Project Number

2004-04-01

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Nomenclature

ASHRAE: American Society of Heating, Refrigeration, and Air Conditioning Engineers

CFM: cubic feet per minute

HALS: hindered amine light stabilizers

RH: relative humidity

UVC: ultra-violet C-band

UVCG: ultra-violet C-band germicidal

Executive Summary

As a new start up company, the client has several ideas for the remittance and prevention of mold growth based on the interaction of humidity with the radiation of ultraviolet light, specifically in the C bandwidth (UVC), but lacks the ability to create a technically sound design that is supported through engineering concepts and research. The group will give a full evaluation of the existing system and propose design changes. This system must be able to be used in the vast majority of residential and commercial buildings in the target market, therefore the design must be flexible enough to be adapted to any situation. Understanding this, it is evident that not one specific design will result; rather the outcome will be a range of engineering specifications that will allow the system to be customized for the greatest impact on the remittance of mold. To this end the group will specify: the most effective arrangement of UVC lighting, the best humidity level to be used the effects of air infiltration and air movement on a house, the materials that should be used in conjunction with the system, and the effects that the system would have on household pests. We have researched UVC light intensity in correlation with humidity. So far we have found that humidity changes do not affect the intensity between 20% and 95% relative humidity (RH). Testing has been conducted to unearth the best arrangement of the UVC lighting for maximum intensity; the arrangement chosen is a staggered system of five foot length. Protective covers for the UVC lighting was determined to lead to an inferior design. Ozone, the byproduct of the UVC lighting, has been concluded not to be produced at harmful levels to humans within the system. High carbon

content plastics are least likely to be degraded by UVC and thus should be used as the vapor barrier. It has been found that reversing the normal convection of air creates a drying affect to the surrounding environment, and the effects of infiltration have been established. The system naturally deters house pests from the house by dehumidification and air movement.

Introduction

The client is an indoor air quality control company from Waterville, Ohio. The company is a start up and currently does not currently have products available on the market. The main products that the client supplies are systems designed to use dehumidification and Ultraviolet Germicidal Irradiation (UVGI) for the remediation and prevention of mold growth and contamination in residential and commercial buildings. The client currently has several prototype systems and ideas that it plans on using in its business model. Currently they are in the process of evaluating the multiple systems for the different environments in which they will be implemented to better understand their capabilities. The projects main goal is to evaluate the performance of these prototype systems and ideas to determine the overall effectiveness. The evaluation will consist of not only evaluating the ability of the system to control mold growth in an environment but also to evaluate the various components that make up the system. From studying and testing, the client will be presented with detailed data and suggestions for altering the various systems to attain the best overall results.

Mold growth within an area where people frequently travel can have a detrimental effect on persons' health. Certain strains of mold, and microorganisms, have been found to cause various illnesses in people. This is an issue because many homes and businesses have mold growth within the buildings and in the heating and ventilation systems. This infiltration of mold within the buildings causes the inhabitants to be exposed to the toxins and mold spores that can cause illnesses. The client's systems are designed to reduce the amount of mold within the dwelling through the use of dehumidification and UVGI. These two methods have been proven to have and adverse effect on the proliferation of mold within an environment. Through the installation and use of The client's systems it is hoped that the levels of mold within homes and other buildings can be reduced to a level that will not have and adverse effect on the health of the people who reside within those confines. Therefore, it is important that the systems being used are evaluated and optimized to perform at peak conditions to ensure the well being of everyone who will be within the buildings.

Project Objectives

The overall objective of the client's project is to provide the client with an evaluation of an existing system which uses UVCG lighting, air movement and humidity control in the remediation of mold. The evaluation of the system will consist of two primary parts. The first part will concern the UVCG lighting system and how efficiently it will eradicate the mold, if covers should over the UVCG bulbs, the types of byproducts produced from UVC light, and how UVC light effects plastics. The second part of the evaluation will be concerned with the movement of air and how it effects the uncontrolled (the basement or crawl space) and controlled environment (the living space) and identifying possible sources of infiltrations. There are also two secondary objectives the client has asked for. The first one being that an explanation is provided as to why reversing the normal convection of air creates drier conditions and the possible affects the system has on house hold pests.

Project Deliverables

By the end of the client's project the team plans to present the client with several recommendation and principles that can be used in the final design of the system.

- Relate the change in UVC light intensity to changing environments of relative humidity.
- Identifying the most effective and realistic level of relative humidity for the irradiation of microorganisms.
- UVC light arrangement that will create the highest intensity of the UVC light.
- Selection of appropriate lights to create desired intensities, within the system that corresponds to previous determined time and percentage kill values.
- A determination if the system needs UVC covers.
- Types of byproducts from the UVC light and the effects UVC light has on plastic.
- An explanation as to way reversing the normal convection of creates a drier environment.
- Volume before a drafty environment may occur.
- Identify sources of infiltration.
- The effects of the system on house hold pests.

Team Members

For the project, each member of the team will be associated with certain research and design areas. Every team member is responsible for researching in the general area of mold and its prevention and remediation. The findings will be shared amongst the team members to ensure everyone has a basic knowledge of the subject at hand. John Clark will be providing an explanation as to why reversing the normal convection of air creates drier conditions, investigating room volume before a drafty environment might occur and establish possible sources of infiltration. Andrew Dauster will be determining how UVC light affects plastics, and identify any byproducts of UVC light. Ryan Schnipke will be researching in the area of UVC effectiveness and its relation to humidity and distance as well as to the various microorganisms that are to be eradicated. Travis Tiell will be investigating the affects of the system on house hold pests, investigate possibility of using covers over the UVCG bulbs and establish possible sources of infiltration.

All team members have specifically defined roles within the team. John Clark has the role of the Group Leader. Mr. Clark has the responsibilities of organizing group meetings and the collective work of the team. He also contacts the client when necessary and handles the presentation and completion of all documentation and requirements for the group. Andrew Dauster holds the position of Technical Liaison and will be the person for contacting and presenting any work that may need to be done by the University of Toledo machine shop.

Design and Analysis

Impact of Relative Humidity on UVC Effectiveness

The evaluation and design will consist not only of the evaluation of the ability of the system as a whole, but the design of the components. The effectiveness of UVC light at varying levels of humidity is an area of interest for the appropriate design of the client's system. The first goal was to determine how relative humidity directly affects the UVC light intensity. In researching it was found that in a study done by Jordan Peccia (Peccia, 3) that the "UV spherical irradiation was well characterized and was not affected by changes in RH ranges between 20% and 95%." In the testing it was found that at 60% RH the average intensity was 7.94 $\mu W/cm^2$ (microwatts per centimeter squared) and the overall average throughout the RH ranges was 7.53 $\mu W/cm^2$. The testing range is a large range, and the system that is being evaluated will operate within this range. To verify Peccia's data, testing has been done at the client's facility with the prototype system and various levels of humidity. The data collected from the test, contained in Appendix A has concurred with research findings.

The other area of interest is an indirect relation between UVC intensity and relative humidity. This topic is concerned with how the relative humidity may alter the microorganisms as well as the relation of this change in microorganism to the increase or decrease in intensity of the light necessary for eradication. This relation has been studied by various scientists and among the journals a correlation can be found. The general consensus is best stated again by Peccia in that "there is a significant decrease in airborne bacteria inactivation rates induced by UV irradiation at RH levels in excess of 50%." This statement essentially says that below 50% RH there is no change in the necessary intensity of UVC for killing microorganisms. As the RH level rises though, in order to kill the same amount of microorganisms, the intensity level must also rise. The studies show that a RH level above 50% is not optimal for the client's system. The system should be designed to create an environment that is close to or below the 50% RH level.

Impact of Distance on UVC Effectiveness

UVC lighting was also evaluated in its effectiveness at varying distances from the source. The general behavior of UVC light intensity as stated by Summer is "UVGI levels were found to decrease as the inverse of the square of the distance from a point source." This statement was verified from data collected by Miller in which light intensities were found from distances ranging from 60 cm to 240 cm, and intensity was found to follow the inverse square law. The study by Miller also showed that the intensity is not equal in all directions from a source. The behavior of the distribution of UVC intensity was tested to verify that the inverse square law would be valid for the system being evaluated. In the system an 18" UVC bulb rated at 15 Watts is being used. This bulbs energy distribution at varying distances was evaluated using a radiometer (ColeParmer Radiometer, Model # EW-09811-54). The UVC lights intensity was measured at distances ranging from .05 meters to 1 meter. The testing was carried out multiple times to verify that the experimental values were repeatable.

This data was then compared to the theoretical UVC intensity as found from using the inverse square law and basing off of a constant intensity at .4 meters. The results of the experimental and theoretical evaluation are located in Appendix A. From the data it can be easily seen that the experimental data does not match up to the theoretical values for intensity distribution; there is a measurable percentage difference between the two data sets. This discrepancy can be attributed to the fact that the inverse square law applies to "point sources" whereas the light being evaluated is actually a line source. This implies that the theoretical formulas for determining the intensity at a determined distance can not be applied to the system that is being evaluated. Due to these issues, it is impossible to theoretically determine the intensities that would be created within the client's systems. To further evaluate and analyze the systems, testing was conducted with prototype systems, UVC lights, and a radiometer to better map out the true behavior of the lights.

Testing of the UVC lights within the system was conducted to determine how multiple lights would interact in regards to intensity distribution. To evaluate this, two separate tests were conducted with a single light source and then with two light sources. The first test with the single light source set baseline data to show the intensities at various locations within the system. The second test with both lights could then be compared with the first test to determine how the two lights interacted. The data points collected showing the intensity distribution for the two tests can be seen in Appendix A. The data from the two experiments were then compared to determine if the intensities from multiple lights could be modeled by using the data from a single light source. Appendix A shows the percentage difference between using two lights and their experimental data points and using a single light source data and adding that data to model the two lights. The percentage difference between the data sets shows that the two light system can be closely modeled by adding the one light data together to account for the two lights. The percentage difference between the two data sets can be contributed to the error associated with the radiometer and its ability to only measure at discrete angles from the face. This is explains why the percentage difference between the data increases as the distance to the light decreases. These test results allow for the system to be approximated and modeled for any given number of lights at any position within the system. The intensities within the system can be calculated by using the data set for the one light test and applying it to all the lights within the theoretically modeled system.

Using the previously determined data collected, we were able to see that as the distance from the bulb exceeded four inches, the intensity of the light dropped drastically. This led us to place the bulbs every eight inches, taking advantage of this four inch window. A staggered system of light installation was decided upon primarily for reasons of air flow. With this staggered system at no time will a cross-section of the housing be less than 24 by 10.5 inches. If an opposed setup were to be used, the possible cross-section would drop to 24 by 7 inches, increasing the air velocity in this region, and decreasing the time that the mold spores would be in this most effective area.

After the light arrangement, the next major question was the length. For this we needed to determine what the intensity was for the worst case situation. This point of lowest intensity was determined to be at a center of three lights, at a distance of 8 inches from one wall and six inches from the other. This point will mean that a mold spore would end up at a distance of 5 inches from the center of any of the three bulbs (figure 1). Through calculations made from our testing it was determined that the intensity from one light bulb at this point would be 1650 μ-watts per cm^2. Three of the bulbs would be close enough to have a major impact on the intensity at this point; the others would be too far away for the added intensity to be of great impact. The intensity at this point is then 4950 μ-watts per cm^2. This level of intensity was approximated as being a continuous level for the entire length of the duct. The calculations section shows how the equations that we had previously found were used to determine the time that a mold spore would need to be in the irradiation at a given intensity for a given K value for a specific kill rate. Our K value was set to .0000344, as this was the lowest and therefore worst case value that we could find for fungus. Fungus was used due to the lack of K value data for mold. A kill rate of 10% was deemed sufficient for the system in question, as the system is continuously recirculating the air in the basement or crawlspace and thus the mold spores that weren't killed would be passed through the system again. Airflow of 800 cfm was used for the calculations, as this was the airflow stipulated by the client. With these parameters, the length of the kill-zone needed turned out to be about 60 inches, or five feet. This five foot staggered setup, as seen in figure 1, requires 16 bulb and fixture sets. Eight of these sets are placed on the bottom of the duct, and eight are placed on the top. The design of the fixtures and mounting system must also include two inch wide spacers on each side of the fixtures, preventing any untreated air from passing next to the fixtures.

Effect of UVC on Plastics

UVC irradiation affects plastics in much the same way as biomaterial already discussed. When the UVC high energy photons strike a polymer chain in polyolefin-based materials, such as polypropylene and polyethylene, the photon is absorbed and the chain is broken, releasing the hydrogen- carbon bond. Both of the newly separated ends of the chains are highly reactive ionic sites known as free radicals. These free radicals can attack other polymer chains, producing even more free radicals or can react with oxygen in the air, producing unstable peroxides. In certain plastics the chain may simply split, resulting in a lower molecular weight and therefore a more brittle substance (Jacoby, 7).

Two distinct approaches can be used to prevent and eliminate this problem. The first concept is the use of free radical scavengers, the most prominent of these being hindered amine light stabilizers (HALS). These materials come in several different weights. Use of the weight will depend on the surface structure as well as the overall structure of the part. High weight HALS are better for fibers or sheets, objects that have a high surface to volume ratio, due to the HALS' high stabilization. Low weight HALS can be used in more voluminous parts with better effect due to more active migratory patterns within the part. As the low weight HALS are used up on the surface, the large volume creates a stored supply that can be drawn upon.

The second method of UVC protection for plastics is through the use of additives that screen or block UV radiation. Primary among these additives are titanium dioxide and carbon black. Carbon black has been noted as being particularly effective when used in concentrations of 2% to 3%.

The vapor barrier that is of the main concern must be cost effective as well as UVC stable. For this reason carbon black has been selected as the method of choice for UVC stabilization. Carbon black is very effective at preventing the embitterment and consequential permeability of the vapor barrier, is very cheap in comparison to the other methods, and is readily available at many building supply yards.

Other considerations have been made for plastic parts that may be found in spaces that will be irradiated by UVC light, particularly PVC piping. It should be noted that UVC does not penetrate beneath the surface of materials farther than a few microns; therefore a coating of paint should be used on exposed piping, preferably latex for ease of use. When used on stable materials, such as the piping, latex paint shows very little structural degradation. Only exterior latex paint should be used, as this paint is specially formulated by the manufacturer to withstand UV lighting.

No major byproducts of any concern have been noted due to the use of the UVC lights. Ozone was the primary byproduct that was established as being off-gassed, but not in any hazardous quantity. What ozone is produced will be unstable and will break down into atmospheric dioxide not far from the UVC bulbs.

Effects of Air Movement

The principle that explains how dryer conditions are produced through reversing the normal convection of air was first thought to be due to negative pressure the system was causing. After further research, it is now thought that the drier conditions are a product of the velocity created from the movement of air by the system. As the air passes over the floor, walls etc. of the where the system is placed, the air transfers energy to the floor, walls etc. to evaporate the water (Lamb, 9). Once the water is evaporated into the air, the air is expelled from the room to the outside. This makes the room drier. Make up air then comes from the adjacent rooms through cracks in the wall, under doors and through any other opening large enough for air to travel through (ASHRAE, 10). This could also be drawing moisture out of the controlled environment as well making the controlled environment drier. One thing worth noting is that it is believed the total moisture in the air cannot be less than that of the make up air. Therefore the open system is not recommended for use when there is a high outside humidity. One possible concern is that the system could create a draft in the controlled environment (Toftum, 11). The room next to the room in which the systems is to be installed needs to be of size such that no draft is produced. The volume was solved for by using the equation for air exchange rate (ASHRAE, 10). The area of infiltration was calculated by using a table (Appendix B) found in the ASHRAE handbook and by estimating how much each of the factors contributed to infiltration in a typical home. The velocity used in the air exchange rate equation was the velocity that the average human finds comfortable at 23 ºC which is 0.4 m/s (Toftum, 11). Room volume was then calculated with the assumption that the air exchange rate was 0.35 per hour which is the air exchange rate recommended in the ASHRAE. The room volume found for the average house was 2309 ft^3. Assuming the house has eight foot ceilings the room volume must be 288 ft^2 or else the room might be drafty. In order to avoid the drafty room effect it is suggested that the open system not be installed in homes were the crawl space is in contact with areas of the house were people spend a lot of time (such as the living room). The closed system should be installed for those situations.

Use of Plastic Protective Covers

The possibility that plastic covers should be placed over the UVC lights has shown itself to be a bad idea. The intent was to protect the lights against dust buildup and wear and tear from particles moving through the air. This seems like a reasonable design. The flaw was found in that UVC is absorbed very easily by most materials, such as glass and most plastics (Appendix A, pg 4). This was the material planned to be used for the cover. However, if a cover were to be used, it would defeat the purpose of having UVC lights. Another reason that UVC lights do not need a protective cover is that UVC lights are self cleaning. If any organic material lands on the bulb, it will rapidly disintegrate and fall off (Carrier, 12).

Effect of UVC on Household Pests

The objective of finding out how insects are affected by UVC exposure, drier conditions, and moving air is going well. Houses with the system already installed have noticeably fewer insects than they had previously. There has been no correlation between UVC lights and the absence of insects. UVA, which is a UV band with a longer wavelength, is known to actually attract insects. UVA has been used for years in bug zappers; it is the light that attracts the bugs into the electrical grid (germ-o-ray, 14). The second consideration of why household pests seem to move out when this system is implemented was that the air movement would blind them. This idea came about because many insects use pressure sensitive hairs to "see" the world around them. However, no research was found to prove this theory. The third and final reason that pests leave a house with a Mold Sentry System installed was that the low humidity levels produced by the system would make an unwelcome able environment for pests. This theory shows the most promise of all; insects along with mold enjoy higher humidity levels. A book on termites (the most detrimental of all household pests) showed that termite nests where eggs for new generations are kept usually have relative humidity (RH) of 98-99% (Howse, 15). With the Mold Sentry System installed, relative humidity is kept around 50%. Even though this is the air RH and not surface RH, the surface RH of interior structure (wood) would be close to the air RH since it has no entering moisture like the exterior structure (foundation block).

Summary

All deliverables have been completed. The changes of the UVC light with relation to humidity has been established and has been thoroughly documented that little change is made with variation of the humidity. Identification of the level and best arrangement of the lights has been researched, and the best arrangement for the lights and fixtures has been found to be a staggered setup of five foot length. The lights that have been chosen are 18 inch, 15 watt fluorescent bulbs. The kill times are based largely on the intensity levels, which were determined through experimentation. Covers were determined to be not needed, and have been removed from the proposed design. The UVC lights have been determined not to produce any hazardous byproducts, and the type of plastic to be used in conjunction with the system has also been decided. The explanation of the reversing of the normal convection of air flow has been documented and final design established, such that reversing the normal convection isn't recommended when the outside environment has high humidity. UVC with respect to household pests has been thoroughly researched and has been determined to have little to no effect on the pests, rather the vacation of the room by the pests were caused by the lack of humidity and the increased air flow.

Budget

The predicted budget for this project has changed greatly throughout the project. The idea of replicating a house to test the product did not work, due to obvious cost and time limitations, not to mention not giving absolute and clear information on what the product does. The necessary information was instead gathered through the creation of a four foot testing box. All of the testing meters and supplies have been previously purchased by the client and were not included in the budget.

On a different note, travel expenses have been accounted for. Based off of, "Mapquest," from www.mapquest.com, the distanced from The University of Toledo to The client's facility is 16.2 miles. With a there and back travel, it would total to 32.4 miles. This trip has been completed a total of 8 times over the course of the project, mostly for testing and informational purposes.

There were no other purchases to be added into this budget; therefore the final budget amounted to $93.28.

Calculations

$I = \frac{Q}{V}$ Air Exchange Rate

$a := 5.7 \cdot in^2$ Area of air infiltration from crawl space access door

$f := 0.032 \cdot \frac{in^2}{ft^2}$ Area of air infiltration from floor to crawlspace

$f_{100} := 0.0324 \frac{in^2}{ft^2} \cdot 100 \cdot ft^2$ Area of air infiltration from floor to crawlspace with a floor area of 100 ft²

$fur := 4.6 \cdot in^2$ Area of air infiltration from furnace

$p := 3.7 \cdot \frac{in^2}{ea}$ Area of air infiltration from piping, plumbing, and wiring penetrations

$p_3 := p \cdot 3 \cdot ea$ Area of air infiltration from 3 penetrations

$v := 0.4 \cdot \frac{m}{s}$ Air velocity for human comfort at 73ºF (23ºC)

$I := 0.35 \cdot \frac{1}{hr}$ Air exchange rate (from ASHRAE standards)

$A_{Total} := f_{100} + a + fur + p_3$ $A_{Total} = 24.64 in^2$ Total air infiltration

$Q := A_{Total} \cdot v$ $Q = 388.031 \frac{in^3}{s}$ Air flow rate

$V := \frac{Q}{I}$ Volume before a drafty environment may occur.

$V = 2.31 \times 10^3 ft^3$ $V = 65.404 m^3$

Asuming 8 ft ceilings

$A_{floor} := \frac{V}{8 \cdot ft}$ $A_{floor} = 288.714 ft^2$ Area of room

SYSTEM SPECIFICATIONS:

Air Flow Rate: $Q := 800 \cdot ft^3 \cdot min^{-1}$

Duct Area: $A_D := (11 \cdot 24) \cdot in^2$

Air Density @ 27 C: $\rho_{air} := 1.1614 \cdot kg \cdot m^{-3}$

Air dynamic viscosity: $\mu_{air} := 184.6 \cdot 10^{-7} \cdot kg \cdot m^{-1} \cdot sec^{-1}$

FLUID DYNAMICS CALCULATIONS:

Equivalent Tube Diameter Approximation:

$$D_{eq} := \left(\frac{4 \cdot A_D}{\pi}\right)^{.5} \qquad D_{eq} = 0.466m$$

Air Velocity in Duct System:

$$Vel := \frac{Q}{A_D} \qquad Vel = 2.217ms^{-1}$$

Reynolds Number Evaluation:

$$Re_D := \frac{(\rho_{air} \cdot Vel \cdot D_{eq})}{\mu_{air}} \qquad Re_D = 6.495 \times 10^4$$

Minimum Velocity for Turbulent Flow:

$$V_{min} := \frac{(10000 \cdot \mu_{air})}{\rho_{air} \cdot D_{eq}} \qquad V_{min} = 0.341ms^{-1}$$

Minimum Air Flow Rate for Turbulent Flow:

$$Q_{min} := V_{min} \cdot A_D \qquad Q_{min} = 0.058m^3 s^{-1}$$

Air is in Turbulent Flow

Time within UVC field:

$t := \frac{5 \cdot ft}{Vel}$ $t = 0.687s$ $t := t \cdot s^{-1}$

K value for Aspergillus niger (highest value for molds):

$k := \frac{\ln(.01)}{-132000}$ $k = 3.489 \times 10^{-5}$

With Maximum Average Intensity and Time, S-value determination

$I_{avgmax} := 8000$

$S_{max} := e^{-k \cdot t \cdot I_{avgmax}}$ $S_{max} = 0.825$ Kill Rate is 17.5%

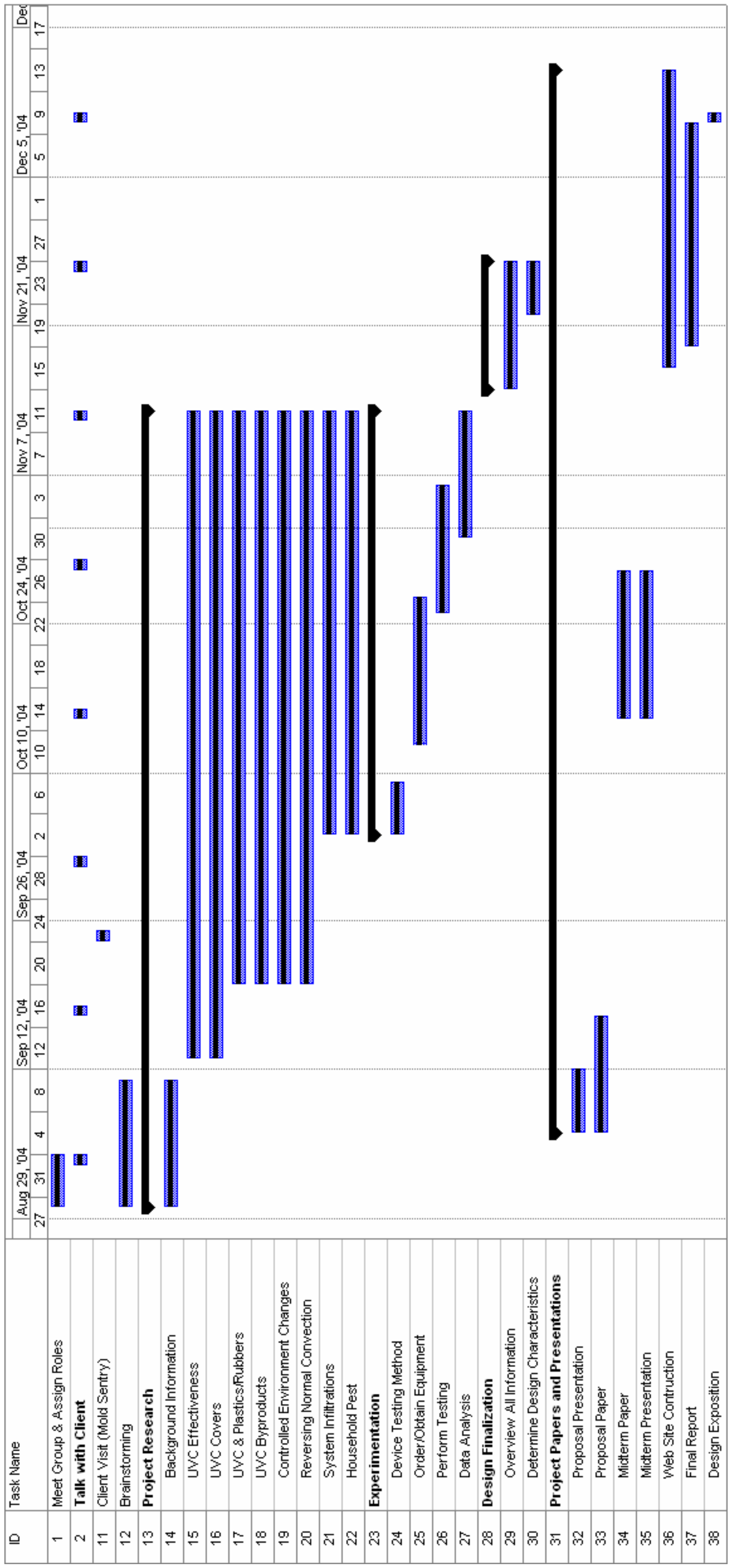
With Minimum Average Intensity, Necessary Time for 11% eradication:

$I_{avgmin} := 4950$

$S_{min} := e^{-k \cdot t \cdot I_{avgmin}}$ $S_{min} = 0.888$ Kill Rate is 11.2%

Timeline

The team has completed all tasks for the project. The initial tasks such as brainstorming, client meeting, and background information gathering were all completed several weeks ago. The area of research has been the main focus for much of the project. The team was behind schedule for a majority of its research, but all required research has been completed. The information gathered is sufficient for creation of all design recommendations, including the adaptability of the system to new sizes, shapes, and components. All tasks in the area of testing and evaluation have been completed. The final section of the timeline that awaits completion is the creation of the webpage and the final presentation. The webpage structure has been established, and only awaits the addition of the papers, presentations, and several pictures. The final presentation will follow the flow of this paper, and thus will be completed by December 9th, when our practice presentation will take place.


ID
Task Name
1 Meet Group & Assign Roles
2 Talk with Client
11 Client Visit (Mold Sentry)
12 Brainstorming
13 Project Research
14 Background Information
15 UVC Effectiveness
16 UVC Covers
17 UVC & Plastics/Rubbers
18 UVC Byproducts
19 Controlled Environment Changes
20 Reversing Normal Convection
21 System Infiltrations
22 Household Pest
23 Experimentation
24 Device Testing Method
25 Order/Obtain Equipment
26 Perform Testing
27 Data Analysis
28 Design Finalization
29 Overview All Information
30 Determine Design Characteristics
31 Project Papers and Presentations
32 Proposal Presentation
33 Proposal Paper
34 Midterm Paper
35 Midterm Presentation
36 Web Site Contruction
37 Final Report
38 Design Exposition
Aug 29, '04
Sep 12, '04
Sep 26, '04
Oct 10, '04
Oct 24, '04
Nov 7, '04
Nov 21, '04
Dec 5, '04
27 31 4 8 12 16 20 24 28 2 6 10 14 18 22 26 30 3 7 11 15 19 23 27 1 5 9 13 17

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Appendices

Appendix A: Charts and Graphs

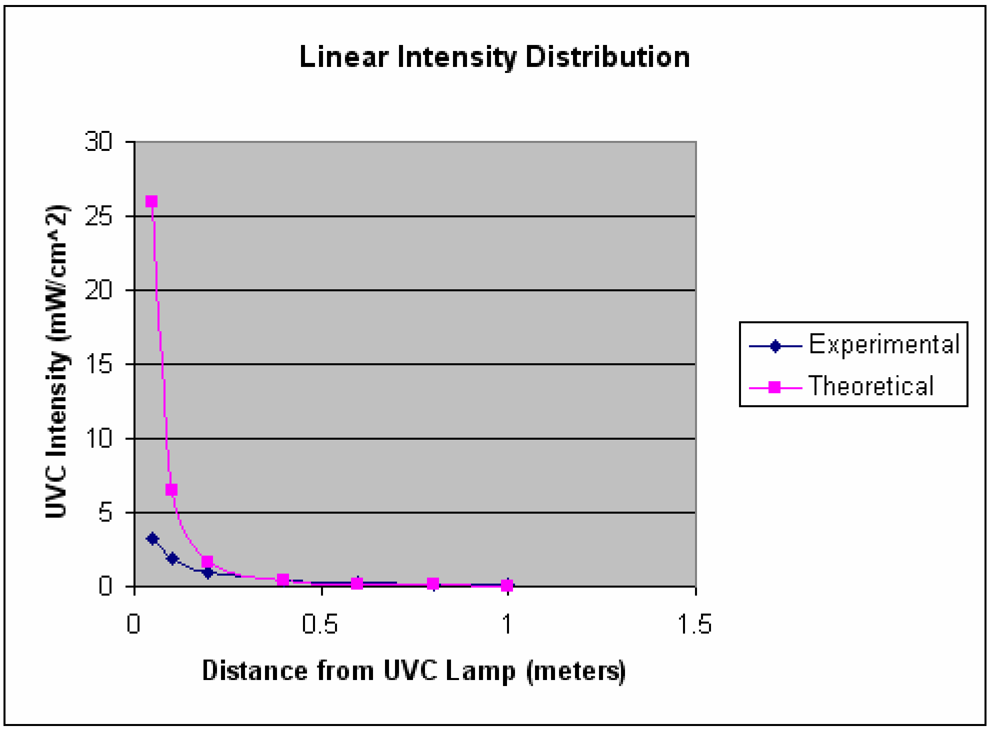
Appendix B: Drawings

Appendix A

Linear Distribution of UVC Intensity

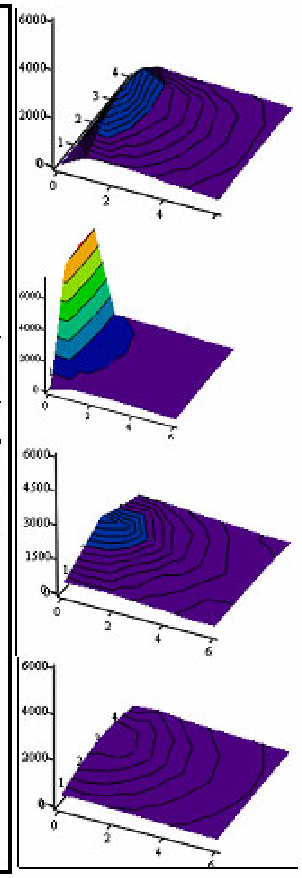
Distance from Light	Experimental Intensities 1	2	3	Average	Theoretical	% Difference
0.05 m	3.430	3.020	3.320	3.257	25.984	87.5%
0.1 m	1.970	1.770	1.954	1.898	6.496	70.8%
0.2 m	.982	.960	1.074	1.005	1.624	38.1%
0.4 m	.402	.390	.426	.406	.406	0.0%
0.6 m	.212	.214	.214	.213	.180	-18.2%
0.8 m	.121	.119	.124	.121	.102	-19.5%
1 m	.078	.081	.082	.080	.065	-23.7%

* Values of intensity are in milliwatts per centimeter squared



UVC Intensity Distribution Within Duct Work (One Light)

Duct Height (z-axis)	Duct Length (x-axis)	Duct Width (y-axis) 0 in	6 in	12 in	18 in	24 in
Level 0 (0 in)	0 in	0	0	0	0	0
	3.94 in	0.56	1.311	1.65	1.428	0.551
	7.874 in	0.6	0.917	1.013	0.93	0.47
	11.811 in	0.555	0.75	0.843	0.768	0.45
	15.748 in	0.429	0.577	0.635	0.57	0.41
	19.685 in	0.373	0.444	0.486	0.455	0.389
	23.622 in	0.291	0.366	0.371	0.366	0.318
Level 1 (4.667 in)	0 in	0.141	6.92	7.15	7.02	0.165
	3.94 in	0.454	1.434	2.01	1.894	0.539
	7.874 in	0.473	0.914	1.076	0.953	0.506
	11.811 in	0.478	0.688	0.755	0.682	0.475
	15.748 in	0.408	0.531	0.595	0.535	0.406
	19.685 in	0.343	0.413	0.469	0.421	0.355
	23.622 in	0.283	0.33	0.364	0.352	0.325
Level 2 (9.333 in)	0 in	0.412	0.932	1.486	0.971	0.596
	3.94 in	0.462	0.885	1.351	0.98	0.573
	7.874 in	0.44	0.638	0.932	0.72	0.493
	11.811 in	0.373	0.463	0.638	0.585	0.417
	15.748 in	0.332	0.408	0.492	0.43	0.36
	19.685 in	0.242	0.303	0.392	0.317	0.293
	23.622 in	0.268	0.299	0.32	0.311	0.258
Level 3 (14 in)	0 in	0.412	0.728	0.874	0.801	0.516
	3.94 in	0.443	0.683	0.871	0.781	0.588
	7.874 in	0.388	0.58	0.709	0.635	0.461
	11.811 in	0.354	0.46	0.534	0.493	0.388
	15.748 in	0.305	0.381	0.426	0.399	0.339
	19.685 in	0.268	0.317	0.347	0.334	0.299
	23.622 in	0.245	0.269	0.291	0.284	0.258



UVC Intensity Distribution Within Duct Work (Two Lights)

Level	Duct Length (x-axis)	Duct Width (y-axis) 0 in	6 in	12 in	18 in	24 in
Level 1/2	0 in	0.593	5.41	6.85	3.93	0.563
	3.94 in	0.588	1.761	1.926	1.888	0.623
	7.874 in	0.685	0.957	1.164	1.06	0.712
	11.811 in	0.651	0.814	0.915	0.868	0.693
	15.748 in	0.589	0.717	0.791	0.742	0.631
	19.685 in	0.548	0.629	0.683	0.653	0.576
	23.622 in	0.499	0.599	0.594	0.587	0.528

* All intensity values are in milliwatts per centimeter squared

Comparitive Evaluation of "One Light" & "Two Light" Tests

Sum of Intensity Distribution of Level 1 & Level 2 (One Light Test)

Duct Length (x-axis)	Duct Width (y-axis) 0 in	6 in	12 in	18 in	24 in
0 in	0.553	7.852	8.636	7.991	0.761
3.94 in	0.916	2.319	3.361	2.874	1.112
7.874 in	0.913	1.552	2.008	1.673	0.999
11.811 in	0.851	1.151	1.393	1.267	0.892
15.748 in	0.74	0.939	1.087	0.965	0.766
19.685 in	0.585	0.716	0.861	0.738	0.648
23.622 in	0.551	0.629	0.684	0.663	0.583

Intensity Distribution of Level 1/2 (Two Light Test)

Duct Length (x-axis)	Duct Width (y-axis) 0 in	6 in	12 in	18 in	24 in
0 in	0.593	5.41	6.85	3.93	0.563
3.94 in	0.588	1.761	1.926	1.888	0.623
7.874 in	0.685	0.957	1.164	1.06	0.712
11.811 in	0.651	0.814	0.915	0.868	0.693
15.748 in	0.589	0.717	0.791	0.742	0.631
19.685 in	0.548	0.629	0.683	0.653	0.576
23.622 in	0.499	0.599	0.594	0.587	0.528

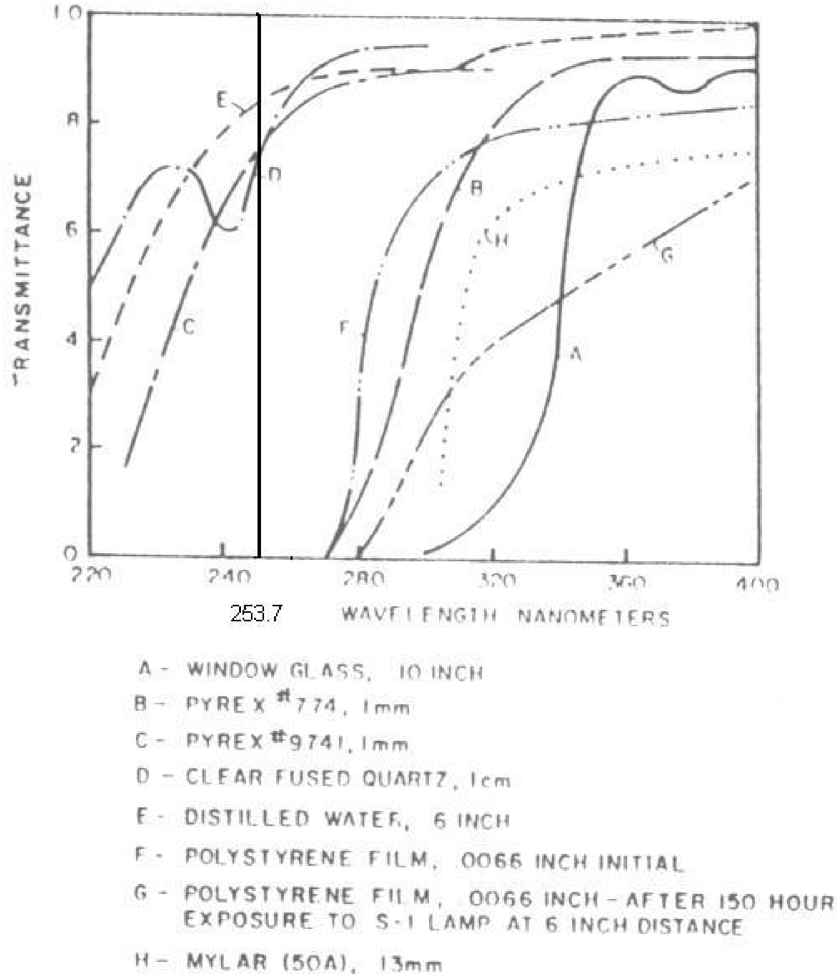
Percent Difference Between Tests

Duct Length (x-axis)	Duct Width (y-axis) 0 in	6 in	12 in	18 in	24 in
0 in	-7.2%	31.1%	20.7%	50.8%	26.0%
3.94 in	35.8%	24.1%	42.7%	34.3%	44.0%
7.874 in	25.0%	38.3%	42.0%	36.6%	28.7%
11.811 in	23.5%	29.3%	34.3%	31.5%	22.3%
15.748 in	20.4%	23.6%	27.2%	23.1%	17.6%
19.685 in	6.3%	12.2%	20.7%	11.5%	11.1%
23.622 in	9.4%	4.8%	13.2%	11.5%	9.4%

Direct Impact of Relative Humidity on UVC Intensity

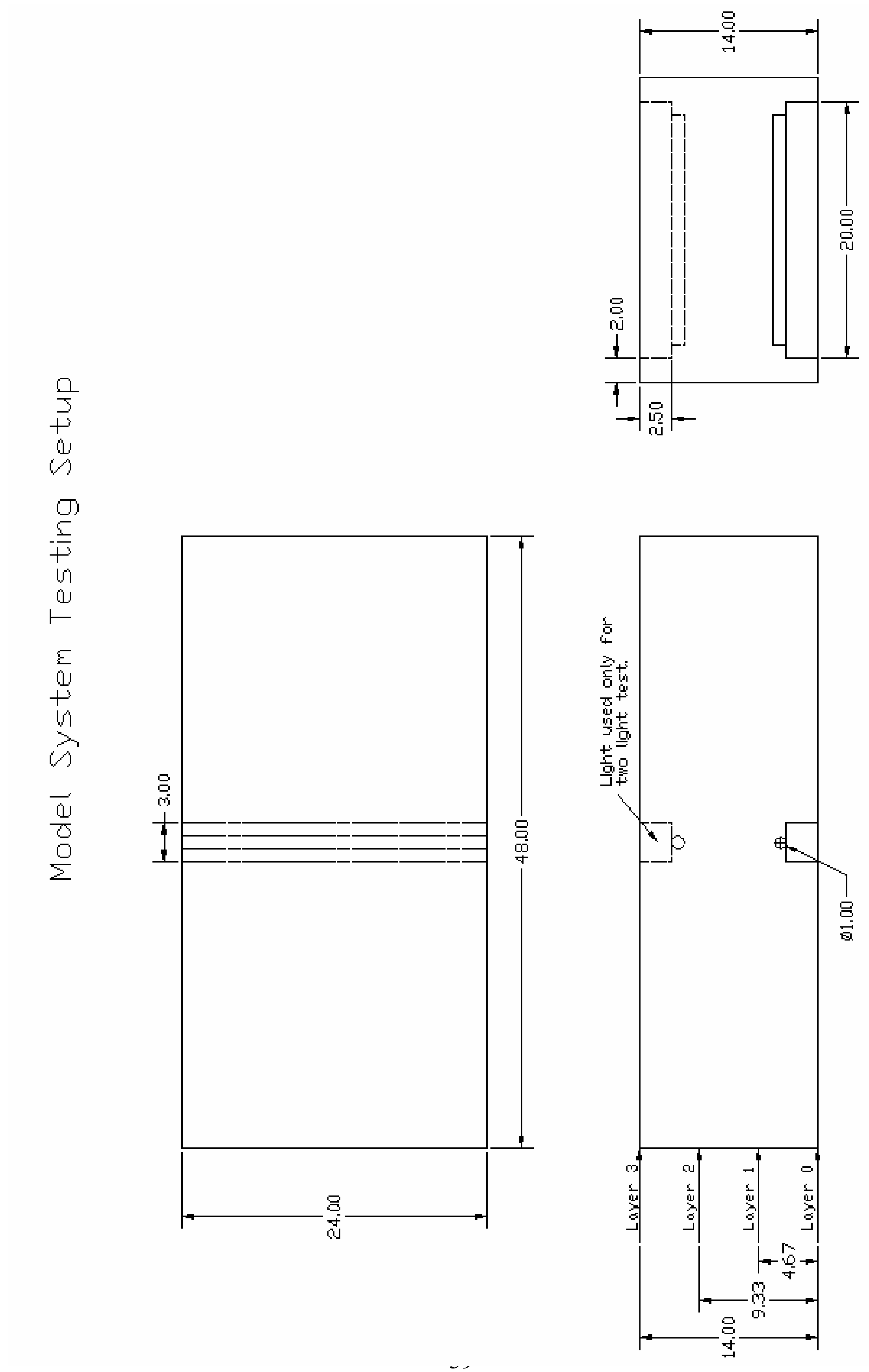
Distance from Light	45% RH		68% RH	
	1.1	1.2	2	% Difference
0.05 m	3.430	3.020	3.320	-2.9%
0.1 m	1.970	1.770	1.954	-4.5%
0.2 m	.982	.960	1.074	-10.6%
0.4 m	.402	.390	.426	-7.6%
0.6 m	.212	.214	.214	-0.5%
0.8 m	.121	.119	.124	-3.3%
1 m	.078	.081	.082	-3.1%

* Values of intensity are in milliwatts per centimeter squared



Typical Transmittance Curves of Common Materials

Appendix B



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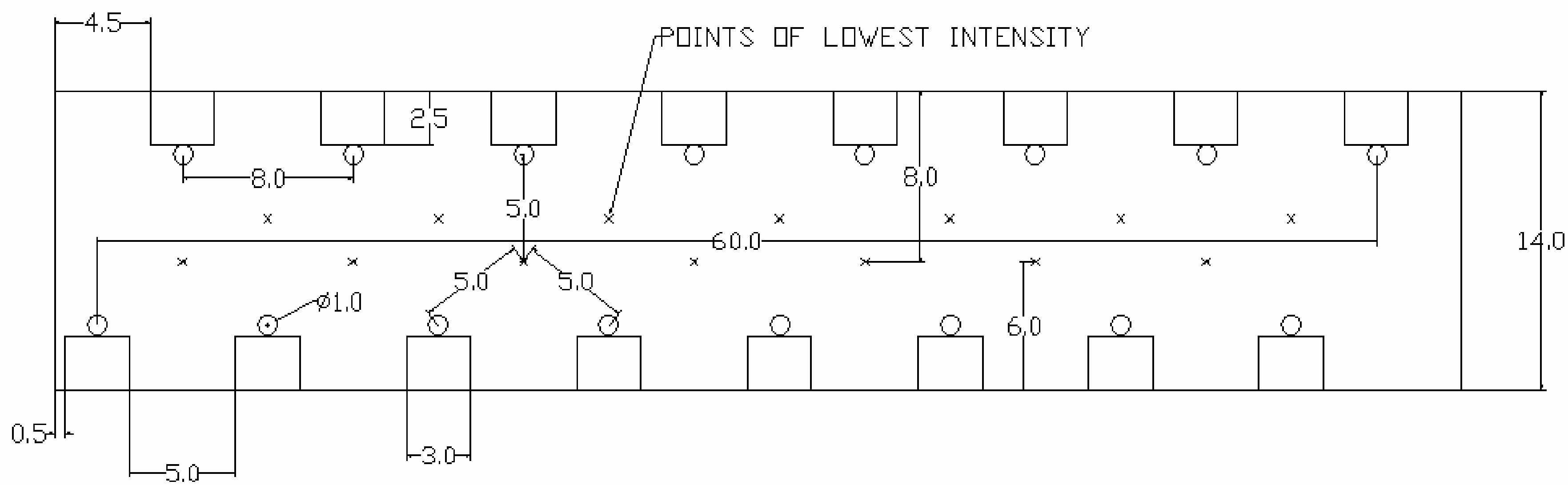

4.5
POINTS OF LOWEST INTENSITY
2.5
8.0
5.0
8.0
60.0
14.0
5.0
5.0
ø1.0
6.0
0.5
3.0
5.0