the graph at the bottom that the meter only reads at 40 percent of the actual UV magnitude at a wavelength of 265 nm, which is what our selected LEDs output. This scaling was taken into account when reading our UV intensity.



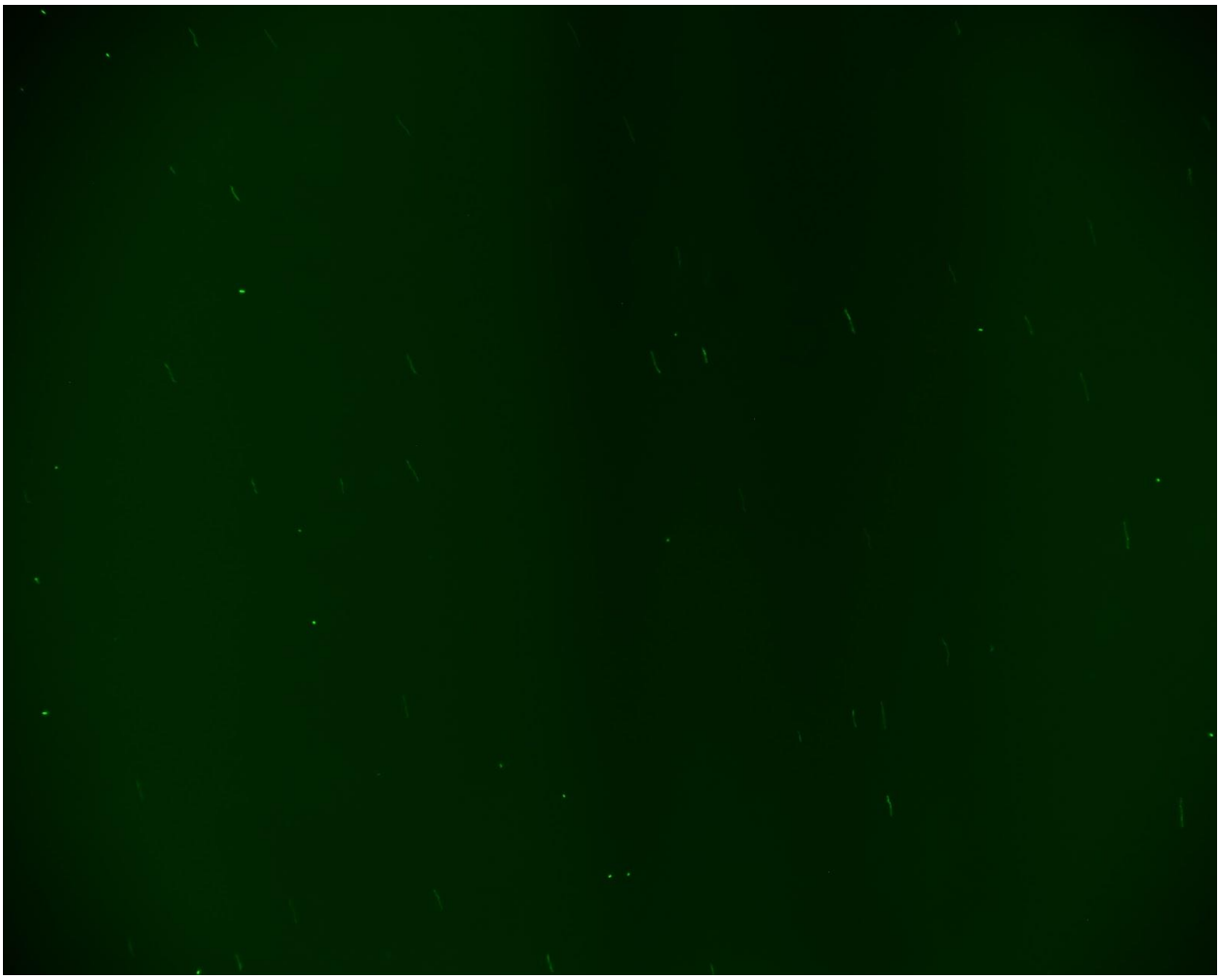
C.2.1 Chip Temperature with Heat Sink

A single UV LED with a heat sink was operated for a time of 10 minutes, while measuring the temperature of the heat sink. This was done without any forced convection. The results illustrate that the heat sink was able to dissipate heat effectively while maintaining a safe operating temperature. After 10 minutes, the sink temperature was less than 30 C.



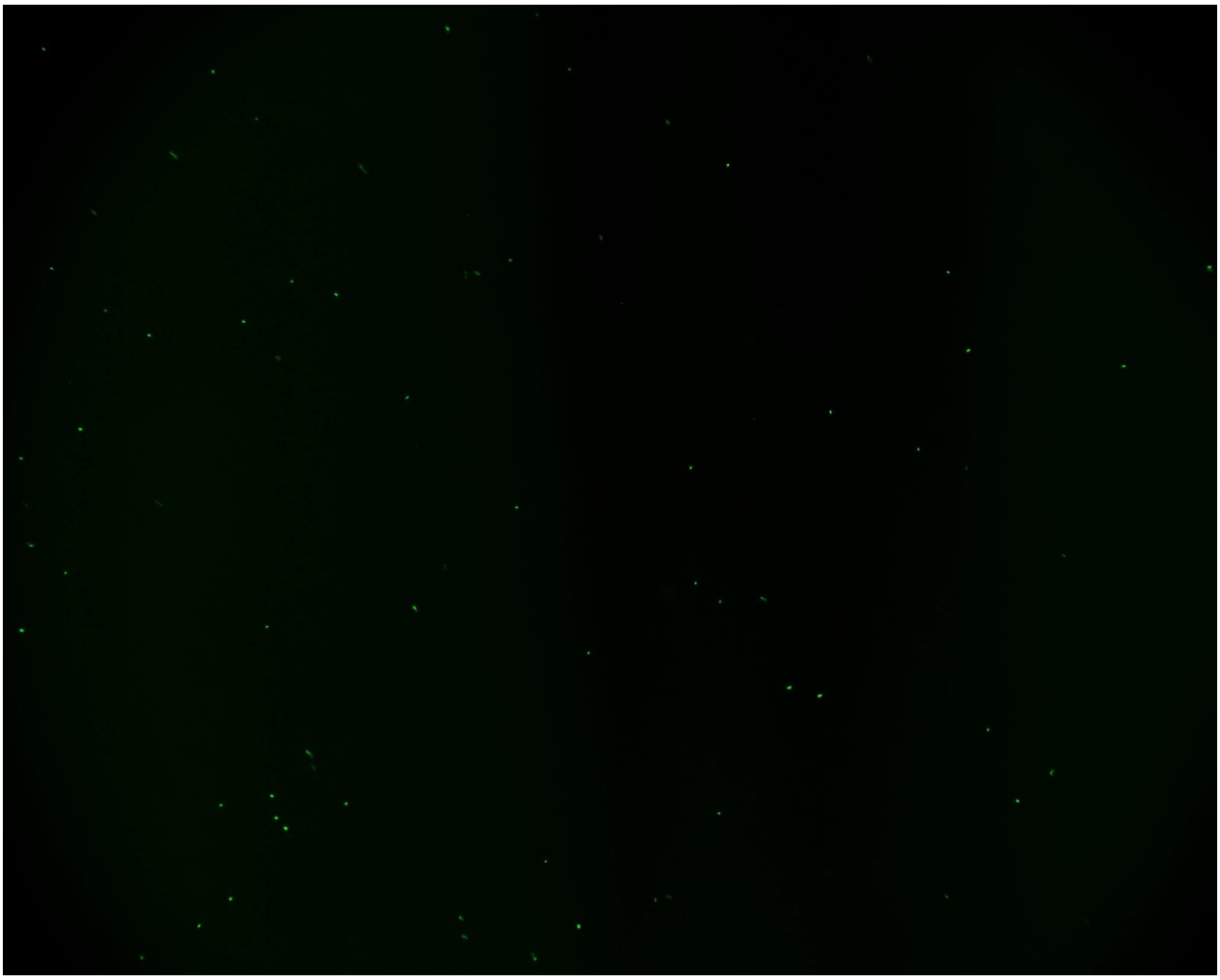
C.2.2 Ultraviolet-C Intensity as a function of Distance

The UV intensity was measured using a Solarmeter Model 8 at varying distances from a single UV LED source. The range of distances was from 0.5 in to 4 in. This was done in 0.5 in increments. The R value of the 2nd order polynomial trend line verifies the inverse square law relationship between UV intensity and distance. An important intensity is the value at 4 inches (max distance from LED). This value was added for 10 LEDs due to symmetry to obtain the total UV intensity. With this value and the target irradiation time, the UV dose was calculated, which was 1.8 times the required value (0.15 kJ/m^2) used from previous literature. *(Note that the readings were adjusted to compensate for the 0.40 spectral response of the UV meter at 265 nm wavelength).



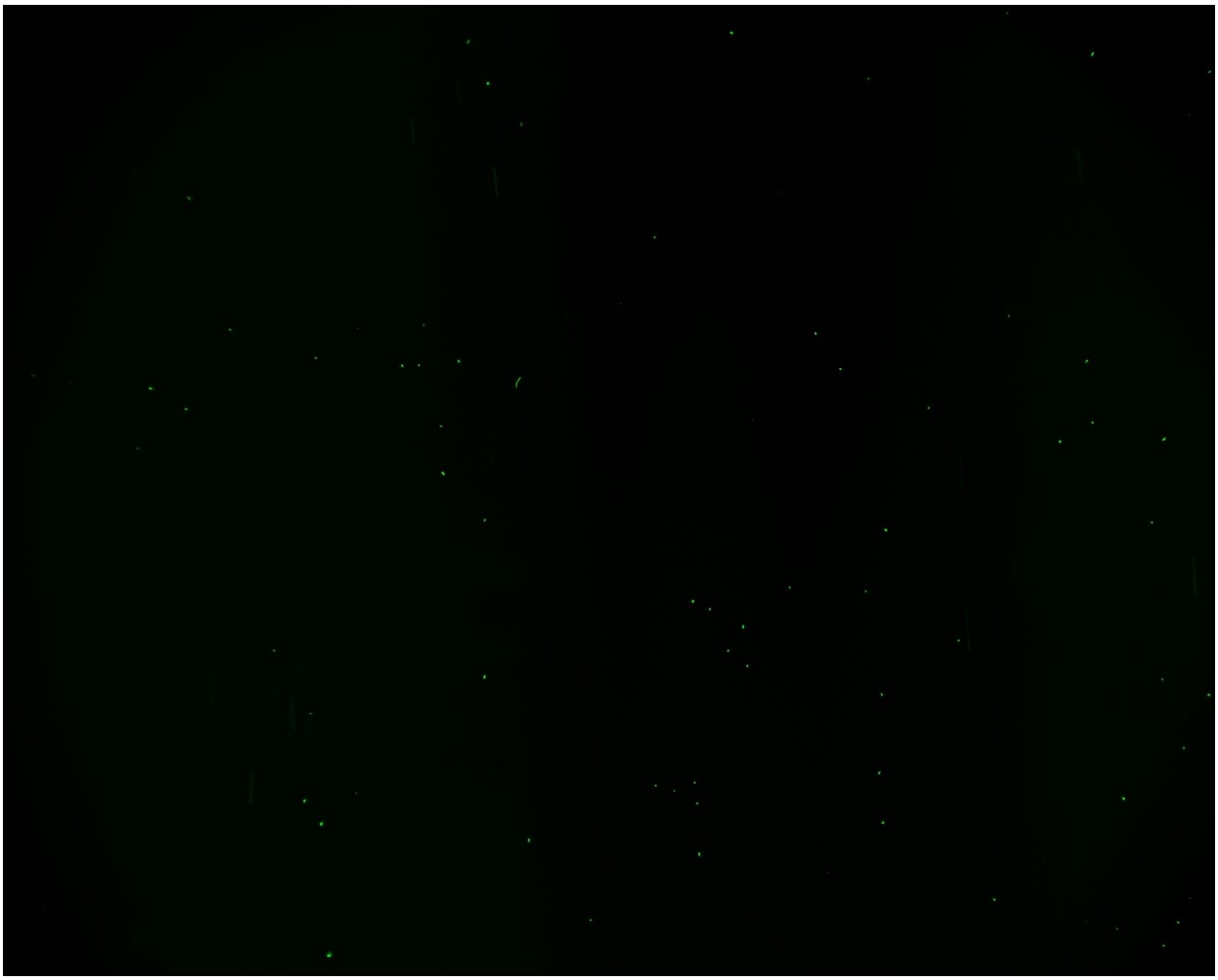
C.3.1 Microscope image of control sample

This is an image of the control sample taken over a duration of 6.5, with a concentration of E. Coli at 10^6/mL. The green specks are bacteria, and the dashes show the movement of active bacteria. The image shows that most bacteria present are very active.



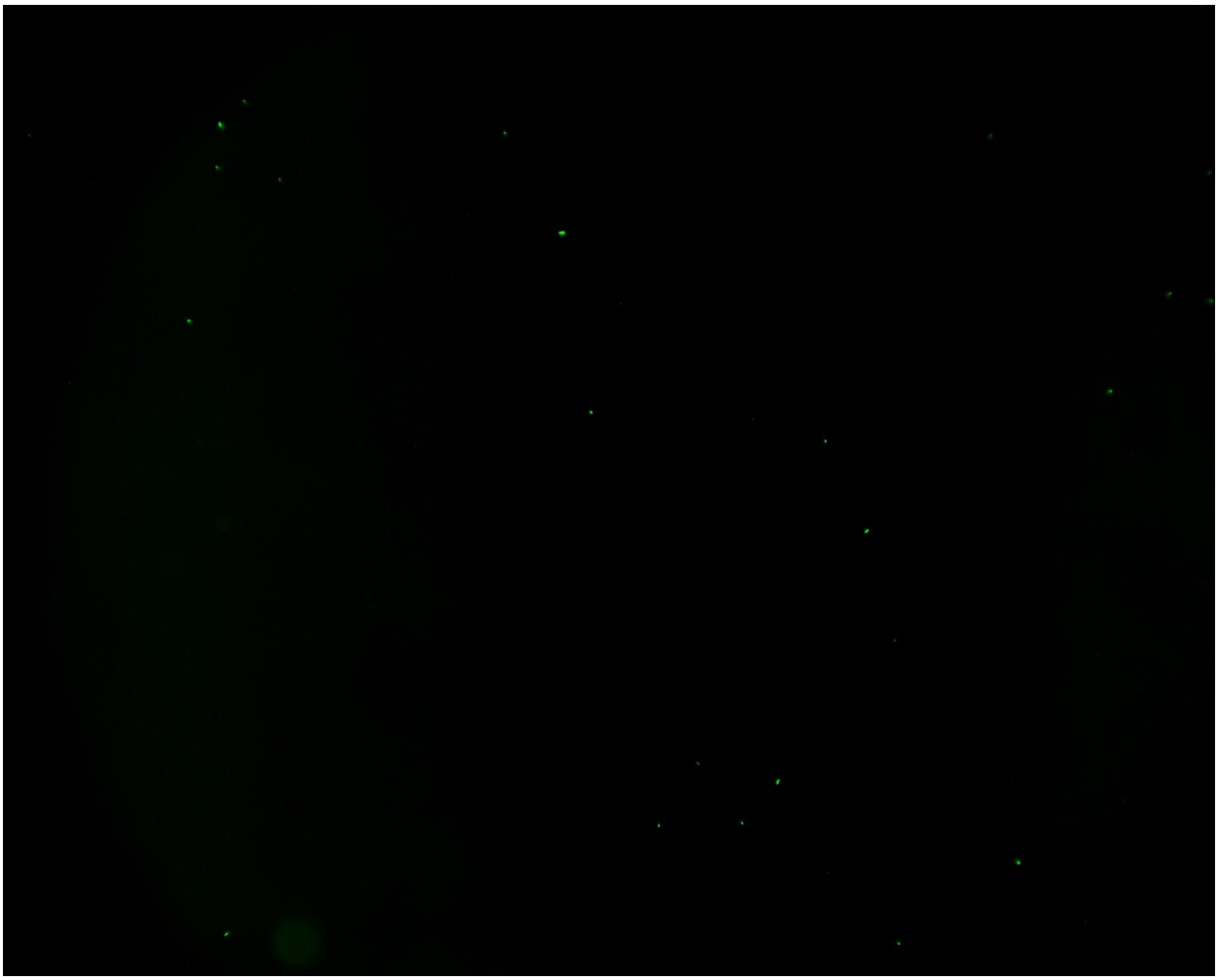
C.3.2 Microscope image of sample after 3 minutes of UV-C exposure

This image shows the same sample as figure C.3.1, but after 3 minutes of UV-C exposure in the prototype. Several bacteria are still fairly active in this image. However, less are active, and their movements are slower than in the control, indicated by shorter dashes. This demonstrates that the exposure to UV-C light impacted many bacteria after only 3 minutes.



C.3.3 Microscope image of sample after 6 minutes of UV-C exposure

This image shows the same sample as figure C.3.1, but after 6 minutes of UV-C exposure in the prototype. Again, several bacteria are still seen to be active in this image. However, the vast majority are inactive. This demonstrates improvement from the 3 minute exposure sample.



C.3.4 Microscope image of sample after 9 minutes of UV-C exposure

This image shows the same sample as figure C.3.1, but after 9 minutes of UV-C exposure in the prototype. Little to no activity can be observed in this image. Each speck has very little blurring, indicating that they moved very little. This reveals that 9 minutes of exposure inflicted significant damage to nearly all bacteria.

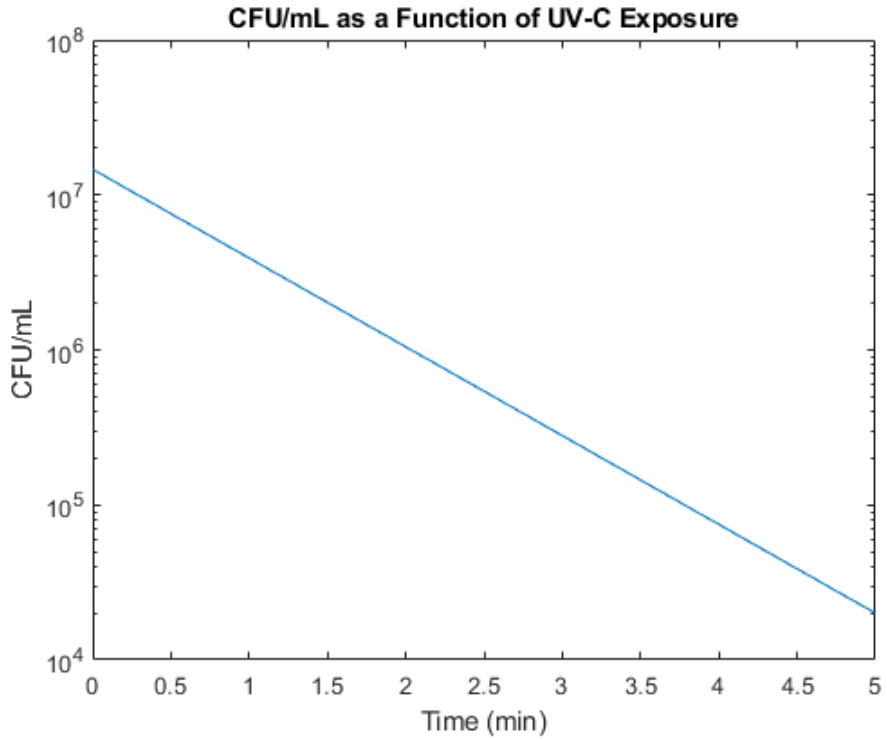
Dilution factor	Number of bacterial colonies (CFUs)			CFUs/mL		
	Control	5 mins	10 min	Control	5 mins	10 min
1:10^{-3}	1464	2	0	$1.464*10^{7}$	$2*10^{4}$	0
1:10^{-4}	988	0	0	$9.88*10^{7}$	0	0
1:10^{-5}	195	0	0	$1.95*10^{8}$	0	0
1:10^{-6}	62	0	0	$6.2*10^{8}$	0	0
1:10^{-7}	20	0	0	$2.0*10^{9}$	0	0
1:10^{-8}	0	0	0	0	0	0

Equation used:

$$\frac{\text{Number of CFU (counting)}}{\text{Volume plated (0.1mL) x total dilution factor}} \rightarrow \frac{\text{Number of CFU}}{\text{mL}}$$

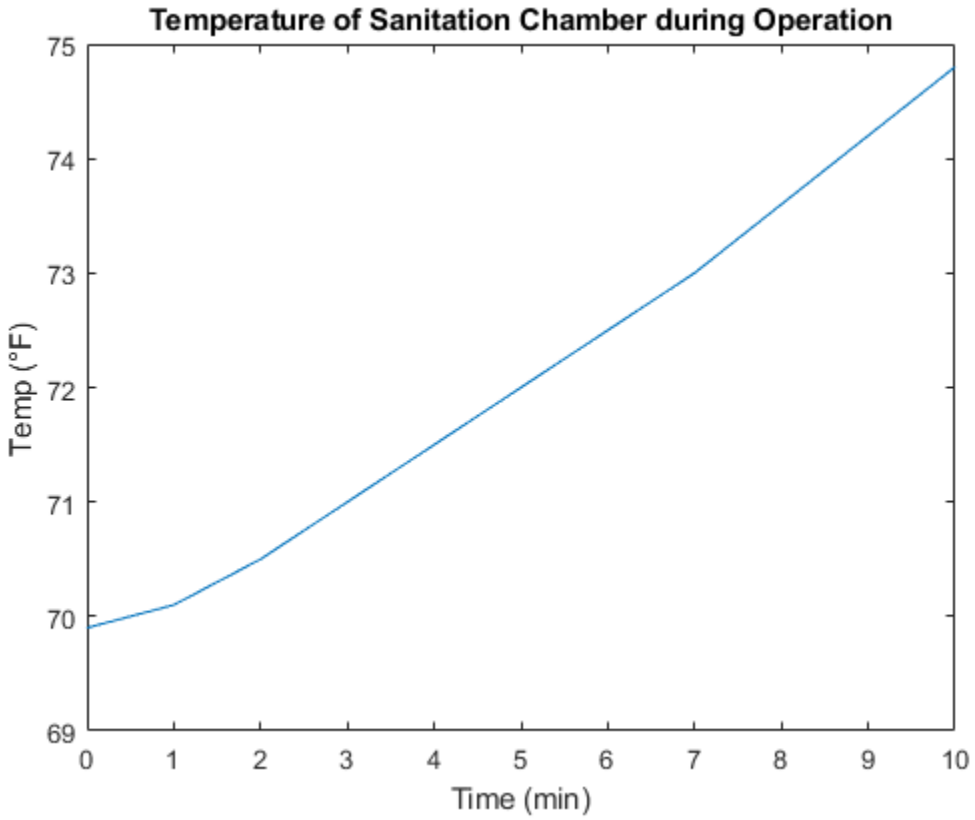
C.3.5 Test results and calculation of CFUs/mL

The left side of this table shows the number of bacteria colonies counted in petri dishes at various dilutions. This was done for a control sample, a sample run through the prototype for 5 minutes, and a sample run through the prototype for 10 minutes. The right side of the table shows the calculated number of CFUs per mL of water, calculated according to the equation shown below the table.



C.3.6 Plot of results showing concentration of bacteria versus UV-C exposure time

This plot shows the data from Table C.3.5 in graphical form. The reduction in CFU/mL is drastic from the control to the 5 minute sample.

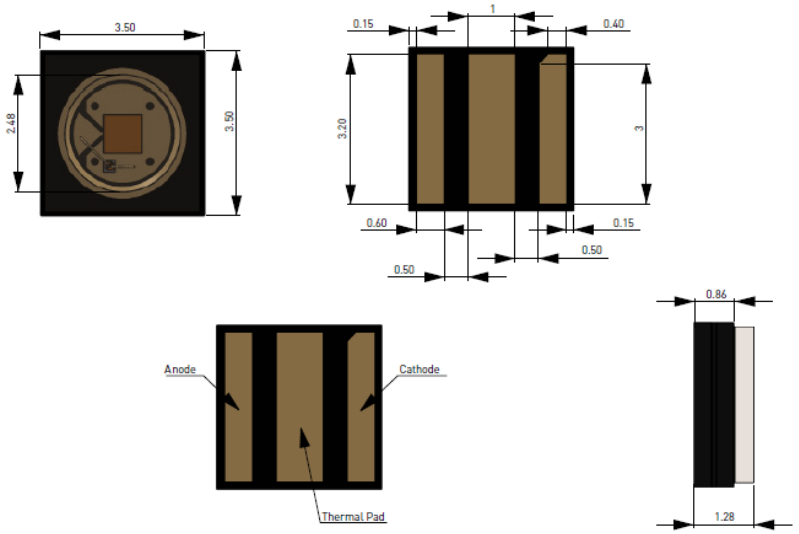


C.3.7 Temperature of internal sanitation chamber versus time in operation

This plot shows the temperature of the internal sanitation chamber over 10 minutes of operation. The results show that the temperature increased by less than 5°F over 10 minutes. This was done with no airflow, and therefore the heat sinks were the sole thermal management. They proved to be more than sufficient, as this increase in temperature is not significant enough to fowl any produce.

Appendix D

Electrical Hardware

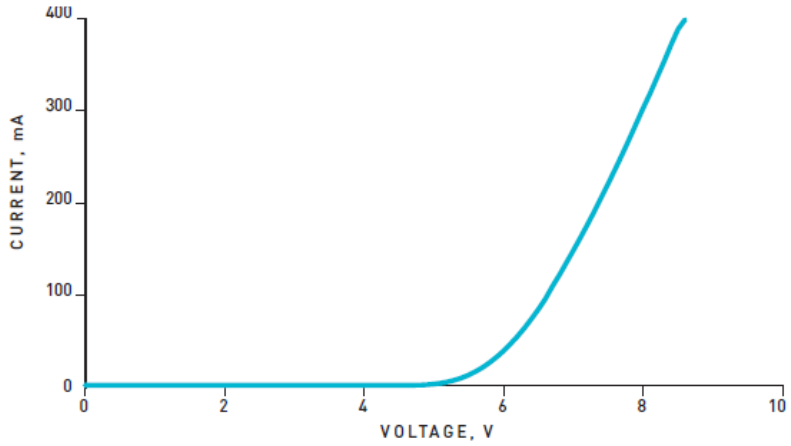


All dimensions are in millimeters. Unless noted otherwise, all dimensions have a tolerance of ± 0.05 mm.

D.1: Mechanical Dimensions of Klaran LEDs (Crystal IS, 2018)

This diagram shows the dimensions of the actual LEDs, all labeled in millimeters. Due to the small dimensions of the diodes, the manufacturer solders them to PCBs which are larger, and allow users to hand solder wires to them.

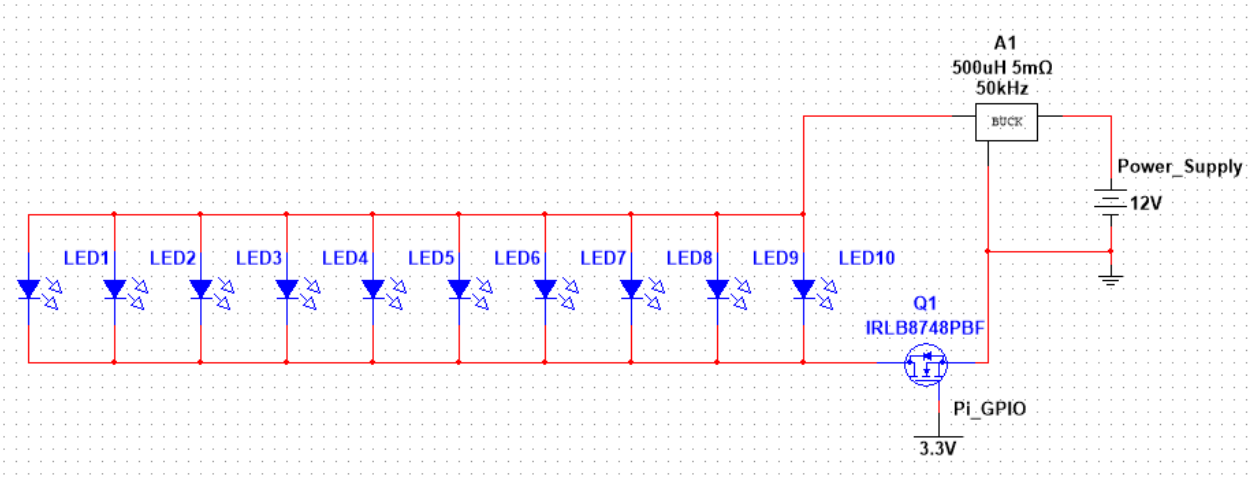
ELECTRICAL CHARACTERISTICS



Test Conditions: Solder temperature (T_s) = 35 °C
Pulse mode operation from 1 mA to 350 mA

D.2: Electrical Characteristics of Klaran LEDs (Crystal IS, 2018)

This graph demonstrates the forward current through an individual LED as a function of the voltage across it. We chose to operate the device at the recommended state of 8.45 volts and 350 mA.



D.3: Circuit Diagram for LED control circuit

This circuit diagram demonstrates the power supply and control for the UV-C LEDs. A 12 VDC power supply is connected to a buck converter, which steps down the voltage to 8.45 volts. An N-Channel power MOSFET is used as a switch, with the gate attached to a Raspberry Pi 3 GPIO pin. When the pin is high (3.3 V), the MOSFET is on and current can flow, turning on the LEDs. When the pin is low (0 V), the MOSFET is off, and thus current cannot flow through the LEDs.

Appendix E

User Guide

The first step to using the device is to plug in both the power supply and the Raspberry Pi 3 power supply into standard 120 volt AC receptacles. This should cause the touchscreen on the device to light up. At this point, the device can be opened, and the produce to be sanitized should be placed inside. The produce must be placed inside the anti-microbial netting. This ensures it will be supported in the center of the device, resulting in even disinfection on all surfaces, and contact with the netting will ensure disinfection on all adjacent surfaces. The user should take special care when placing leafy greens in the netting. It is important that the leaf not be placed in the netting with minimal crumpling or bending to maximize surface area exposed to the light. *It is highly recommended to flip the leaf halfway through the sanitation cycle to ensure even disinfection.* Once the produce is properly inserted in the netting, the device must be closed completely so that the contact sensors are touching. At this point the user may select the appropriate produce on the screen. This will initiate a sanitation cycle. If the user wishes to end the sanitation cycle prematurely they can either select the *cancel* option on the screen, or open the device. If either of these happen the LEDs will instantly turn off, and *the produce will not be sanitized completely*. When the cycle is complete, the screen will alert the user that it is safe to open the device and extract the produce. At this point the user may safely remove the produce from the device and consume it.

Troubleshooting

The touchscreen does not turn on.

1. Check that both power cords are plugged into active standard 120 volt AC receptacles.
2. Check that the ribbon cable between the Raspberry Pi 3 and the touchscreen is connected properly.
3. Check that the power light on the Raspberry Pi 3 board is on, indicating it is receiving power.
4. If all of these conditions are met and the screen still does not turn on there is likely a hardware issue, and either the board, screen, or power cord may need to be replaced.

The screen is on, but the device will not initiate a sanitation cycle.

1. Check that the device is closed the entire way, and the contact sensors are touching.

A sanitation cycle initiates, but the cooling fans did not turn on.

1. A probe must be used to ensure that the GPIO pins on the Raspberry Pi 3 used to control the fan maintain 5 volts when a sanitation cycle is running.
    a. *If there is 5 volts:*
        i. There is likely a hardware issue with the fan and it should be replaced.
    b. *If there is not 5 volts:*
        i. There is likely a hardware issue with the board and it should be replaced.

A sanitation cycle initiates, but a LED(s) does not turn on.

WARNING: To test this an engineer must use proper personal protective equipment (PPE) to ensure UV-C rays are not exposed to the eyes. The engineer must also remove one contact sensor and connect it to the other one while the device is open to allow the

device to run. ***This should only be done by an engineer using proper PPE to test that all LEDs are operational.***

1. Check that both power cords are plugged into active standard 120 volt AC receptacles.
2. Check that the corresponding GPIO pin on the Raspberry Pi 3 maintain 3.3 volts DC when a sanitation cycle is running.
    a. If it does not maintain this voltage there is likely a hardware issue with the board and it should be replaced.
3. Check that the output of the external power supply maintains 12 volts DC at all times.
    a. If it does not maintain this voltage there is likely a hardware issue with the power supply and it should be replaced.
4. Check that the anode of the LEDs maintain 8.45 volts DC when a sanitation cycle is running.
    a. If it does not maintain this voltage there is likely a hardware issue with the MOSFET and it should be replaced.
5. If all of the above conditions are met and the LED(s) still do not turn on there is likely a hardware issue with the LED(s) and they should be replaced.

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