Sterilization Through Utilization of Ultraviolet Radiation

Application Note 104

Introduction

Soon after the discovery of microorganisms, biologists began to observe that many varieties of these creatures were able to be incapacitated by exposure to sunlight. Following the discovery of the ultraviolet bandwidth in 1801, scientists attributed the sun's lethal effect to this invisible energy. Facilitated by the findings of a large body of experimental evidence collected in the decades following these initial hypotheses, contemporary scientists have determined that nearly all bacterial activity can be eradicated or at least attenuated by some wavelength of ultraviolet energy. Due to the overwhelming diversity of microorganisms present in the environment, the resistively and rate of lyses of each species varies greatly. Generally bacteria who live in environments saturated with sunlight are more resistant to UV sterilization when compared to those species whose domain is general absent of solar exposure. The practice of sterilization via ultraviolet energy exposure was discontinued around the early 1900's due to the development of sterilization technology utilizing chlorination and ozonation. However, there has been a general trend in industry during the last few decades towards the use of UV for germicidal purification due to its lack of toxic chemical byproducts.

Photochemical Background

The ultraviolet bandwidth occupies wavelengths roughly between 200 and 400 nanometers. To put into relative terms UV radiation is sandwiched between the higher energy, soft X-rays and lower energy visible light. Purification via exposure to ultraviolet radiation is unique from other types of sterilization modalities due to the fact that it does not necessarily cause death of the target organism. In those pathogens it does not directly kill, the UV radiation effectively alters the creature's genetic structure. By causing damage to the target bacteria's Deoxyribonucleic Acid (DNA), the bacteria is sterilized at the genetic level. Thus the organism is no longer able to reproduce and cause disease

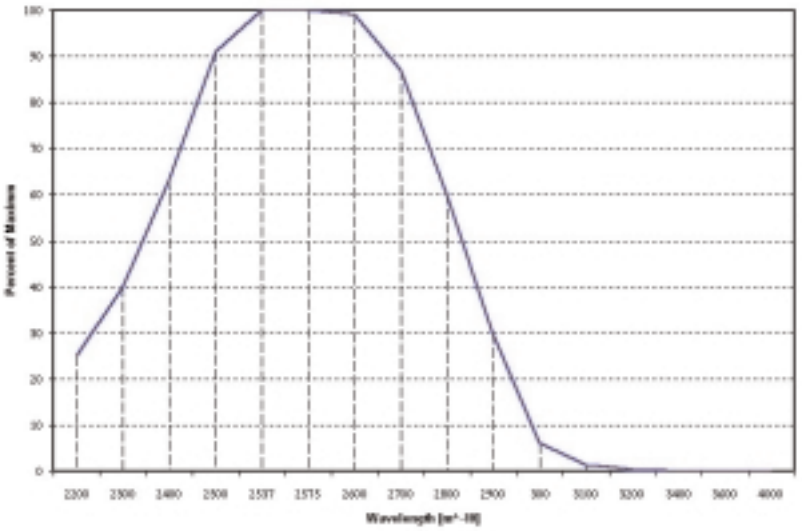
Approximate Guidelines

Researchers in the past (Hollaender, Gates, Claus, Coblentz, and Fulton to name a few), have determined general parameters for UV wavelengths of maximal effectiveness for germicidal purification. The most cited recommended dose is 16,000 µW s / cm2 but , as stated previously, a pathogen's resistance to sterilization can differ greatly. It is generally accepted that bacteria are the least resistant microorganism to ultraviolet radiation and as such they require the least relatively least amount of radiation exposure to treat.

The Advent of Germicidal Lamps

Based on experiments which compared the effectiveness of various light sources on the survival ratio of different species of bacteria, scientists were able to determine the wavelength of ultraviolet light which produced the maximal germicidal effectiveness. This wavelength was determined to be 253.7 nm. This finding explained why sunlight is only marginally effective in the treatment of pathogens. This wavelength is far beyond the short-wave limit of solar light. The graph on the following page is based on the ground breaking work of Luckiesh, Holladay, and Taylor which examines the germicidal effectiveness of the various wavelengths of radiation in the killing of B. coli bacteria.

Relative Bacterial Effectiveness of Radiant Energy



SOLAR LIGHT CO. INC.

721 Oak Lane • Philadelphia, PA 19126-3342
Tel: **(215) 927-4206** • Fax: (215) 927-6347
E-mail: **info@solar.com** • Internet: **www.solar.com**

Sterilization Through Utilization of Ultraviolet Radiation

Application Note 104

From the data presented on the preceeding page, it can be inferred that for the most effective germicidal treatment, a radiation source emitting light with a spectral peak at approximately 254 nm is necessary. To determine the most efficient light source , the before mentioned experimenters carried out a study comparing two of the most viable candidates for UV sterilization radiation sources. The scientists compared a 360 Watt, 115 Volt Quartz Mercury Arc Lamp to a 30 Watt, 115 Volt Low-Pressure Mercury Arc Lamp contained in a tube of glass which allows the transmission of wavelengths of ultraviolet light. Their results are tabulated below.

Parameter	Quartz Arc	Germicidal Lamp
Watts Input		
Lamps	360	30
Ballast	60	9
Total:	420	39
Watts Output		
2200 - 2800	10.4	7.9
2800 - 3165	10.3	0.21
3165 - 3800	8.3	0.16
3800 - 7600	17.4	0.9
2200 - 7600	46.4	9.17
Watts Output of Germicidal Flux		
2200 - 2800	8.74	7.9
2800 - 3165	1.03	
3165 - 3800	0.003	
3800 - 7600	0.001	
Microwatts of Germicidal Flux per sq. cm. @ one meter (energy of 2537 or its equivalent)	105	82
Relative Germicidal Flux per watt of total input	**11.5**	**100**

By analyzing the above data , the researchers were able to conclude the following: the germicidal efficiency, as defined as the output of germicidal flux per watt, of a 360W Quartz Mercury Arc Lamp is 98.5% less effective than the 30W Low-Pressure Mercury Arc Lamp. The argument for the use of the Low-Pressure Mecury Lamp, hence refered to as a “germicidal lamp,” for germicidal purposes is further strengthened by the fact that the lamp produces much less heat in comparison to the less effective Quartz Lamp. It follows that a germicidal lamp’s usefulness is increased due to the fact that it can be placed closer to the target area, augmenting the amount of radiation delivered to a specified area, without causing any adverse reactions due to heat. Luckiesh states that, “Taking all the practical aspects into account one may conclude conservatively that a 30W germicidal lamp can often be more effective in practice than a 300W, quartz mercury arc.”

Dose Requirements

Scientist of the latter half of the 20th century have continued to study the effectiveness of UV sterilization. Accepting that the most effective wavelength for bacterial treatment is 254 nm, researchers have focused their study on determining the exposure necessary to kill pathogens in terms of intensity and time of exposure. High intensities for a short period of time, or low intensities for a longer period are fundamentally equal in lethal dose distribution. The intensity of light falling on a given area is governed by the inverse law; that is the killing intensity decreases as the distance increases from the source. The table below comes from a Westinghouse brochure entitled - "Westinghouse Sterilamp Germicidal Ultraviolet Tubes." It lists the product of the intensity of the radiation and the exposure time required to cause sterilization of a variety of microorganisms. The radiation source is a standard germicidal lamp (254 nm wavelength output).

Comparison of the Germicidal Effectiveness of Two Radiation Sources

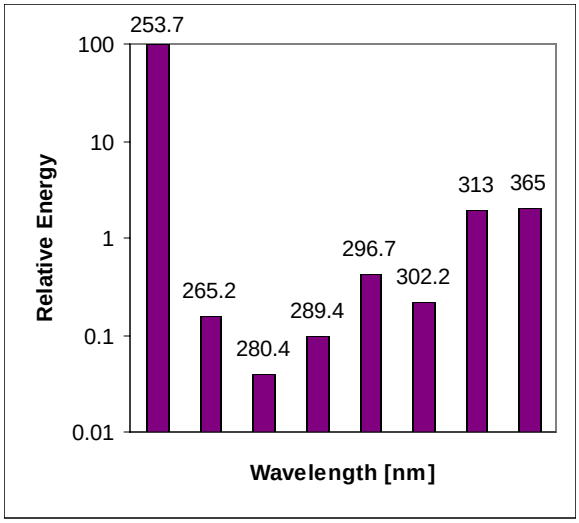
Organism		Microwatt Seconds per square cm.
Mold Spores	Penicillum roqueforti	26,400
	Penicillum expansum	22,000
	Penicillum digitiatum	88,000
	Aspergillus glaucus	88,000
	Aspergillus flavus	99,000
	Aspergillus niger	330,000
	Rhizopus nigricans	220,000
	Mucor racemosus A	35,200
	Mucor racemosus B	35,200
	Oospora lactis	11,000
Yeasts	Saccharomyces ellipsoideus	13,200
	Saccharomyces sp.	17,600
	Saccharomyces cerevisiae	13,200
	Brewer’s Yeast	6,600

Sterilization Through Utilization of Ultraviolet Radiation

Application Note 104

Organism		Microwatt Seconds per square cm.
	Baker's Yeast	8,800
	Common Cake Yeast	13,200
Virus	Baceriophage (E. Coli)	6,600
	Tobacco Masaic	440,000
	Influenze	3,400
Bacteria	Streptococcus lactis	8,800
	Streptococcus Hermolyticus	5,500
	Staphylococcus aureus	6,600
	Staphylococcus albus	5,720
	Micrococcus sphaeroides	15,400
	Sarcina lutea	26,400
	Pseudomonas fluorescens	7,040
	Escherichia coli	7,040
	Proteus vulgaris	7,480
	Serratia marcescens	6,160
	Bacillus subtilis	11,000
	Bacillus subtilis Spores	22,000
	Spirillum rubrum	6,160

Typical Emission Spectra of a Germicidal Lamp



It should be noted that the above spectrum is only typical, and the exact emission profile will varry according to specific manufacturer specifications.

Definition of the "Survival Ratio"

Through years of study, scientist have been able to mathematically define the statistical effectiveness of ultraviolet sterilization of microorganisms. Defined as the "survival raitio," the equation below relates germicidal radiation exposure to the fraction of the original concentration of, in this instance, bacteria surviving after said exposure. Thus:

$$(P / P_0) = e^{-KEt}$$

where: P is concentration of suviving bacteria

P_0 is the initial concentration of bacteria

K is a constant determined from environment (humidity, temperature, misc. variables)

E is intentsity of germicidal flux

t is the time of exposure

It should be noted that this is an emperically derived formula and due to the varitable resistance pathogens exhibit towards UV radiation, this equation cannot be blindly acceptted. With detailed analysis, the experamentor can affix the proper value to the constant, K, which increases the accuracy of the above relationship.

Sterilization Through Utilization of Ultraviolet Radiation

Application Note 104

Applying UV Sterilization to Industry

Sterilization through the utilization of ultraviolet radiation has experienced an upsurgence of popularity in the last decade. Industry has embraced this technology due to its convenience, safety, and relative cost effectiveness. We will focus on three specific applications of UV purification in the remaining parts of this text.

I. Sterilization witihin the Food Industry

With the advent of packaged goods, the food processing and distribution industry has required a way to ensure the safety and longevity of their products. Companies involved have labored to develop a means to consistantly and relatively inexpensively ensure that consumers' health and wellbeing are not jepordized by tainted products. Many have utilized UV sterilization as a part of their quality assurance procedures. Food packaging is routinely and safely sterilized using ultraviolet radiation. Manufacturers specializing in sterilization technologies have produced integrated systems designed to significantly reduce microbial contamination levels in all meat, fish and food products. These systems are engineered so that workers are not in tactile contact with food stuffs. They are also non penetrative in that they eliminate 99% of product contamination without affecting sub-surface tissues. Another benefit is that ultraviolet radiation does not transfer heat energy to target foods. Thus, there is no potentially adverse effect on taste. These types of treatments produce no chemical waste and therefore tend to be clean, dry processes. Finally, UV radiation has been approved to control surface microorganisms in food and food products in a range of 220-300 nanometers under FDA regulations.

Ultraviolet light is also used in the purification of ingestable liquids. Highly absorbative fluids such as beer, wine, and vinegar charactoristically absorb almost all germicidal energy at their immediate surface. However, by controlling the rate of flow of a liquid through a chamber of UV sources, thin layers of liquid can recieve an adaquite dose across a large enough surface area to ensure proper sterilization of present microbes.

For reference, a table originally presented in Luckiesh's "Applications of Germicidal, Erythemal, and Infrared Energy," is given below. It analytically details the percent of germicidal energy penetration in no-turbid, homogenious media:

Absorbtion Coefficient (per inch)	Depth in Inches									
	0.1	**0.2**	**0.5**	**1**	**2**	**5**	**10**	**20**	**50**	**100**
0.01	0.1	0.2	0.5	1.0	2.0	5.0	9.0	18	40	60
0.02	0.2	0.4	1.0	2.0	4.0	9.0	18	33	60	85
0.05	0.5	1.0	2.5	5.0	10	22	40	60	90	98
0.10	1.0	2.0	5.0	9.8	18	38	60	86	98	
0.20	2.0	4.0	9.0	18	32	60	85	98		
0.50	4.8	9.0	22	38	60	91	98			
1.0	9.0	18	38	60	85	98				
2.0	18	32	60	85	90					
5.0	37	60	90	98						
10	60	85	98							
20	85	98								
50	98									

The data in the preceeding table was determined using the exponential law for clear or non-turbid homogenious media:

$$P = 100 (1 - e^{-ad})$$

where: P = Percentage of germicidal energy absorbed

a = Absorbtion coefficient

d = Depth of absorbing media

The federal government has also set guidlines for employee exposure to UV radiation. These statutes require the monitoring of the exposure workers recieve in a period of time. *Solar Light Company* offers the 6D UV Hazard Meter, which is a valuable safety tool for any industry that involves worker exposure to UV radiation. It is sensitive to ultraviolet radiation specified as hazardous in standards published by the American Conference of Governmental Industrial Hygienists. Those standards state that the total UV exposure in an eight-hour period should not exceed 3 millijoules per square centimeter at 270nm. Other wavelengths have hazardous potential related to that of 270nm by the Spectral Weighting Function. The Safety Meter monitors the integrated effect of all ultraviolet wavelengths from the light source.

II. UV Water Purification Systems

The treatment of water via ultraviolet radiation expoure has been acceptted by the scientific community as a means to kill disease producing microorganisms. Diseases such as cholera, dysentery, and typhoid are conditions that have been proven to be caused by the ingestion of pathogen-laden drinking water. At one time, municipal athorities solely depended on chlorination and filtration techniques to provide a safe water supply to their customers. However, in the last decade more and more communities are turning to UV purification technologies in an attempt to decrease the amount of residual chemical byproducts left behind after the the chlorination purification process. Today, ultraviolet-based water refining equipment can be found in large, industrial and municipal applications as well as on the counter top in the adverage household.

The advent of the low wattage germicidal lamp has facilitaed these advances. As seen in the previous table, these low power, and thus, low operating cost sources are very adept at killing pathogens in comparison to quartz mercury-arc lamps which were impractical for many germicidal applications due to their high wattage requirements. Industry now has a tool to purify water which comes with its own set of advantages over previously utilized chemical-based techniques.

UV water purification does not alter the taste or odor of the media due to the absence of chemical infusion. The degree of purification is almost entirely up to the needs of the application. This facilitates laboratory based applications. Although there are varieties of pathogens that are extremely resistent to UV sterilization, the multitute that are effected certainly validifies this technology as a viable alternative to chemical purification processes.

Sterilization Through Utilization of Ultraviolet Radiation

Application Note 104

Water Purification Technology

When designing UV purification equipment, engineers must be concerned with several difficulties associated with the interaction between radiation and an absorbative medium. When UV light travels through air, there is only nominal absorbtion, and as such situations associated with media absorbtion of transient energy can be neglected. However, when radiation is incident and passes through a liquid, these effects can no longer be ignored. Water's readily absorbs transient energy and this dgree of absorbtion can varry greaty as a funtion of the water's source. Below is a table published by Luckiesh which tabulates the absorbtion coefficients for germicidal energy per centimeter thickness of various waters and the percentage of this energy transmitted to various depths in inches:

Source of Water	Absorbtion Coefficient (per cm)	Percent Transmitted to Various Depths			
		3 Inch	6 Inch	12 Inch	24 Inch
Distilled	0.008	92	88	78	61
Swimmung Pool	0.031	78	62	39	15
Ashtabula Tap	0.037	74	56	32	10
Cleveland Tap	0.050	67	46	22	4.7
Drilled Well	0.056	64	42	18	3.1
Fish Pool	0.070	58	34	12	1.3
Lake Erie	0.083	52	28	8	0.6
Concrete Cistern	0.297	10	1	..	..

As one can see, the degree of absorbtion varries greatly from source to source. Experamentors have determined that this is in part due to the presence of common impurities found in drinking water. The impurity which has the greatest effect on the absorbtion of germicidal energy is iron. Luckiesh and his assistants showed that the addition of 1 part of iron to 1,000,000 parts highly distilled water caused a reduction of transmission of germicidal energy by 66%. Thus, water that is to be treated by UV radiation must be filtered by physical means to some extent before passing through any type of germicidal radiation chamber. A process integrating filtration (removal of suspended particles), distillation (removal of materials in solution), and finally UV purification (removal of microbes and limited viruses) seems to be the safest application of UV to the drinking water purification process.

This approach has been taken by municipal facilities interested in steralizing community waste waters. After extensive filtration and, in some cases, a degree of chemical processing, waste water passes through banks of germicidal light sources. The size and number of lamps used is determined by the volume of water being processed and the amount of time the water will be exposed to said lamps. The flow rate of the water through the UV banks must be calculated to ensure that the proper dose of germicidal energy is delivered to the media. Thus, high volume facilities will require larger lamp banks than those plants whose needs are not so great.

Consistant monitoring of germicidal lamp output is necessary to ensure this delivered dose is adequate to kill tainting microbes. Lamp effectiveness can deminished when lamps fail, become dirty, or when their output decreases over time. *Solar Light Company* designed and manufactures an integrated detector / monitoring system to be used by water treatment facilities to ensure top performance of their germicidal sources. The *GLM-100 Lamp Monitoring System* reduces plant maintenance costs by determining exactly when lamps need to be serviced. The *LM-100* continuously monitors relative lamp output from 0% to 100%, providing a cost-effective and trouble-free method of determining exactly when lamps need to be removed for cleaning.

III. Sterilization of Air

The need for sufficiently sterilized air in buildings where people exist in close contact has been known to researchers since it was determined that pathogenic organisms can be transferred via the communal air. Organisms found to be the cause of diphtheria, scarlet fever, measles, mumps, influenza, tuberculosis, septic sore throat, pneumonia, cerebrospinal meningitis, and whooping cough all eneter the body through the nose and mouth. These pathogrens are exhalled by the infected person and are passed to others via direct contact or inhalation. There is also concern over naturally existing air-borne microbes that may eneter an enclosure and be continually recycled through the structure's air mass, increasing the chance of infection. With the widespread use of contained air conditioning systems in densely populated buildings, purification of recycled air has become an increasingly important issue to sanitation engineers. When examining the possible use of UV germicidal energy to sterilize air, one must look at the various situations which promote the exchange of air between people.

Disinfection of "Controlled" and "Communal" Air

In this text we will refer to "contolled air" as an air mass that is cycled throughout a building via some type of air conditioning system. This contolled air tends to be circulated throughout a structure, periodically passing through a system dedicated to altering the gases' temperature. These systems are dynamic in that the air within is moved throughout a large volume, occuping a variety of environments periodically. "Communal" air is an air mass that is not dynamic. This situation occurs when due to architectural limitations, a room occupied by a number of people does not have access to a fresh air supply regularly. An example of this is a classroom that, due to space limitations, is not fitted with any windows to the outside. This is similar to a situation of a room located in a cold climate where a periodically open window is not practical. Extending the idea of the before mentioned concept of "flow rate," one can discern the difference between the above two cases. In a controlled air environment, the disinfection of air via treatment is offset by the ability to replace the air supply with a fresh volume. In a communal air setting, the need for locallized air sterilization is greater. It is advantagous to have an air purification system which incorperates both air circulation and germicidal dose irradiance to ensure air quality.

In encosures with a communal air supply, the best application of ultraviolet sterilization is germicidal lamps located on the ceiling of the room, with the lower portion of the structure screened of from the radiation. Thus, the upper air strata is purified and recirculates back into the environment. An advantage that the UV treatment of air has over

Sterilization Through Utilization of Ultraviolet Radiation

Application Note 104

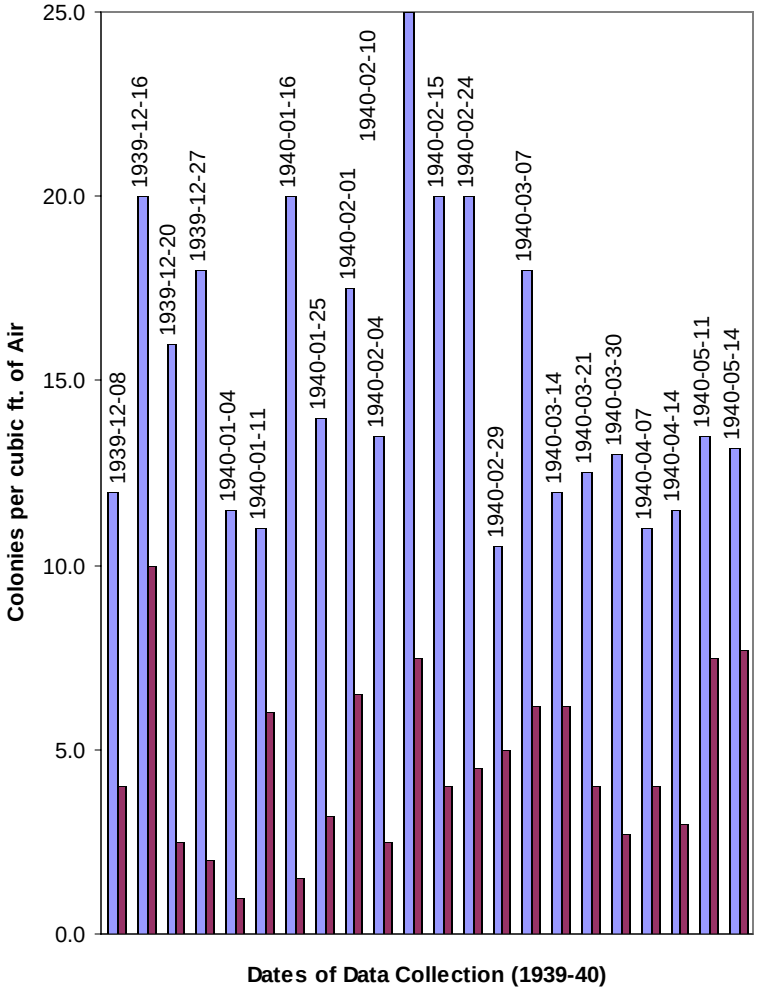
the treatment of liquid media is that air only nominally absorbs germicidal radiation. Therefore, the number and size of the germicidal lamps utilized is less than a comparable liquid sterilization system.. A wavefront of radiation emitted by a source can interact with air-borne microbes and continue on to disable the same quantity without its path ever "ending" due to absorbtion. Screens to prevent germicidal energy from reaching room occupants can be constructed from specially treated aluminum fabricted into a fine, porous sheet.

Interiors featuring a contolled air supply enjoy the luxury of air circulation. In a communal air supply "fresh" air is that entering the breathable air supply from the upper strata of the room, controlled air systems can be designed to deliver frsh air to an enclosure from a seperate source. This dynamic flow also serves to flush the room of microbe laden air. UV disinfection can be used to sterilized the body of air injected into an area as well as clean the stagnent air leaving the space. This system is analogous to a municipal wastewater treatment plant. A definate volume of air at a specified rate flows through a chamber containing germicidal sources to kill air-borne pathogens. Due to the before mentioned lack of absorbtion of germicidal energy, the size of these structures needed to sterilize a volume of air is smaller than the structure needed to treat the same volume of liquid.

Another similarity to water treatment facilities is the need to monitor source output to ensure comprehensive air sterilization. *Solar Light Company* is the manufacturer of the *PMA2122 Germicidal Detector*. Linked to either the *PMA2100* or *PMA2200 Personal Assistant Radiometer*, the detector provides fast and accurate irradiance measurements of effective germicidal radiation. UV producing lamps in purification systems must be monitored to insure that the bacteria and air-borne microbes are receiving lethal doses of germicidal radiation. Expensive UV lamps can be monitored to ensure that their maximum life has been reached before replacement. The germicidal detector can also be used to insure that the proper lamp has been installed after replacement.

Mundo and MeKhann Study

From late 1939 to mid 1940, researchers Mundo and MeKhann performed a study in an infant's hospital by weekly collecting air bacterial samples in rooms equipped with and without germicidal lamps. The graph below shows the relative bacterial content of air in irradiated (dark bars) and unirradiated (light bars) wards.



Resource

Luckiesh, Matthew. "Applications of Germicidal, Erythemal, and Infrared Energy." 1946. D. Van Nostrand Company, Inc., New York.

SOLAR LIGHT CO. INC.

721 Oak Lane • Philadelphia, PA 19126-3342
Tel: **(215) 927-4206** • Fax: (215) 927-6347
E-mail: **info@solar.com** • Internet: **www.solar.com**