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THESIS

**FEASIBILITY AND ASSESSMENT OF APPLYING
ULTRAVIOLET GERMICIDAL IRRADIATION (UVGI)
SYSTEMS ABOARD U.S. NAVY SHIPS**

by

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March 2022

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GERMICIDAL IRRADIATION (UVGI) SYSTEMS ABOARD U.S. NAVY SHIPS**

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ABSTRACT

This thesis explores the feasibility of using ultraviolet germicidal irradiation (UVGI) to help clean the air aboard U.S. Navy ships. Recent airborne-related infections on naval vessels, including the COVID-19 outbreak aboard a United States aircraft carrier, highlight the need to improve disinfection techniques used aboard naval vessels. Application of 200-280 nm wavelength UVC light to the ship's heating, ventilation, air conditioning (HVAC) system in using specific exposure profiles makes inactivation and termination of airborne pathogens possible. Research has shown that UVGI is also successful at destroying biological warfare agents such as anthrax. Proper implementation of UVGI within a ship's ventilation system and in-room spaces can achieve high disinfection rates of airborne pathogens, reduce airborne-related illnesses, and increase operational availability. Commercial maritime employment of UVGI is also instructive. Recommendations include completing a multi-disciplinary design effort to install commercial-based prototypes on naval ships.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHU	Air Handling Unit
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBR	Chemical, Biological and Radiological
CDC	Centers for Disease Control and Prevention
CFL	Compact Fluorescent Lightbulbs
CLTD	Cooling Load Temperature Difference
CPS	Collective Protection System
LED	Light Emitting Diodes
EPA	Environmental Protection Agency
HB	Heat Balance
HEPA	High Efficiency Particulate Air
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
ISO	International Organization for Standardization
IUVA	International Ultraviolet Association
LD	Lethal Dose
MVOC	Microbial Volatile Organic Compounds
NAFA	National Air Filter Association
NAVSEA	Naval Sea Systems Command
NSTM	Navy Ship Technical Manual
OPNAVINST	Chief of Naval Operations Instructions
REHVA	Federation of European Heating, Ventilation and Air Conditioning Association
TB	Tuberculosis
TP	Total Protection Systems
TVOCs	Total Volatile Organic Compounds
UMVOC	Unique Microbial Volatile Organic Compounds
UVA	Ultraviolet Irradiation (315-400 nm) wavelength spectrum
UVB	Ultraviolet Irradiation (280-315 nm) wavelength spectrum

UVC	Ultraviolet Irradiation (200-280 nm) wavelength spectrum
UVGI	Ultraviolet Germicidal Irradiation
WHO	World Health Organization
VA	Department of Veterans Affairs

EXECUTIVE SUMMARY

This thesis explores the feasibility of applying ultraviolet germicidal irradiation (UVGI) devices to clean the air aboard U.S. Navy ships. Airborne transmission of diseases can have a severe impact on U.S. Navy vessels at sea. The U.S. Navy aircraft carrier, USS *Theodore Roosevelt* (CVN 71), was struck by a severe SARS-CoV-2 in 2020, which resulted in 1,271 confirmed infections and one COVID-19-related death (Kasper et al. 2020). This incident forced the ship into a Navy base in Guam and away from its mission (Kasper et al. 2020). The guided-missile destroyer USS *Kidd* (DDG 100) also suffered a COVID-19 outbreak at sea when approximately 100 sailors were infected (USNI News 2020a). Airborne pandemics can spread quickly due to the close-quarter environments aboard Navy vessels. Presently, no air disinfection systems exist for Navy ships. Navy ships equipped with chemical, biological, and radiological (CBR) systems will clean the air before sea deployments; however, many Navy ships do not have the CBR system and even then, only certain CBR zones are cleaned.

Many UVGI devices use ultraviolet irradiation UVC light to inactivate or destroy airborne pathogens such as COVID-19 and tuberculosis. UVC light has been used for decades to provide disinfection of airborne diseases and reduce the spread of tuberculosis and bacteria (Food and Drug Administration [FDA] 2021). UVC refers to wavelengths of ultraviolet light (200–280 nm) in the electromagnetic spectrum that has a germicidal effect on viruses and germs. UVGI devices are very effective against a variety of airborne diseases such as COVID-19 when properly implemented.

Although direct, prolonged exposure to UVC light can cause some health concerns for individuals, the proper application of UVGI is both safe and effective. UVGI systems are currently used in hospitals, schools, commercial buildings, and even homes to provide air disinfection and to prevent bacterial buildup upon heating, ventilation, and air conditioning (HVAC) coils. Another fast-growing area of UVGI adoption is by cruise ship companies. High interest for UVGI air disinfection occurred after the cruise ship the *Diamond Princess* suffered a severe COVID-19 outbreak in 2020 that was brought on by one passenger (Mundell 2020). This event resulted in approximately 700 passenger

infections and seven deaths (Mundell 2020). As a result of this incident, several cruise ship companies are applying UVGI technology to provide supplemental air disinfection for their passengers and crew. Carnival Cruise Lines graciously provided details of their UVGI implementation methods to assist in this study.

The size of SARS-Cov-2 particles can be in either in the form of large respiratory particles that are $> 5\text{--}10\text{ }\mu\text{m}$ in diameter or in smaller droplet nuclei less than $< 5\text{ }\mu\text{m}$ in size (Lee 2020). These aerosolized particles can remain aloft in air currents for minutes or hours (Centers for Disease Control and Prevention n.d.). The possibility exists that aerosolized COVID-19 particles can travel through HVAC systems and cause infections in individuals. In other scenarios, an infected person can expel COVID-19 aerosolized particles when they cough or sneeze. These particles can travel throughout a room or space and infect other individuals. Current commercial applications of UVGI for air disinfection include the installation of UVGI lamps inside the HVAC system, which include installing UVGI lamps in air handling units and in the ductwork. Upper-room and standalone UVGI air purifiers can be used to clean the air in rooms or spaces.

UVGI has also been proven to be effective against bio-weaponized air pathogens such as bacteria, fungi, endospores parasites, and viruses (Vatansever et al. 2013). The use of UVGI technology could be an effective means for air disinfection if a Navy ship was exposed to a biological attack.

This feasibility topic has been mentioned before after an airborne tuberculosis outbreak on a Navy ship in 1998. An article in the *Military Medicine Journal* suggested using UVGI for air disinfection. The article stated, “Considering the huge expenditure of resources associated with this outbreak and the emerging threat of attack with biological agents, the potential for UVGI systems to decrease respiratory disease rates and the feasibility of their installation aboard ships should be investigated by the Navy” (Lamar and Malakooti 2003, 527).

Cruise ship lines are beginning to adopt UVGI technology to reduce airborne disease outbreaks for the safety and wellbeing of passengers and crew. Carnival Cruise Lines provided access to the senior HVAC UVGI working group and pictures of their

UVGI systems for the benefit of this study. The engineers understand at Carnival that UVC germicidal light is a proven and capable means of eliminating COVID-19 and similar viruses.

In addition to Carnival Cruises, Windstar and MSC Cruise lines are also adopting UVGI systems. The Windstar Cruises website states that they are implementing “HEPA filters and UV-C ultraviolet germicidal irradiation to filter and disinfect air” (Windstar 2020). The MSC Cruises website says that they are a “Safe-Air” system using UVC lamps in conjunction with the ship’s air conditioning system, which will prevent the circulation of mold, bacteria, and viruses (MSC Cruises 2020).

This thesis concludes that the application of UVGI to clean the air aboard ships is feasible, necessary, and cost-effective. Both rapid and long-term actions for UVGI implementation should be utilized by Navy stakeholders.

Rapid implementations of UVGI include the installation of stand-alone and upper-room devices. These systems would require low effort for installation since they would not be installed in HVAC systems. An example of a stand-alone deck-mounted UVGI device can provide air disinfection for 20,000 cubic feet at six-room air exchanges per hour for approximately \$17,000. Upper-room and bulkhead-mounted devices can treat a 3,800 cubic-foot room at six air exchanges per hour for approximately \$4,000. The costs do not include labor or peripheral considerations (BuyUltraviolet.com n.d.).

Long-term design considerations include the installation of UVGI into the ships’ ventilation systems. Navy ships have multiple, redundant, and decentralized ventilation systems and are considerably different from that in an office building. The level of effort needed for installation, plus the use of mercury vapor lamps inside HVAC systems, would require additional testing and evaluation by NAVSEA. Monitoring systems would also need to be installed to ensure that UVC light sources are properly working and making sure that no ozone is introduced into the ventilation system, though that is highly unlikely.

The application of UVGI for Navy ships is not intended to replace any existing HVAC components or filters. Navy ships’ HVAC systems have dramatic variance regarding size and complexity, but short-term solutions can be deployed immediately.

Immediate action is needed now for reducing COVID-19 exposure at sea since this is crucial for both sailor and operational mission requirements. Two critical recommendations are as follows:

- Commercial-off-the-Shelf (COTS) UVGI ventilation equipment needs to be installed aboard all deploying ships.
- Develop execution plans based on a multi-disciplinary system engineering methodology to sustainably deploy UVGI ventilation equipment aboard all Navy and Coast Guard ships and submarines across their full life cycles.

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I. INTRODUCTION

A. BACKGROUND

Ships at sea have been crippled by respiratory disease outbreaks, such as SARS-Cov-2, the virus which causes Corona Virus Disease -2019 (COVID-19). These shipboard epidemics can impact operational readiness, crew health, and international perception of naval strength. Medical departments on the United States naval vessels can be quickly overwhelmed by infected patients and can force ships to divert to a safe port to obtain medical care for impacted crew members. Close-quarter conditions aboard ships may spread infection rapidly through aerosolized diseased particles or large droplet transmission. The air aboard ships needs to be cleaned of pathogens and given the same priority as surface disinfection in common places.

The nuclear-powered aircraft carrier, USS *Theodore Roosevelt* (CVN 71), suffered one of the first public and serious outbreaks of COVID-19 aboard a naval vessel after visiting a port in Vietnam during the spring of 2020. The outbreak resulted in 1,271 of 4,779 crew members becoming infected with COVID-19 (U.S. Navy 2020). The median age of USS *Theodore Roosevelt*'s crew was 27 years old and all members of the ship's crew met U.S. Navy standards for duty at sea (Kasper et al. 2020). The outbreak infected everyone equally, without regard to race, rank, or sex. Crew members who worked in weapons bays or engineering rooms, where working conditions were more confined, had higher percentages of testing positive. Most of the ship's crew did not experience severe symptoms. Twenty-three crew members needed hospitalization (1.7%), four crew members were admitted to intensive care (0.03%), and one crew member died of cardiovascular complications due to COVID-19 (Kasper et al. 2020). The *New England Journal of Health* cited a study that crew members with pre-existing conditions, such as medically managed asthma, lung disease, hypertension, and liver-related disease, suffered more severe symptoms (Kasper et al. 2020).

Airborne infections are not unique to COVID-19. Tuberculosis (TB) outbreaks have occurred on U.S. Navy ships previously. In 1987, a TB outbreak aboard USS Saipan

(LHA 2) infected 24.6% of the crew (Distasio and Trump 1990). An investigation found that the ship's closed ventilation system contributed to the outbreak.

A severe COVID-19 outbreak on the civilian cruise ship, the Diamond Princess occurred with 3,711 passengers and crew aboard. 700 passengers and crew were infected and nine passengers died (Moriarty 2020). The Diamond Princess incident is critical in the study of airborne transmission aboard ships and relates to the spread of COVID-19 via droplets or by aerosol. Spreading by droplets is defined as the transmission of the virus via respiratory droplets that are generally greater than 5–10 micrometers and spreading by aerosol is defined as the transmission of the virus through particles smaller than 5 micrometers (Jayaweera et al. 2020). Aerosol transmission is generally spread rapidly in enclosed spaces, or in areas where personnel are in close contact with each other for extended periods of time (World Health Organization 2020). The Centers for Disease Control and Prevention (CDC) and WHO had issued previous statements that COVID-19 transmission was primarily from large droplets (D'Ambrosio 2021).

COVID infections spreading at sea are an ongoing problem, as shown by news reports as of this final writing (NPR 2021). A Norwegian Cruise Lines vessel with over 12 infection cases arrived in New Orleans, with health officials struggling to respond effectively. No short-term resolution is expected, especially with Omicron variants rapidly spreading. The need for UVGI techniques to reduce infection rates at sea remains a vitally needed capability.

In a statement addressed to the World Health Organization (WHO) (Morawska and Milton 2020), 239 researchers and scientists signed a letter stating that COVID-19 can be spread through aerosol transmission or microdroplets (smaller than 5 μm). These microdroplets can travel in the air for tens of meters. Diseased particles this small may be capable of traveling throughout the HVAC and infecting crew and passengers (ASHRAE 2020a). The Diamond Princess cruise ship did not have medical-grade HEPA filters installed to filter its air supply (Allimadi 2021).

In late 2021, WHO stated that aerosolized COVID-19 cannot be ruled out (World Health Organization 2021). Virology researchers and scientists from several disciplines

recommend that ventilation systems should be cleaned via “supplemental general ventilation with airborne infection controls such as local exhaust, high-efficiency air filtration, and germicidal ultraviolet lights” (Morawska and Milton 2020, 2312).

Ultraviolet light is a proven means of providing supplemental disinfection against bacteria, germs, and viruses, including COVID-19 (VanOsdell 2002); (Heilingloh et al. 2020). UVGI air and surface disinfection are currently used in hospitals, prisons, schools, large office buildings, homes and on some cruise ships lines

Commercial applications of UVGI air disinfection are in increasing use and development. Use of these UV light sources includes disinfection of surfaces and disinfection of devices used in medical equipment. Commercial use of UVGI air disinfection methods may benefit the U.S. Navy and improve the safety of shipboard air supply systems.

B. MOTIVATION

The motivation of this thesis is to reduce sickness for Navy sailors and prevent loss of mission effectiveness aboard Navy ships due to the spread of airborne disease pathogens. A severe outbreak at sea can cause extreme stress on ship personnel and resources. Airborne-related diseases have occurred many times in the past on U.S. Navy ships, including COVID-19, tuberculosis, and influenza infections. In addition to cleaning shipboard air, ultraviolet germicidal irradiation can neutralize some bioterror agents such as anthrax when appropriately applied.

C. OBJECTIVE

With successful UVGI implementation, service aboard ships at sea may provide more airborne disease prevention than onshore systems. The objective of this thesis is to explore the feasibility of the application of ultraviolet germicidal irradiation (UVGI) to clean air aboard U.S. Navy vessels. The primary focus is to review the common methods of UVGI air disinfection that are currently used in office buildings, hospitals, schools, etc. These methods include the installation of UVGI devices in the HVAC systems which may

safely irradiate the air and reduce possible virus transmission. Immediate and long-term implementation strategy for UVGI disinfection will be provided.

D. SCOPE

The primary scope of this thesis pertains to the ventilation systems and room air aboard U.S. Navy ships. The methodology appears applicable to submarines and Coast Guard vessels as well.

Secondly, the scope pertains only to airborne transmission of pathogens. Airborne pathogens include any number of microorganisms that can be transmitted through the air, such as COVID-19 and its variants, influenza, bacteria, and fungi. The scope does not apply to water transmission of diseases, person-to-person contact, contaminated objects, infected surfaces, and other methods of fomite transmission. Fomite transmission refers to germs settling on objects, such as desks, doorknobs, and other surfaces.

E. ORGANIZATION OF THIS THESIS

This thesis is designed to provide a broad overview HVAC system, how ultraviolet germicidal irradiation works and what are the current implementation methods for UVGI to disinfect air systems. Projections determine what is feasible in the short-term and what UVGI will take much longer to implement on naval ships. Recommendations for future research will be given in the concluding chapter on how to proceed with UVGI installation for U.S. Navy ships.

II. HVAC AND UVC PROBLEM SPACE EXPLORATION

A. INTRODUCTION

This chapter provides a general description of heating, ventilation, and air conditioning systems. Next, a background to ultraviolet germicidal irradiation (UVGI) is provided and how ultraviolet light inactivates viruses. Finally, the primary methods of UVGI used in commercial applications are discussed.

For reader clarification, there is a difference in the terminology “disinfection” and “sterilization” (Kowalski and Bahnfleth 2000). The use of the word disinfection implies that there has been a reduction in the number of microorganisms, whereas sterilization is the nearly complete elimination of all microorganisms.

Filtration is the primary means of removing particles from the air, including dust, dirt, lint, and larger debris, generally conducted by a filtration system. The application of UVGI to the ship’s ventilation system does not filter dust, dirt, and debris from the air, so a filtration system is still needed.

Three significant information sources for the understanding of UVGI are the American Society of Heating, Refrigeration and Air Condition Engineers (ASHRAE) and the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA). ASHRAE represents 55,000 members from 130 countries, and REHVA represents more than 100,000 members in 30 countries. These two professional organizations have numerous up-to-date articles and documentation relating to HVAC and UVGI systems written by their members. The third source is the *Ultraviolet Germicidal Irradiation Handbook UVGI for Air and Surface Disinfection* (Kowalski 2009), providing a comprehensive and detailed UVGI system and methodology analysis.

B. HVAC GENERAL DESCRIPTION

The 2006 Surface Ships HVAC manual states “The purpose of heating, ventilating, air conditioning and other environmental control is to maintain a crew that is physically fit and mentally alert and provides an atmosphere that will enable the body to maintain proper

heat balance, air that has sufficient oxygen supply and free from harmful components” (Naval Sea Systems Command 2006, 51–5).

There are three primary systems used in a Navy ship heating, ventilation, and air conditioning system. They include ventilation systems, heating systems, and air conditioning systems. The purpose of the HVAC aboard ships is to prove the distribution of and control of air throughout the ship and these functions are accomplished by the following:

- Supply fresh outside air throughout the ship.
- Exhaust contaminated and stale air from the ship.
- Provide cooled or heated air to various rooms and spaces throughout the ship including messing, berthing, medical, and control spaces as required.
- Control temperature and humidity.
- Provide cooling for electronic systems and to chill potable water through the circulation of chilled water through heat exchangers.
- Control humidity and temperature
- Heat ventilated air and increase temperatures during the heating system.
- Provide air-conditioned cool spaces within the ship (Naval Sea Systems Command 2006)

A U.S. Navy ship’s ventilation system is designed to provide fresh air in accordance with NAVSEA guidance. Ventilation systems also remove smoke and contaminants following a fire. No ventilation-system components designed for killing germs or viruses were encountered during this study.

Ventilation systems are a major part of the HVAC operation. The job of the ventilation is to supply outside air to a ship’s interior while exhausting used air. Proper air quality is achieved by removing contaminants from the indoor air and by diluting it with

fresh air from outside (Persily et al. 2007). Figure 1 shows a typical HVAC shipboard recirculation system.

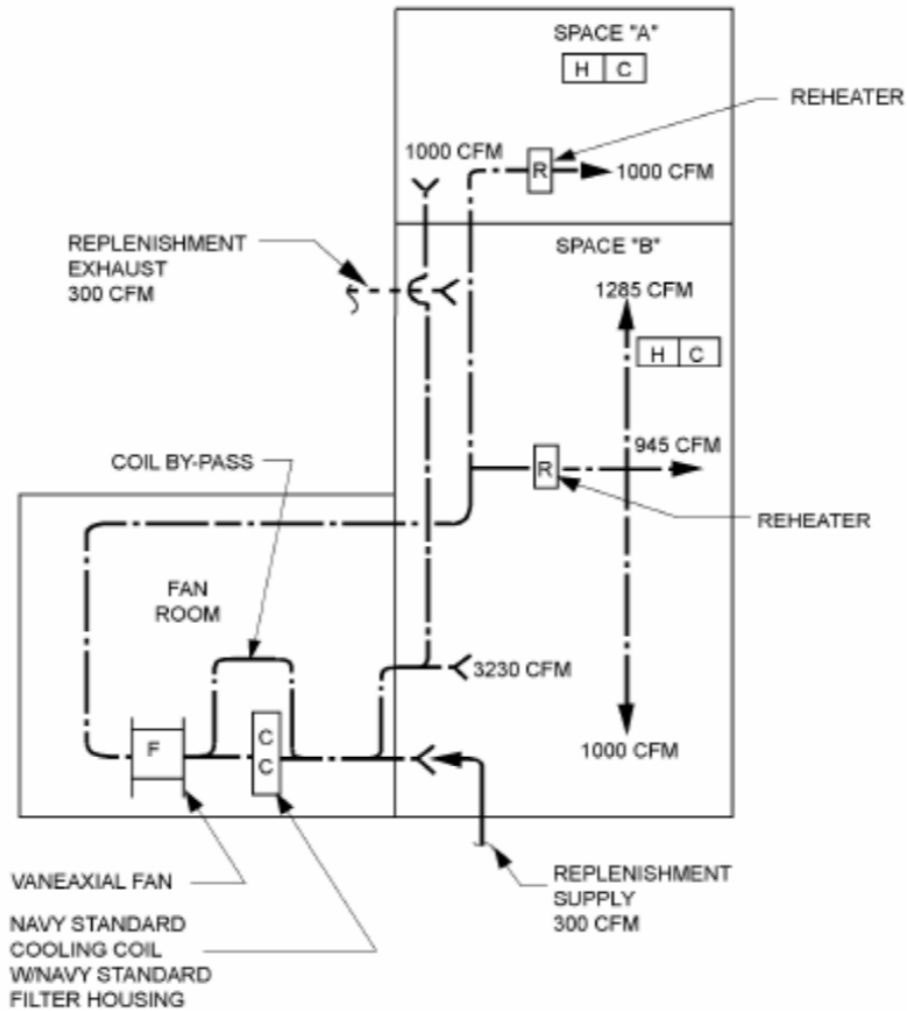


Figure 1. Typical HVAC shipboard recirculation system. The diagram shows that this HVAC system is providing heating and cooling for two different spaces. Individual thermostats control the temperature for each room. Source: Frank and Helmick (2007).

The air in a ship's ventilation system, may or may not be tempered, meaning heated or cooled (Naval Sea Systems Command 2006). Any modifications to a ship's ventilation

system must follow proper approving authority. Modification designs and approval can take years to implement so long-term planning and design needs to begin now.

There are two common types of HVAC systems used in Navy ships. These systems can use mechanical means or natural means to move air through the system. Most systems operate with mechanical ventilation systems by using fans to move air, but natural ventilation systems work by using air pressure differences between outside and inside weather can also help to draw fresh air into the ship. Fresh air is supplied by a ventilation supply air terminal, which helps replenish oxygen, remove carbon dioxide, and particulates. Outside air may include airborne pathogens which can be drawn into the ventilated air system. These pathogens can collect on various surfaces within the HVAC system, but most are intercepted by the HVAC air filtration system.

C. TYPES OF VENTILATION SYSTEMS

The *Navy Ship Technical Manual* describes three types of ventilation systems. These are the supply side, exhaust side and machinery space exhaust systems. Due to ship requirements, the ventilation systems must meet strict NAVSEA requirements for water tightness, air tightness, cleanliness, maintainability, and repairability (Naval Sea Systems Command 2006).

Supply Systems: Bring in fresh outside air and replenish the air to the air-conditioning recirculation systems. The components of the supply systems are weather intake with a screen, an airlift, a preheater, a fan, supply system ductwork and supply terminals. For the purposes of cleaning the air system within the ship, the supply side systems will be the focus.

Exhaust Systems: The purpose of the exhaust system is to remove the old stale, air from the ship and exhaust it overboard. The air that is removed by the exhaust system is replenished by the supply system.

Machinery Space Exhaust: The purpose of machinery space exhaust is to remove the hot air from machinery spaces. If there were no machinery exhaust systems, then this hot air would be forced through compartments in the ship.

D. FANS

The fans are driven by motors and can be operated either by remote or local controls. The supply fans draw in outside air from weather deck inlets and distribute the air through ventilation ductwork that is then distributed throughout the ship. Exhaust fans take the contaminated and stale air from compartments and add heat or chilled air for proper temperature control. The replenished air for recirculating systems is taken from supply-side fans that distribute air toward the recirculation air intake. To supply additional clean air for critical equipment, electrostatic precipitators are used (O'Connor 1982).

E. AIR HANDLING UNITS

The functions of an air handling unit (AHU) are to clean, regulate and circulate air in an HVAC system. Air handling units are used in commercial office structures and surface ships. Navy air handling units are constructed with strong materials to withstand shipboard motion and extreme environments due to heat, cold, humidity, and salty air. There are several subcomponents that make up an air handler (Naval Sea Systems Command 2006).

- Air Handler Fan—moves air through the air handler. The air handler fan is also known as a “blower.”
- Air Filter—cleans the unconditioned air that is drawn in from outside air or recycled interior air. The filtration system in the air handling unit is important since it not only removes dirt and debris from the air but it also prevents dust and dirt from building up within the HVAC on the air handler.
- Heat Exchanger Coil—will heat or cool air by using either a direct heat exchanger or an indirect heat exchanger.
- Control Valve—controls the amount of water or gas that flows through the coil.
- Air Damper—controls the amount of airflow going through the air handler unit.

- Ductwork—while not technically part of the air handler unit, AHUs incorporate ductwork into their design to connect with the ship ductwork. Two types of ductwork are possible, metal and textile material. Figure 2 shows an example of textile ducting.



Figure 2. The purpose of the textile ducting is to distribute air used in HVAC systems aboard U.S. Navy Ships. The ductwork can be either from fire-resistant textile material or galvanized steel or aluminum. Galvanized steel and aluminum may provide higher reflective values for the installation of UVGI lamps. Adapted from Naval Sea Systems Command (2006).

F. FILTERS

The purpose of filters in HVAC systems is to remove particulates from the air system and decrease debris build-up within the system and coil. The efficiency of removing contaminants from the air system affects the ability of airflow through the filter. The higher efficiency rating of air filters will generally require more airflow to push air through the system. It is understood that “Generally, increasing filter efficiency leads to increased pressure drop which can reduce airflow through the HVAC system, more energy use for the fan to compensate for the increased resistance, or both” (ASHRAE n.d.). The Navy uses standard air filters installed in front of cooling fins to prevent the accumulation of foreign material on the coil, which can block airflow and decrease the system’s efficiency over time (Naval Sea Systems Command 2006). There are a variety of standard and disposable type filters approved for shipboard use. Most of these are designed to catch dirt, lint, and larger debris. They act as a pre-filter and are located upstream of other filtration systems such as chemical, biological, radiological (CBR) and (high-efficiency particulate air) HEPA filters in the Collective Protection Systems (CPS).

NAVSEA defines a CPS system as a full-time air filtration system that is integrated into a ship’s HVAC system. The CPS system produces positive pressure in some areas that will keep dirty, contaminated from entering CPS spaces in the event of a chemical outbreak. CPS systems are generally used on Navy combatant ships and are designed to offer additional protection against nuclear, biological, and chemical (NBC) threats (Boerum 1984). Many classes of Navy ships do not have a sophisticated system such as CPS and may use only standard air filtration systems.

Filters are typically classified on their Minimum Efficiency Reporting Values (MERV) on particles 0.3 to 10 microns (μm). ASHRAE has derived a test method based on the MERV rating and when a higher MERV rating is given, the more effective the filter is at trapping specific types of particles (EPA 2021). Table 1 describes MERV ratings and the typical filter type that they are used for.

The ASHRAE MERV ratings is a standardized rating system for filter efficiencies between 0.3 and 10 microns in size. The higher the rating, the better the filter will be at

removing small particles. This system was standardized by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE).

Table 1. MERV ratings are given from lower to higher efficiencies with the size particles that they are designed to filter. The average arrestance refers to the ability of the filter to remove synthetic dust, used to determine the MERV efficiency. Source: NAFA (2018).

MERV Std 52.2	Intended Dust Spot Efficiency Std 52.1 (1)	Average Arrestance	Particle Size Ranges	Typical Applications	Typical Filter Type
1 - 4	<20%	60 to 80%	> 10.0 μm	Residential/Minimum Light Commercial/ Minimum Equipment Protection	Permanent / Self Charging (passive) Washable / Metal, Foam / Synthetics Disposable Panels Fiberglass / Synthetics
5 - 8	<20 to 60%	80 to 95%	3.0-10.0 μm	Industrial Workplaces Commercial Better / Residential Paint Booth / Finishing	Pleated Filters Extended Surface Filters Media Panel Filters
9 - 12	40 to 85%	>90 to 98%	1.0-3.0 μm	Superior/Residential Better/Industrial Workplaces Better/Commercial Buildings	Non-Supported / Pocket Filter / Rigid Box Rigid Cell / Cartridge V-Cells
13 - 16	70 - 98%	>95 to 99%	0.30-1.0 μm	Smoke Removal General Surgery Hospitals & Health Care Superior/ Commercial Buildings	Rigid Cell / Cartridge Rigid Box / Non-Supported / Pocket Filter V-Cells

MERV filters are a candidate technology for the reduction of COVID-19 and are beneficial to UV effectiveness. Studies have shown that MERV 12 filtration systems can be more efficient than a UVGI system (Lee, Bahnfleth, and Auer 2009). However, they provoke an extreme pressure drop and would consequently reduce the existing airflow aboard ships. As a result, they are not considered as an alternative to UVGI equipment in this thesis. Future work considering alternative ventilation system design may be warranted. It should be noted that HEPA filters are not rated under the MERV and ASHRAE 52.2 standards. HEPA filters are rated using the International Organization for Standardization (ISO) standards (ISO 29463-1:2017), which are for high-efficiency filters. These filter types remove fine particles from the air.

G. HVAC FILTER EFFECTIVENESS AGAINST COVID-19

According to ASHRAE, the SARS-CoV-2 virus can be extremely small. COVID-19 may be in respiratory droplets or in droplet nuclei or aerosol may be $\leq 2.5 \mu\text{m}$ in diameter (Nor et al. 2021). Aerosolization can occur sneezing, breathing, coughing or any other forms of human transmission. ASHRAE currently recommends a minimum MERV value of 13 to filter COVID-19 sized particles. A high-efficiency particulate air filter (HEPA) is even more efficient since they are designed to stop 99.7% of particles in the $0.3 \mu\text{m}$ size (ASHRAE n.d.).

H. INTRODUCTION TO UVC

There are three primary electromagnetic wavelengths of ultraviolet light. These wavelengths are UVA (315-400 nm), UVB (280-315 nm), and UVC (100- 280 nm). UVA and UVB wavelengths of UV light are responsible for skin aging and sunburns. (source) Skin Foundation. Figure 3 shows the frequencies and wavelengths in relation to UVC light in the electromagnetic spectrum (UV Resources 2021).

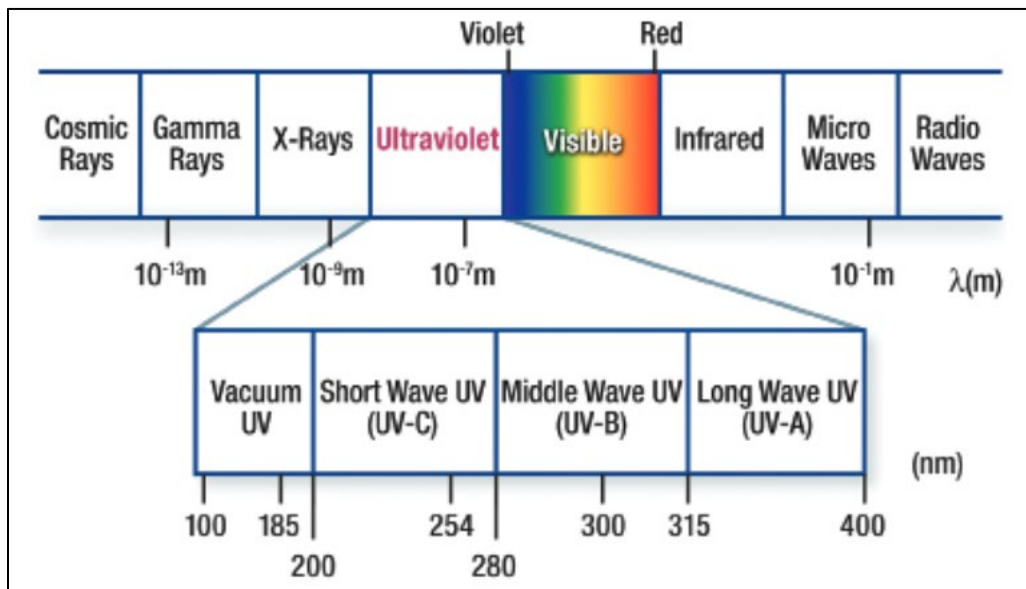


Figure 3. Depiction of the various bands of light in the electromagnetic spectrum illustrates that UVC light has a shorter wavelength than UVB and UVC. UVC exists in the 200–280 nanometer wavelengths. Adapted from UV Resources (2021).

UVC does not reach the Earth's surface at all and only 5% of UVB reaches the earth's surface (WHO 2016). UVA does reach the Earth's surface in sufficient quantities and is responsible for sunburns in humans. UVC light from reaching the Earth's surface Most UVC light on Earth is created by UV light sources and used in commercial applications. Mercury lamps emit approximately 85% of its light at the 253.7 nm wavelength in the electromagnetic spectrum, which makes them an excellent source for producing ultraviolet germicidal irradiation.

UVC is a very effective means of sanitization against many different forms of microorganisms such as mold, bacteria, and fungi. The application of sunlight to at least prevent microbial growth by scientists Downes and Blunt has been understood since 1877 (Reed 2010). Researchers have understood the ultraviolet germicidal effectiveness against bacteria since 1903 (Barnard and Morgan 1903). In 1935, the scientist William F. Wells demonstrated that UVGI could be used to prevent the spread of airborne infection (Reed 2010). Ultraviolet germicidal disinfection is a proven and successful method of providing supplemental disinfection against microorganisms (Kowalski and Bahnfleth 2000). Today, UVGI technology is currently used in hospitals, schools, and a variety of other commercial applications.

I. UVC INACTIVATION OF VIRUSES

A virus is a biological entity with a core of nucleic acids consisting of deoxyribonucleic acid (DNA) or ribonucleic acid (RNA), which are complex molecules, surrounded by a coating of protein, fat (lipid), or glycoprotein. DNA stores unique genetic codes specific to the host, which arranges amino acids into complex proteins, the building blocks of life. RNA functions to convert the genetic information from DNA to build proteins. Figure 4 illustrates the differences between DNA and RNA. DNA has a double-helix formation and RNA is a single-stranded molecule. There are four chemical base pairs that makeup DNA and RNA with the difference being Thymine in DNA and Uracil in RNA.

Differences between DNA and RNA (DNA vs RNA)

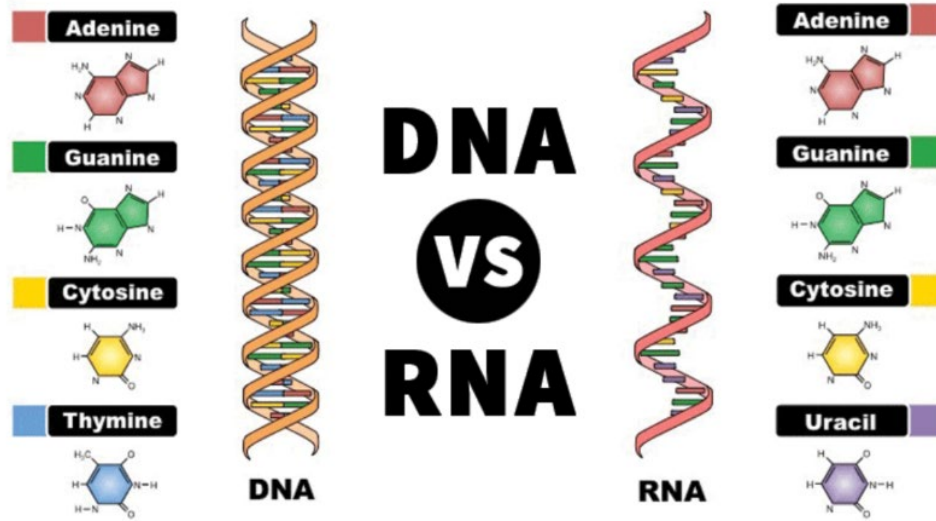


Figure 4. Graphic illustrating differences between DNA and RNA molecules.
Source: Mackenzie (2021).

UVC light when implemented with the appropriate dosage, disrupts the DNA and RNA molecules in viruses, making them inert and harmless (Brickner et al. 2003). Figure 5 shows the process of UVC inactivation of a virus within a cell.

HOW UV-C (UVGI) DESTROYS PATHOGENS

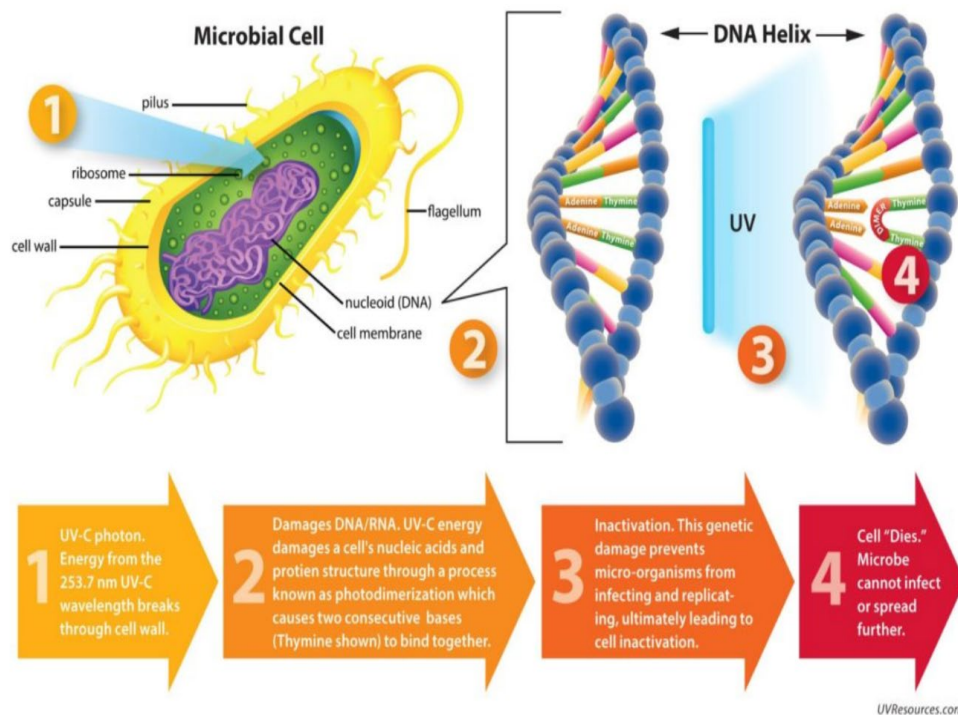


Figure 5. UVC inactivation process of viruses. Graphic shows that UVC light is causing the thymine bonding in DNA, a process called photodimerization. In RNA, uracil bonding occurs when photons of UVC bombard the cell. If there is enough photodimerization bonding taking place inside a cell, the cell is not able to replicate. The wavelength of light that is most absorbed by the capsid protein coating of a virus is at 254 nm, which disrupts the weak hydrogen bonds between the pairs. UVC irradiation causes a dimer bond to form between two consecutive bases in a process known as photodimerization. Source: UV Resources (2021).

Since a virus in scientific terms is not considered to be alive before it infects a host (Villarreal 2008), the term “kills viruses” may be technically inaccurate, which is why virus inactivation is more appropriate. Deactivation and inactivation have similar meanings, but deactivation is used more in an engineering description whereas inactivation is used more in a biological context.

The ultraviolet “k” rate constants define the constant amount of UV dosage required to inactivate a specific microorganism. Different research studies may state different k rates due to the varying environmental factors in a lab, including lamp strength, intensity, and other factors. When reviewing UVC studies regarding the k rates, the UVC irradiation is sometimes tested against viruses in a water-based solution and in other studies, the testing is performed on an aerosolized particle. UVC dosage is measured in joules per meter squared (J/m^2) or millijoules per centimeter squared (mJ/cm^2). UVC intensity is measured in milliwatts per centimeter squared (mW/cm^2) (Canadian Centre for Occupational Health and Safety 2016). Exposure time is measured in seconds. The strength of UVC light that is irradiated on a surface is sometimes called fluence. Irradiance watts are different than electrical watts. The irradiance of a UVC source is a measure of how much specific UVC light falls on a particular object or microorganism at a given distance.

$$\text{Exposure Dosage (J/m}^2\text{)} = \text{UV Irradiance (mW/ m}^2\text{)} = \text{UV Irradiance}$$

$$1 \text{ Joule} = 1 \text{ watt-second}$$

In general, airborne pathogens are easier to kill or inactivate due to several reasons (Hao and Zhong 2021):

1. Water can absorb some UV light, requiring more UVC dosage lethality for microorganisms in the water.
2. Microorganisms are more evenly diffused in the air.
3. Some airborne pathogens are damaged and are made more fragile after they have become aerosolized and expelled into the air.

There are success factors for UVC light to properly inactivate viruses and kill microorganisms. The higher the intensity of the UVC, the more effective the disinfection rate will be. Another success factor is the amount of time that the pathogen is exposed to UVC light. The longer the amount of time, the higher the disinfection rate. In ventilation ductwork, faster-moving air may decrease the exposure time of the virus or pathogen. One

way to increase UVC effectiveness is by installing multiple lamps along the path in the ductwork, to increase exposure time. The critical factors for the lethality of UVC light depend mostly on the intensity of UVC light and exposure time.

When applying UVC lamps for germicidal purposes, the inverse square law of light needs to be understood and taken into consideration. The amount of UV dosage required to successfully inactivate or kill a microorganism is exponentially reduced the further the UVC light away from the microorganism. As distance increases, the intensity of UVC effectiveness decreases considerably. For example, if the UVC lamp is placed three feet away from the coil, it will take nine times as much UV dosage to be effective as it would be at one foot away. If the microorganism is too far away from the UVC light source, it may not receive sufficient UVC irradiation to cause its destruction.

J. INVERSE SQUARE LAW OF LIGHT

As the distance increases between an object and a light source increase, the intensity of the light on the object inversely drops significantly. This is because the photons of light spread apart further as the object is moved away. As an example, the light energy at 4 times the distance is spread over 16 times the area. The inverse square law states that the intensity of light “equals the inverse of the square of the distance from the source” (Energy Education 2017).

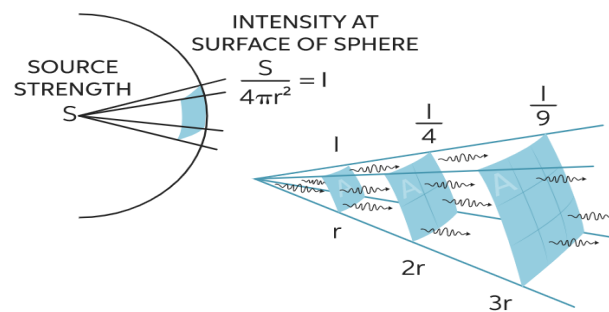


Figure 6. Inverse square law of light relates to UVGI lamps since the farther airborne pathogen is away from the UV light source, the effectiveness of UVC irradiation drops significantly. Source: Chegg (n.d.).

$$\text{Energy} \propto \frac{1}{\text{Distance}^2}$$

To find the intensity for the surface section of a spherical enclosure, the following formula can be used. $4\pi r^2$ is the formula for surface area of sphere.

$$\begin{aligned} I &= \text{Intensity} \\ S &= \text{strength} \end{aligned}$$

$$\frac{S}{4\pi r^2} = I$$

As an example, to find the intensity of a light source that has been moved at a distance of “5r”, the equation can be derived as follows:

$$\frac{S}{4\pi(5r)^2} = \frac{I}{25}$$

Figure 6 illustrates how quickly the intensity of the energy, in this case, UVC light, dissipates the further the intended target is moved away from the UVGI light source. Having the UVGI light source too far away from the pathogens will greatly reduce probably of virus inactivation. The inverse square-law formula and the example given, demonstrate that the intensity of light diminishes inversely proportional to the surface area of a sphere from the UVGI light source.

K. UV MERCURY LAMPS

The most common type of UVGI lamp are mercury lamps, which emit 85% of their light at the 253.7 nm wavelength. These lamps burn mercury in a carefully engineered clear, glass tube, which allows the UV light to radiate outward unfiltered. These lamps have a unique blueish color while they are activated, which is caused by argon gas inside the tube (Fencel 2013). Mercury lamps require lamps ballasts to operate. Lamp ballasts provide sufficient energy that allows the lamp to start up and maintain a steady rate of current. Without a lamp ballast, a mercury lamp “would rapidly and uncontrollably increase its current draw” (NLPIP 2003). A YouTube video showing a mercury lamp

overload with a variable ballast can be found in the reference section (DanTheAwesomeMan 2014).

UVC lamp irradiance is measured in $\mu\text{W}/\text{cm}^2$ (microwatts per square centimeter). This is the amount of electromagnetic radiation produced across a surface area (ISO 2021).

L. UVC LED

Currently, mercury lamps have broader commercial acceptance over UVC LED light sources. Although UVC technology is still expanding and being researched, there are several advantages that UVC LED light emitters have over traditional mercury lamps used in the UVGI industry. UVC LEDs are mercury free which may make them easier to adopt by NAVSEA if the mercury-based lamps are a concern for use in ship ventilation systems. Another advantage is that UVC LEDs can be made waterproof, and this could have several benefits relating to water treatment as well as water may be able to provide an additional source for cooling. LED UVC lamps are ruggedized and shockproof, which can make them perfect for mobile use or in areas where there is a lot of vibration. UVC LEDs have extremely high radiation densities, are ozone free and do not have any heat up times. They also have the advantage of producing multiple UVC wavelengths such as 265, 275 and 278 nm which allows them to have higher germicidal efficiencies for some disinfection purposes. Although UVC LEDs have several clear advantages over mercury lamps, they remain relatively expensive and are currently not mass produced yet. UVC LEDs appear to be an effective alternative to the more fragile mercury-based lamps. The material for this section was based on the information provided by Fraunhofer IOSB, a German based company that specializes in advanced UV LED technologies. It should be noted that although very promising, UV LEDs may not currently produce enough 254 nm UV light in sufficient quantities, for proper air disinfection.

M. SAFETY CONCERNS

The primary issues with UVC safety come from exposure to UVC light (NEA 2021). UVC, when appropriately used, is safe, and is used worldwide in many hospitals, office environments, or wherever disinfection is needed. Most UVC exposures can be

limited since they may be installed inside HVAC equipment or in devices that do not emit UVC light toward personnel.

UVC can cause skin erythema, which is redness of the skin. This is the same condition as sunburn from UVB sunlight exposure. Due to the shorter wavelengths of UVC (200-280 nm), as compared to UVB (280-315 nm), UVC will cause less sunburn than regular sun exposure (Brickner, Vincent et al. 2003). This is due to the fact that UVC is almost totally absorbed by the stratum corneum in the skin layer.

According to the FDA, UVC exposure can cause eye and skin burns, blurred or double vision, headaches, and nausea (FDA 2021). Personnel should not be exposed directly to UVC light. Powerful UVC lamps used in hospitals for surface disinfection, often have a movement sensor that deactivates the device if someone walks into the room.

Looking directly at UVC light can result in photokeratitis, leading to temporary blindness and causing eye inflammation. Photokeratitis is similar to “snow blindness” and occurs when the eye is exposed to ultraviolet rays. Photokeratitis usually clears in 24 to 48 hours (Brickner, Vincent et al., 2003).

Some UVC mercury lamps may emit small amounts of ozone. Ozone is a byproduct of some UVC lamps since a small percentage of the electromagnetic radiation given off by UVC lamps is around 185 nm. Ozone is a known irritant and can cause coughing, difficulty breathing, nasal irritation, headaches, asthma attacks and may worsen chronic respiratory diseases

Figure 7 shows that many mercury lamp manufacturers use a protective coating over the quartz glass to prevent mercury spillage and mercury vapor from escaping.



Figure 7. The picture shows a broken mercury lamp that is still safe to handle. Mercury lamp UVC manufacturers use a protective system that covers the quartz glass material. Should the mercury lamp break, the glass fixture or mercury inside the lamp will not escape because it is encased in a special safety shield. This process allows mercury lamps to be safely used in many different applications. Source: Amorite (2021).

Mercury lamps use an electric discharge through argon which ignites mercury vapor to produce UVC light. Mercury lamps may release mercury vapor if broken. While mercury lamps are generally safe and currently used in commercial ducting systems, the mercury and mercury vapor contained in the lamps may qualify them as a hazardous material which could lead to accreditation delays for use in Navy ships. The amount of mercury in most UVC germicidal mercury lamps is very minimal, and the mercury vapor will dissipate quickly. The EPA states that the amount of mercury in UVC lamps is less than 1/100th of the mercury that is contained in a thermometer and “not to be alarmed” during the cleaning process, even if mercury exposure did occur (EPA Guidance on Cleaning CFLs 2021).

N. PHOTODEGRADATION CONCERNS

Exposure to UVC light can photodegrade some petroleum-based materials such as rubber and other petroleum-based products. If upper-room UVGI lamps are installed in a

space, consideration needs to be given since photodegradation may produce cracking and brittleness with petroleum-based products such as seals, filters, gaskets, wiring and insulation. ASHRAE states that:

Although UV-C photodegradation is of concern, with the selection of the proper material or metallic shielding of other components, the problem is significantly reduced, and components can be expected to meet product design life. As a simple, practical approach, it is wise to shield all organic material components within about 5 feet of the UV lamp. (ASHRAE 2020b, 17.7)

O. POSSIBLE COVID-19 TRANSMISSION THROUGH HVAC SYSTEMS

COVID-19 is thought to be primarily spread by large respiratory droplets within 6 feet of an infected individual (Centers for Disease Control and Prevention 2019). Some doubt remains as to whether COVID-19 can travel through an HVAC system, including filters, coils and many meters of ductwork, and then cause an infection. In a Harvard study (Azimi et al. 2021), 21,600 modeling scenarios were simulated showing the transmission routes for the COVID-19 outbreak aboard the Diamond Princess Cruise Ship. The primary findings from the study indicated that 59% of small respiratory aerosols possibly contributed to disease transmission and only 41% of the large droplets were responsible for infections, which contradicts the prevailing theory of how the epidemic was spread on the cruise ship. Researchers indicated that infected passengers were most likely infected due to proximity and by aerosolized transmission, not by the circulation of larger droplets. The transmission of COVID-19 through the Diamond Princess HVAC system is still disputed by other research studies (Xu et al. 2020), but it does remain plausible that infection from the SARS-Cov-2 virus traveled through the ventilation system and caused infections to the ship's passengers and crew.

The Environmental Protection Agency (EPA), as with most organizations and agencies, is cautious with affirming the spread of COVID-19 through HVAC systems. EPA guidance on this matter refers to the statements released by ASHRAE. ASHRAE has released the following statement regarding the transmission of SARS-CoV-2 through HVAC systems:

Airborne transmission of SARS-CoV-2 is significant and should be controlled. Changes to building operations, including the operation of heating, ventilating, and air-conditioning systems, can reduce airborne exposures. (ASHRAE 2020a)

Ventilation and filtration provided by heating, ventilating and air conditioning can reduce the airborne concentrations of SARS-CoV-2 and thus the risk of transmission through the air. Unconditioned spaces can cause thermal stress to people that may be directly life-threatening and that may also lower resistance to infection. In general, the disabling of heating, ventilating, and air conditioning systems is not a recommended measure to reduce the elimination of the virus. (ASHRAE 2020a)

REHVA, which is the European equivalent to ASHRAE, provided a little more detail on its position as to whether COVID-19 can travel through HVAC systems and cause infections REHVA (2020).

The size of coronavirus particle is 80–160 nanometre² and it remains active at common indoor conditions up to 3 hours in indoor air and 2–3 days on room surfaces (unless there is specific cleaning). Such small virus particles stay airborne and can travel long distances carried by airflows in the rooms or in the extract air ducts of ventilation systems. Airborne transmission has caused infections of SARS-CoV-1 in the past; currently there is no reported evidence yet specifically for Corona disease (COVID-19) infection via this route. One indication for this: Coronavirus SARS-CoV-2 has been isolated from swabs taken from exhaust vents in rooms occupied by infected patients. This mechanism implies that keeping 1–2 m distance from infected persons might not be enough and increasing ventilation is useful because of the removal of more particles. (REHVA 2020, 6–2)

The predominant view on infectious aerosol transmission may be changing. The overwhelming view of virologists is that aerosolized pathogens are primarily spread by large droplets. Some research states that there is no evidence to support this. The primary means of transmission may be through small-particle aerosols rather than by large droplets (REHVA Guidance Document 2020).

P. DROPLETS/ AEROSOL TRANSMISSION

Viruses can be transmitted in several ways including large droplets, aerosols, or direct contact. These disease transmission paths are not mutually exclusive with one another (Tellier 2006). Large droplets usually settle within a few seconds and are greater

than 10–20 μm in size. The current guidance to maintain social distancing standards of 6 feet apart was based on the well-known Wells evaporation curve (Wells 1934). This study researched the effect of relative humidity, the velocity of the air, and respiratory jets and became the accepted view for many years, of airborne transmission by large droplets. The Center for Disease Control states, as of May 2021, that infectious exposure can occur through “inhalation of air carrying very small fine droplets and aerosol particles that contain an infectious virus” (Centers for Disease Control and Prevention 2021a).

Aerosols are “suspensions in the air (or in gas) of solid or liquid particles, small enough that they remain airborne for prolonged periods because of their low settling velocity” (Tellier 2006, 1657). Biological aerosol particles, such as a virus, can be ≤ 2.5 μm in diameter when they become airborne (Nor et al. 2021). Depending on the size of the particle diameter, they may lodge in different areas of the body when they are breathed in. These particles may end up in the head airways and upper and lower respiratory tracks within the body (Baron 2010). Disease pathogens, such as viruses, can be aerosolized from an infected person by coughing, sneezing, or breathing. Aerosolized pathogenic particles can remain in the air for hours if they are small enough, and a single SARS-CoV-2 particle, 0.09 μm in size, can remain in the air for hundreds of hours. However, the average size of respiratory fluid particles containing SARS-Cov-2, which is approximately 9.3 μm , means they will generally remain in the air for seconds or minutes (Lee 2020). Figure 8 demonstrates the different air suspension times for respiratory droplets depending on the length of the particle. The size of respiratory particles can be reduced after being exhaled from an infected individual due to water evaporation on the surface of the particles (Friedlander 2000). Viruses, such as SARS-Cov-2, can be distributed in clusters inside respiratory droplets, nonhomogeneous, and this can contribute to variation in particle size (Lee 2020).

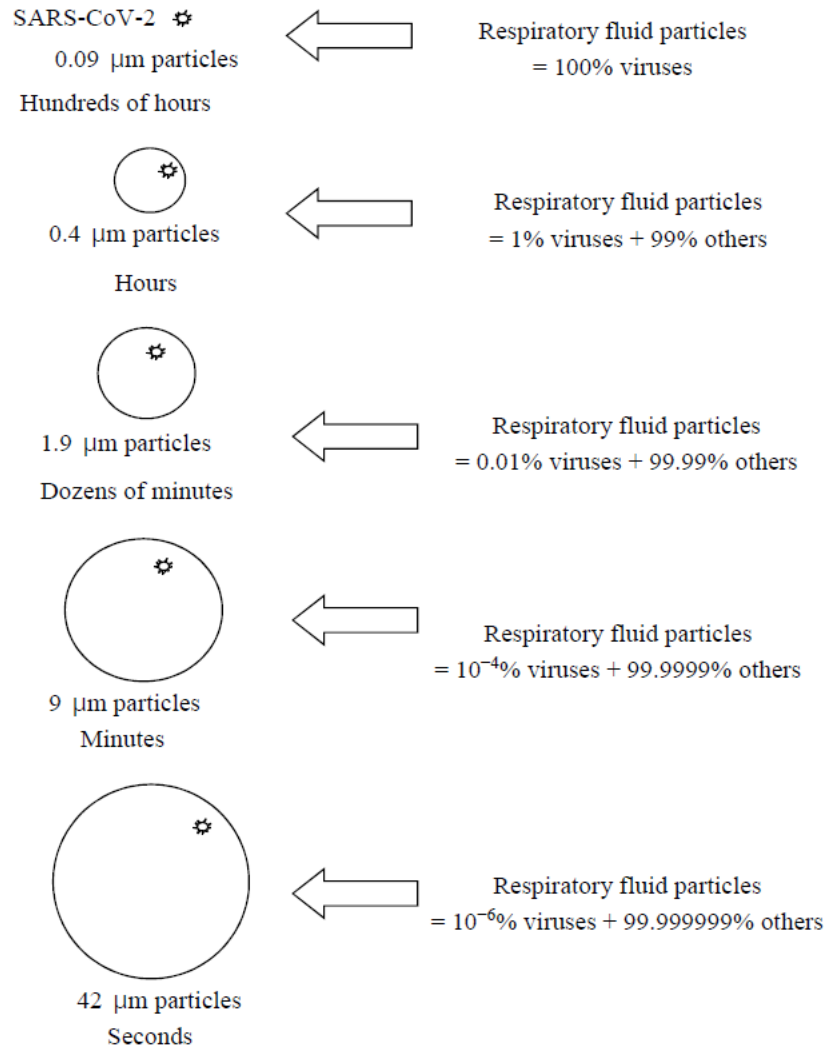


Figure 8. Estimated air suspension times for particles, assuming homogeneous distribution, containing SARS-Cov-2. Source: Lee (2020).

Q. COVID-19 EXPIRATION DECAY TIME ESTIMATION

Figure 9 illustrates the half-life times of SARS-CoV-2 and SARS-CoV-1, which is an exponential decay process. SARS-CoV-2 has an approximate half-life of 1.1-1.2 hours as an aerosol which is similar to SARS-CoV-1 (Doremalen et al. 2020). In the REVHA article (REVHA 2020), research indicated that COVID-19 could be active as an aerosol for

up to 3 hours in indoor air and be viable on surfaces for 2–3 days. An article in the *New England Journal of Medicine* concerning COVID-19 survival times attests that:

Our results indicate that aerosol and fomite transmission of SARS-Cov-2 is plausible since the virus can remain viable and infectious in aerosols for hours and on surfaces up to days (depending on the inoculum shed). These findings echo those with SARS-CoV-1, in which these forms of transmission were associated with the nosocomial spread and super-spreading events, and they provide information for pandemic mitigation efforts. (Doremalen et al. 2020)

SARS-CoV-2 and SARS-Cov-1 have similar survival times when aerosolized. Although similar, there are several differences between the two regarding epidemiology. SARS-CoV-2 can be transmitted when an infected individual is asymptomatic, and SARS-CoV-2 has “high viral loads in the upper respiratory tract” (Doremalen et al. 2020).

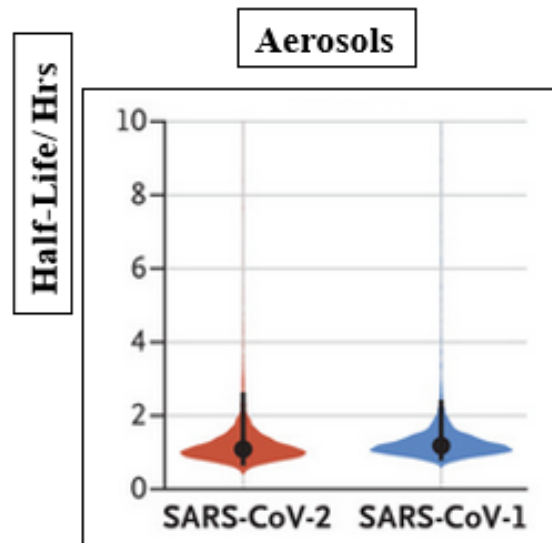


Figure 9. The violin plots indicate the lower measured distribution for the half-life of SARS-CoV-1 and SARS-CoV-2. Survival rates are very similar for both. The black lines indicate that there is a 95% certainty for half-life times. Adapted from Doremalen et al. (2020).

R. AIR EXCHANGE RATES

The number of times that the air within a space is replaced is known as the air exchange rate. Air exchange rates remove the diseased air out of a space, so the more frequently that the air is removed and replaced, the better. Since cubic feet per minute (CFM) is expressed in minutes, it is necessary to multiply by 60. The formula for air changes per hour can be expressed by:

Air Changes Per Hour = Room CFM x 60 ÷ Room Volume in Cubic Feet (area x height)

S. UVC EFFECTIVENESS AGAINST COVID 19

The use of ultraviolet germicidal irradiation for inactivation of SARS-CoV-2, the virus which causes the COVID-19 disease, has been proven successful by the scientific community. ASHRAE, REVHA, IUVA, the CDC and EPA all support the use of UVC light sources in the fight against COVID-19 in relation to aerosolized transmission.

The ASHRAE Technical Committee 2.9 on UVGI effectiveness against airborne SARS-Cov-2 states the following:

Despite eight decades of peer-reviewed scientific research proving the air airstream disinfection efficacy of germicidal UV-C, there remains doubt that UV-C can inactivate airborne pathogens. The members of TC 2.9 hope this pandemic has left no doubt the 254 nm germicidal wavelength can inactivate the genetic material in the SARS-Cov-2 virus. Moreover, when aerosolized, SARS-CoV-2 is likely to be more susceptible to UV-C damage than other coronaviruses such as SARS-CoV-1 (that led to the 2003 severe acute respiratory syndrome) or MERS-CoV (that caused the 2012 Middle East Respiratory syndrome). (ASHRAE 2021)

The International Ultraviolet Association (IUVA) states that the dosage values using 10–20 mJ/cm² in comparable viruses have been proven to have a 99.9% disinfection rate with a wavelength at 254 nm. However, IUVA recommends higher dosage values to ensure disinfection since direct UVC exposure is required, and some viruses might be partially hidden or in the shadows when not directly exposed to UVC lighting (IUVA 2021).

T. UVGI EFFECTIVENESS AGAINST BIOWEAPONS

Research has shown that ultraviolet germicidal irradiation, when the appropriate dosage of UVC is applied, can have some success at destroying or inactivating all microorganisms including those used for bioweapons, including anthrax, botulism, plague, smallpox, tularemia, and viral hemorrhagic fever (Brickner et al. 2003).

Potential value for UVGI is its effectiveness as a prevention method against a biological weapon attack on a ship's ventilation system. If appropriately applied to the ventilation system or in a room area aboard a ship, UVGI may be able to disinfect the air from such unexpected agents.

Bio-engineered weaponized microorganisms used for biological warfare are usually more resilient and hardier than other similar bacteria since adversaries require them for this benefit. A study on bioterrorism concerns stated that "a review of the literature revealed that *B. anthracis* Sterne spores may be three or four times more resistant to 254-nm wavelength UV than are spores of commonly used indicator strains of *Bacillus subtilis*" (Nicholson, Wayne, and B. Galeano 2003, 1327). *Bacillus subtilis* is a commonly used model bacterial species used in laboratory studies (Earl, Losick and Kolter 2008). The durability of anthrax spores also makes them effective in being transmitted in aerosolized form, which might be potentially introduced in the atmosphere surrounding Navy ships.

Bioweapons can be tolerant to extreme conditions. Research evidence shows that anthrax, botulism, the plague, and other bioweapon agents have been neutralized by UVC light in a lab. In device testing of UVC and HEPA air purifiers by Dr. Wladyslaw Kowalski, he and his team were able to test its effectiveness against several bioweapons including anthrax, smallpox, botulinum toxin, the Ebola virus and plague simulated estimates were computed using computer modeling and analysis (Kowalski 2015). Two airflow measurements were conducted for such testing. One test was done by applying a UV dosage of 35.5 J/m^2 at 50 cfm and the other was for 5.22 J/m^2 at 340 cfm. The UVC bulb was approximately 7 inches long with 19 W of power input and 6 W of UV output. The lamp rating specification is $55 \text{ } \mu\text{W/cm}^2$. By using a combination of UV and HEPA filtration, the removal rates of 8 different bioweapons were achieved at 99.999% for 50

cfm and even the much higher 340 cfm produced 99.998% removal of the pathogens. Table 2 demonstrates how different airflow rates affect the amount of UVC dosage a pathogen will receive. With an air velocity of 340 cfm, an organism will receive approximately 5.22 J/m² as compared to 35.50 J/m² with a slower velocity. To compensate for the higher air flow rates, more UVGI lamps will need to be placed along the path (Kowalski 2015). The results in Table 3 provide examples for UV exposure on several bioagents although for some microbes, high UV kill rates were not achieved.

Table 2. Airflow vs. UV Exposure Time. Adapted from Life Enthusiast.
Adapted from Kowalski (2015).

Airflow	50	cfm	340	cfm
Irradiance	95.256	W/ m ²	95.256	W/ m ²
Exposure Time	0.372689156	Sec	0.054807229	sec
UV Dose	35.50	J/m ²	5.220	J/m ²
UVGI Rating Value	14		10	

Table 3. This table demonstrates the effects of UVC on different airborne pathogens for different bioweapons. Adapted from Kowalski (2015).

Microbe/Agent	UV D90 J/ m ²	UV K m ² / J	UV Kill Rate %	Diameter microns	HEPA Removal %	Total Removal %
Airflow 50 cfm						
Mycobacterium tuberculosis	5	0.4271	100.00	0.637	100.0000	100.0000
Bacillus Anthrax	85	0.02702	61.68	1.118	100.0000	100.0000
Variola (smallpox)	26	0.055561	95.69	0.224	99.9516	99.9979
Ebola virus	28.4	0.081	94.36	0.09	99.9950	99.9997
Yersinia pestis	24	0.095941	96.68	0.7	100.0000	100.0000
Airflow 340 cfm						
Mycobacterium tuberculosis	5	0.4271	100.00	0.637	100.0000	100.0000
Bacillus Anthrax	85	0.02702	13.16	1.118	100.0000	100.0000
Variola (smallpox)	26	0.088561	37.02	0.224	99.9516	99.9979
Ebola virus	28.4	0.081	34.48	0.09	99.9950	99.9997
Yersinia pestis	24	0.095941	39.40	0.7	100.0000	100.0000

The testing procedures were done in a lab through computer simulations and by analyzing existing research. Real scenarios of UVGI effectiveness against bioweapons might be quite different and could give an overly optimistic success rate. When UVGI and HEPA were combined, near sterilization rates occurred against bioagents. Table 4 evaluates the UV dosage required to inhibit colony growth at 90% for different microorganisms. In many studies, researchers will list the 90% exposure (10%) rate. This is due to the assumption that the full graph can be reconstructed by drawing a straight line from the coordinates “100% – 0 exposure to the 10% survival-experimentally determined value” (First, Nardell, Chaisson, and Riley 1999, 872). Table 4 also provides the testing medium (air or plates) used in the research. In general, ultraviolet exposure is much more effective against aerosolized microbes than microbes in water.

Because the log scale representing survival fraction never goes to zero, total kill is theoretically impossible; although, as a practical matter, when survivors become few, it becomes difficult to distinguish that condition from total kill. At the other end of the exposure spectrum, it is not possible to confirm with statistical certainty that very low doses have no lethal effect.

Table 4. UVGI effectiveness on microorganisms in relation to exposure, decay rate, type, and test medium, which is the lethal dose that kills 90% of the colony (LD₉₀) and 10% survival. Adapted from Brickner et al. (2003).

Microorganism	(H) Radiant exposure $J \cdot m^{-2}$	(K) Decay rate constant $m^2 \cdot J^{-1}$	Reference	Type	Test medium
<i>Bacillus anthracis</i>	45.2	0.051	Sharp 1938 ⁷⁰	Bacteria	Air
<i>Bacillus anthracis</i> (spores)		0.0031	Knudson 1986 ³⁶	Bacteria	Plates
<i>S. enteritidis</i>	40.0	0.058	Dreyer et al. 1936 ⁷¹	Bacteria	Plates
<i>B. megatherium</i> sp. (veg.)	37.5*	0.061	Hercik 1937 ⁷²	Bacteria	Plates
<i>B. megatherium</i> sp. (spores)	28.0	0.082	Hercik 1937 ⁷²	Bacteria	Plates
<i>B. paratyphosus</i>	32.0	0.072	Dreyer et al. 1936 ⁷¹	Bacteria	Plates
<i>B. subtilis</i> (mixed)	71.0	0.032	Rentschler et al. 1941 ⁷³	Bacteria	Air
	60.0	0.038	Koller 1939 ⁷⁴	Bacteria	Air
<i>B. subtilis</i> spores	120.0	0.019	Rentschler et al. 1941 ⁷³	Bacteria	Air
<i>Corynebacterium diphtheriae</i>	34.0	0.068	Sharp 1938 ⁷⁰	Bacteria	Air
		0.0701	Sharp 1939 ⁷⁵	Bacteria	Plates
<i>Salmonella typhi</i> (<i>Eberthella typhosa</i>)	21.4	0.108	Sharp 1938 ⁷⁰	Bacteria	Air
<i>Micrococcus candidus</i>	60.5	0.038	Ehrismann et al. 1932 ⁷⁶	Bacteria	Plates
<i>Micrococcus piltonensis</i>	81.0	0.028	Rentschler et al. 1941 ⁷³	Bacteria	Air
<i>Micrococcus sphaeroides</i>	100.0	0.023	Rentschler et al. 1941 ⁷³	Bacteria	Air
<i>Neisseria catarrhalis</i>	44.0	0.052	Rentschler et al. 1941 ⁷³	Bacteria	Air
<i>Agrobacterium tumefaciens</i> (<i>Phytopomonas tumefaciens</i>)	44.0	0.052	Rentschler et al. 1941 ⁷³	Bacteria	Air
<i>Proteus vulgaris</i>	27.0	0.085	Rentschler et al. 1941 ⁷³	Bacteria	Air
<i>Pseudomonas aeruginosa</i>		0.2375	Collins 1971 ⁷⁷	Bacteria	Plates
		0.5721	Sharp 1940 ⁷⁸	Bacteria	Air
	55.0	0.042	Ehrismann et al. 1932 ⁷⁶	Bacteria	Plates
<i>B. pyocyaneus</i>	55.0	0.052	Ehrismann et al. 1932 ⁷⁶	Bacteria	Plates
<i>Pseudomonas fluorescens</i>	35.0	0.066	Ehrismann et al. 1932 ⁷⁶	Bacteria	Plates
<i>S. typhimurium</i>	80.0	0.029	Dreyer et al. 1936 ⁷¹	Bacteria	Plates
<i>Micrococcus luteus</i> (<i>Sarcina lutea</i>)	197.0	0.012	Rentschler et al. 1941 ⁷⁶	Bacteria	Air
<i>Serratia marcescens</i>	24.2	0.095	Rentschler et al. 1941 ⁷⁶	Bacteria	Air
	22.0	0.105	Sharp 1938 ⁶²	Bacteria	Air
	8.3	0.277	Ehrismann et al. 1932 ⁷⁶	Bacteria	Plates
		0.2208	Collins 1971 ⁷⁷	Bacteria	Plates
		0.214	Riley 1976 ⁷⁹	Bacteria	Air
		0.4449	Sharp 1940 ⁷⁸	Bacteria	Air
<i>Dysentery bacilli</i>	22.0	0.105	Dreyer et al. ⁷¹	Bacteria	Plates
<i>Shigella paradysenteriae</i>	16.8	0.137	Sharp 1938 ⁷⁶	Bacteria	Air
<i>Rhodospirillum rubrum</i> (<i>Spirillum rubrum</i>)	44.0	0.052	Rentschler et al. 1941 ⁷³	Bacteria	Air
<i>Staphylococcus albus</i>	18.4	0.125	Sharp 1938 ⁷⁰	Bacteria	Air
	33.0	0.070	Rentschler et al. 1941 ⁷³	Bacteria	Air
	18.4	0.125	Rentschler et al. 1941 ⁷³	Bacteria	Air

(Table 4 continued)

Microorganism	(H) Radiant Exposure $J \cdot m^{-2}$	(K) Decay Rate Constant $m^2 \cdot J^{-1}$	Reference	Type	Test Medium
<i>Staphylococcus aureus</i>	21.8	0.106	Gates 1929/1930 ⁸⁰	Bacteria	Plates
	49.5	0.047	Ehrismann et al. 1932 ⁷⁶	Bacteria	
		0.0886	Sharp 1939 ⁷⁵	Bacteria	Plates
		0.3476	Sharp 1940 ⁷⁸	Bacteria	Air
		0.0419	Abshire 1981 ⁸¹	Bacteria	Plates
<i>Streptococcus pyogenes</i> (<i>Streptococcus hemolyticus</i>)		0.9602	Luckiesh 1946 ¹⁵	Bacteria	Air
	26.0	0.089	Sharp 1938/39 ^{70,75}	Bacteria	Air/Plate
	21.6	0.107	Sharp 1938 ⁷⁰	Bacteria	Air
		0.6161	Lidwell 1950 ⁸²	Bacteria	Plates
		0.1066	Misterlich 1984 ⁸³	Bacteria	Air
<i>Streptococcus lactis</i>	61.5	0.037	Rentschler et al. 1941 ⁷³	Bacteria	Air
<i>Streptococcus viridans</i>	20.0	0.115	Sharp 1938 ⁷⁰	Bacteria	Air
<i>Clostridium tetani</i>	49.0	0.047	Sharp 1939 ⁷⁵	Bacteria	Plates
<i>Streptococcus salivarius</i>	20.0	0.115	Sharp 1939 ⁷⁵	Bacteria	Plates
<i>Streptococcus albus</i>	18.4	0.125	Sharp 1939 ⁷⁵	Bacteria	Plates
<i>B. prodigiosus</i>	8.3	0.329	Ehrismann et al. 1932 ⁷⁶	Bacteria	Plates
<i>Mycobacterium tuberculosis</i>		0.0987	David 1973 ⁸⁴	Bacteria	Plates
		0.4721	Riley 1976 ³³	Bacteria	Air
		0.2132	Collins 1971 ⁷⁷	Bacteria	Plates
	100.0	0.023	Prospect Philips ⁸⁵	Bacteria	Plates
		0.0364	David 1973 ⁸³	Bacteria	Air
<i>(Tubercle bacillus)</i>		0.0406	David 1973 ⁸⁴	Bacteria	Air
<i>Mycobacterium avium-intra.</i>		0.0927	Sharp 1939 ⁷⁵	Bacteria	Plates
<i>Escherichia coli</i>		0.3759	Sharp 1940 ⁷⁹	Bacteria	Air
<i>Haemophilus influenzae</i>		0.0599	Mongold 1992 ⁸⁶	Bacteria	Plates
<i>Adenovirus</i>		0.0546	Jensen 1964 ³⁴	Virus	Air
		0.0047	Rainbow 1973 ⁸⁷	Virus	Plates
<i>Vaccinia</i>		0.1528	Jensen 1964 ³⁴	Virus	Air
		0.1542	Galasso 1965 ⁸⁸	Virus	Plates
<i>Coxsackievirus</i>		0.1108	Jensen 1964 ³⁴	Virus	Air
<i>Influenza A</i>		0.1187	Jensen 1964 ³⁴	Virus	Air
<i>Cryptococcus neoformans</i>		0.0102	Wang 1994 ⁸⁹	Fungal spores	Plates
<i>Fusarium oxysporum</i>		0.0112	Asthana 1992 ⁹⁰	Fungal spores	Plates
<i>Fusarium solani</i>		0.00706	Asthana 1992 ⁹⁰	Fungal spores	Plates
<i>Penicillium italicum</i>		0.01259	Asthana 1992 ⁹⁰	Fungal spores	Plates
<i>Penicillium digitatum</i>		0.00718	Asthana 1992 ⁹⁰	Fungal spores	Plates
<i>Rhizopus nigricans</i> spores		0.00861	Luckiesh 1946 ¹⁵	Fungal spores	Air
<i>Cladosporium herbarum</i>		0.00370	Luckiesh 1946 ¹⁵	Fungal spores	Air
<i>Scopulariopsis brevicaulis</i>		0.00344	Luckiesh 1946 ¹⁵	Fungal spores	Air
<i>Mucor mucedo</i>		0.00399	Luckiesh 1946 ¹⁵	Fungal spores	Air
<i>Penicillium chrysogenum</i>		0.00434	Luckiesh 1946 ¹⁵	Fungal spores	Air
<i>Aspergillus amstelodami</i>		0.00344	Luckiesh 1946 ¹⁵	Fungal spores	Air

U. BACTERIAL SPORE RESISTANCE TO UVC

Nearly all bacteria and viruses can be destroyed or inactivated by UVGI exposure (Kowalski and Bahnfleth 2000). In the evaluation of UVGI effectiveness against bioweapons, bacterial spores are extremely resilient to UVC irradiation. A bioweapon research study stated that “these spores are also significantly more resistant than their corresponding cells to 254 nm radiation with spores generally being 5- to 50-fold more

resistant” (Setlow 2021, 97). It is recommended to use high-efficiency filters in conjunction with UVGI systems for the elimination of all spores (Kowalski and Bahnfleth 2000).

V. CHAPTER SUMMARY

UVGI is a successful means of inactivating viruses and microorganisms, including COVID-19, tuberculosis, and other airborne pathogens. UVC is capable of neutralizing biological warfare agents such as anthrax and bacterial spores, however, bioweapons may require significantly higher UV irradiance and exposure times for complete sterilization. The use of UVC in commercial systems is well known, documented, and safe. COVID-19 can travel distances farther than 6 feet due to its small size when aerosolized. There is still ongoing scientific debate of whether COVID-19 can travel throughout ventilation systems and cause infections, but this scenario remains plausible.

III. UVGI AIR DISINFECTION METHODS

A. INTRODUCTION

This chapter will review common UVGI air disinfection strategies mainly used in commercial industries. These are all safe and successful commercial-off-the-shelf (COTS) systems that have been in a wide variety of applications. The intent is to offer an overview of what is currently used in the civilian sector to ultimately see if these same systems are feasible for use in small and large classes of naval ships.

B. COMMERCIAL APPLICATIONS OF UVGI

Commercial UVGI systems are successfully being implemented in office buildings, schools, hospitals, shelters, prisons, and clinics. The four primary methods of using UVGI to commercial clean ventilated air are:

- UVGI upper-room devices
- Application of UVGI inside air handling units
- Application of UVGI to in-duct ventilation
- Portable or deck-mounted room air purification units.

The Federation of European Heating, Ventilation and Air Conditioning Associations states that the two advantages of using UVC devices in ventilation systems are 1) they help clean air handling unit components, such as filters and cooling coils, and 2) they reduce the spread of airborne pathogens in ventilation systems with recirculation, which can save energy (Lungu 2020). Given the size and scope of U.S. naval vessels, specialized software is needed for correct UVGI ventilation determination.

The CDC recommends a “layered strategy” to reduce exposure to pathogens. The “layered” strategy incorporates proper use of face masks, physical distancing, cleaning and disinfection, hand hygiene and ventilation strategies. A ventilation strategy to reduce sickness includes “opening windows, using fans, adding high-efficiency particulate air

filters (HEPA) fan/ filter systems, and adding upper-room ultraviolet irradiation” (Centers for Disease Control and Prevention 2021b).

C. UPPER ROOM UVGI

Upper-room UVGI systems have been recommended by the Center for Disease and Control and Prevention (Centers for Disease Control and Prevention 2021b) as one method of disinfecting the air in an indoor setting. These are bulkhead-mounted devices and have been used employed since the 1950s to combat airborne pathogens such as tuberculosis. Upper-room UVGI devices are usually installed approximately seven feet above the deck and irradiate their UVC light upward at an angle, away from people. The UV-C light is pointed upward, usually with louvers, to prevent the UVC light from irradiating downward to persons in the room. Some of these devices may also include a fan to help circulate the air. As an example, if an infectious person coughs, sneezes or exhales contagious pathogens, some of these pathogens may be aerosolized. With an upper-room UVGI system, those tiny pathogenic particles would float upward and into the UVC light, which will then become inactivated and harmless. Figure 10 shows an upper-room UVGI device that irradiates airborne pathogens in the airstream as they travel through the UVC disinfection zone. Upper-room UVGI could be very effective at providing air disinfection in a variety of room spaces including a hospital room, as shown in Figure 11.

The CDC recommendation for a room of 500 square feet in size, is to use approximately two or three of these devices for adequate air disinfection (Centers for Disease Control and Prevention 2021b), but vendor’s specifications should be followed. If there is already sufficient HVAC filtration or sufficient outdoor airflow in the room or area, then the CDC notes that upper-room UVGI devices may not add much benefit. As a reminder, the photodegradation property of UV-C could affect plastics, rubber gaskets, wiring, etc., in the room, if they are exposed and irradiated by the upper-room device UV-C lamp.

The CDC states that upper-room UVGI devices can be used for any room with at least an eight-foot ceiling, but notable areas of application are:

- Areas where sick people are likely to congregate such as hospital waiting rooms, doctors' offices, etc.).
- Crowded spaces such as meeting rooms, hallways, offices, engine rooms, weight rooms, etc.
- Galleys, lunch areas, where people may remove their masks to eat or talk.
- Any crowded space where it is difficult to maintain social distancing.

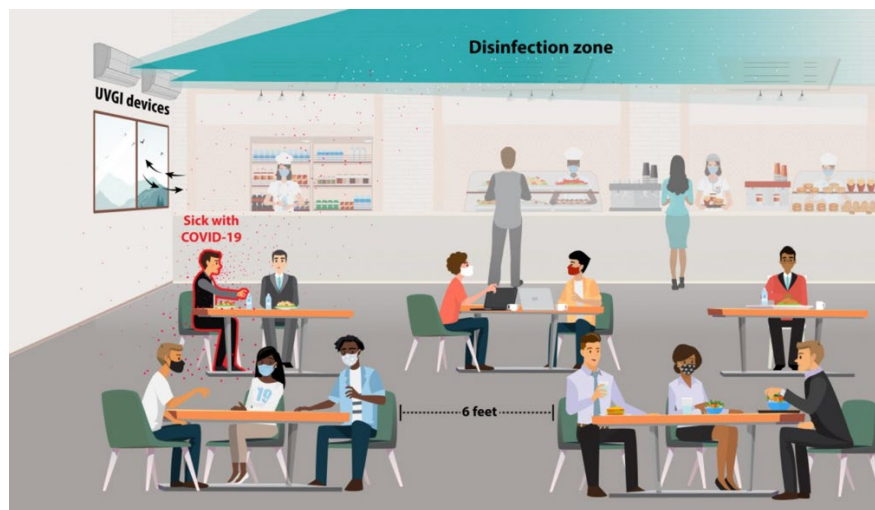


Figure 10. Aerosolized particles from an infectious person spread throughout a room. These airborne pathogens can stay aloft in the room for some time before settling. Air currents can carry these tiny respirator particles into the UVC disinfection zone where they will be inactivated with UVC germicidal light. Source: Centers for Disease Control and Prevention (2021b).

UVGI has been successfully used since the 1930s (Wells, Wells, and Wilder 1942) against a wide variety of pathogens. The CDC recommends the use of UVGI devices for the control of tuberculosis. Pulmonary tuberculosis (TB), which is a bacterium and not a virus, is also an airborne pathogen. TB can be passed from person to person when an infected person coughs, sneezes or speaks. People who pass through areas of TB disease particles in the air can become infected. TB droplets are usually in the form of very small

water droplets and can remain in the air for several hours (Centers for Disease Control and Prevention 2019).



Figure 11. Photo of an upper-room UVGI device used in a hospital room. UVGI systems have been used to disinfect the air inside rooms where tuberculosis patients have resided. Louvers on the UVC device unit reflect the UVC light up and away from any pathogens present in the room. It is important to follow device safety instructions by placing these units 7 or 8 feet above the deck. Source: Chang (2020).

D. UVGI IN HVAC AIR HANDLING UNITS (AHU)

Wet, humid conditions in air handling units (AHUs) can cause bacteria and mold to accumulate on the coil when goes into a drain pan. Mold and bacteria can slowly create a biofilm which makes the air handling less efficient and disperses pathogens into the air stream. Many of these airborne pathogens are too small to be stopped by the AHU primary filter and they can travel through the ventilation system, into the ductwork and throughout the various rooms and compartments inside a ship. If the filter is too restrictive, this creates a significant pressure drop on one side, making the HVAC system inefficient. As the moisture from the coil inside the AHU cools, it turns into water, which collects into a drain pan. This water can collect mold and bacteria as well, if not properly drained.

ASHRAE (2019) states that the specific benefits of coil cleaning are to:

1) Reduce the amount of time needed to clean the coil, 2) Reduce or eliminate bacteria and mold build-up on the coil and 3) Maintain performance parameters of the coil unit.

The Air Movement and Control Association International (AMCA) and ASHRAE recommend placing UV lamps upstream of the HVAC coil for air-stream disinfection and UV downstream of coil for coil maintenance and cleaning if space is available, to clean the air traveling through the system and to keep the coil clean of bacteria and mold. Monitoring devices will be needed to ensure ozone is not released into any air ventilation system. In high-quality commercial UVGI systems, the release of ozone is zero or very minimal; however, ozone monitoring devices are recommended if mercury lamps are used. Figure 12 shows UVGI light sources installed in an air handling unit. Note that UVGI lamps can be installed both downstream and upstream of the coil. Figure 13 shows possible UVGI installation locations for a Navy ship HVAC system.

The estimation for cleaning one squared meter (10.76 square feet) of HVAC coil is a 36-inch high-output 80-Watt mercury lamp. By dividing the lamp wattage of 80 watts by 10.76 square feet, this yields 7.43 lamp watts per square feet. By using an approximation of 85" in height and 120" in width, this gives us a total of 10,200 square inches. To get square feet, we would divide this by 144 inches, giving a surface area of 70.8 square feet. Multiplying 70.8 square feet by 7.43 lamp watts will require 526 watts to properly irradiate the coil to prevent bacterial and mold buildup on each coil.

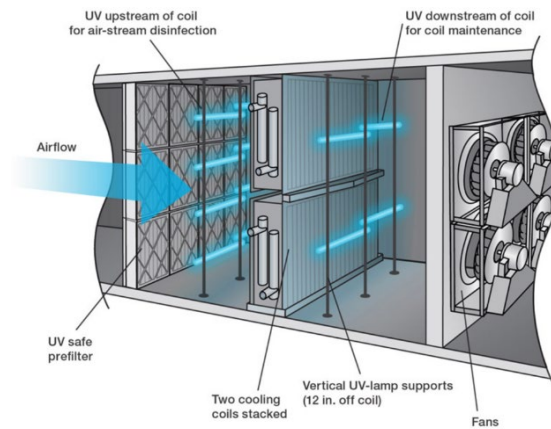


Figure 12. This illustration shows a commercial air handling unit. UVC lamps are installed in front of the coil to prevent bacterial growth. UVC can also be installed downstream of the filter to provide air disinfection of airborne pathogens if any disease particles pass through. Source: Jones and Ivanovich (2020).

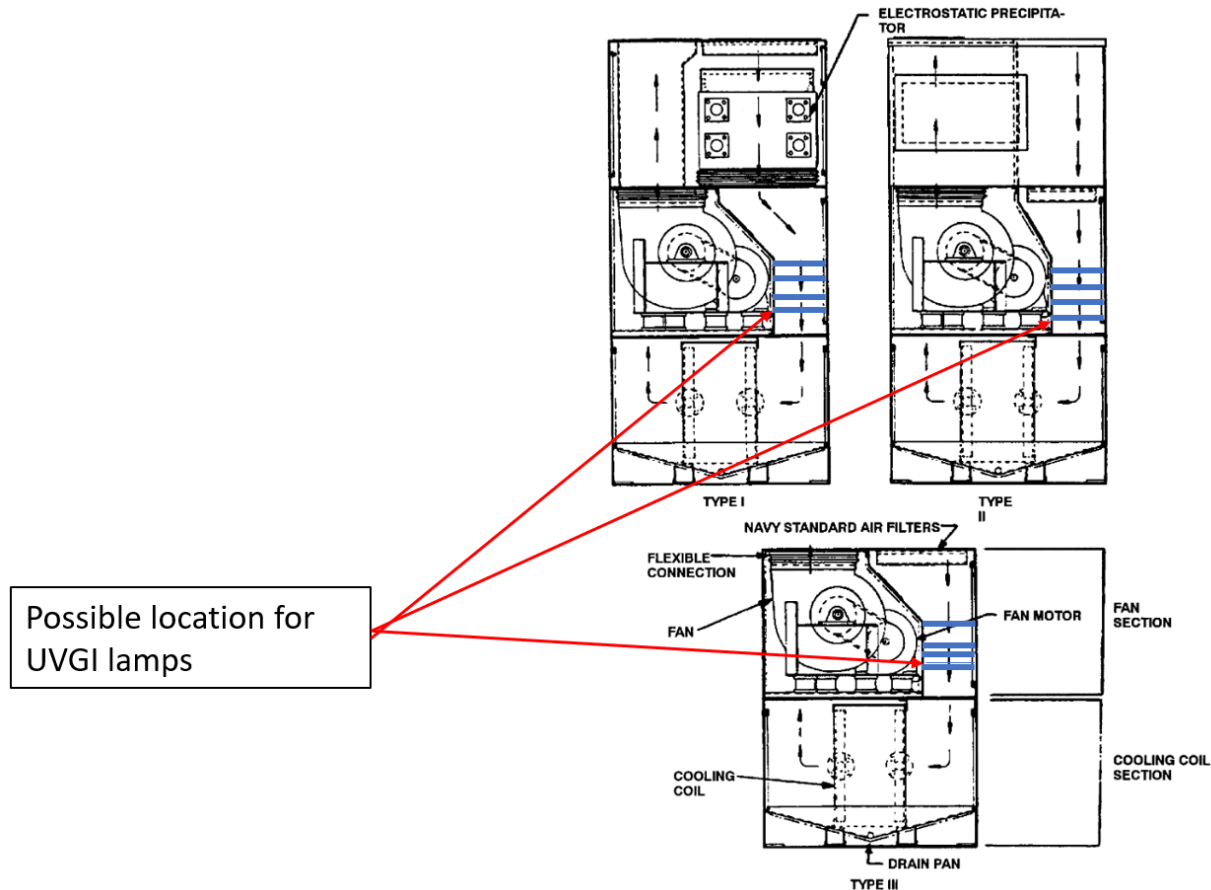


Figure 510-4-3 Fan-Coil Assemblies (Sectional) Type I, II, and III Airflows

Figure 13. UVGI lamps could be placed in line with fan coil assemblies. These systems would require a greater level of effort as compared to traditional commercial air handling units since there are multiple, redundant systems. Future design considerations for HVAC systems should include UVGI implementation as part of a long-term air disinfection strategy. Adapted from Naval Sea Systems Command (2006).

E. UVC AIR PURIFICATION UNITS FOR RAPID DEPLOYMENT

UVC air purification units can be mounted on the deck, attached to bulkheads, or be moved around a room on wheels. These units operate by drawing in room air and passing it through powerful UVC lamps internally inside the unit. The air is then disinfected with germicidal UVC light, and clean air is circulated into the room. These types of units may

work in conjunction with HEPA-grade air filters to remove fine particles and dirt, but some UVC air purification units just have UVC lamps to disinfect the air of COVID-19 and other airborne pathogens. For potential deployment aboard a large Navy vessel, it appears that installation of a Sanitaire RM2680 (or similar) in a ship's fan room looks promising.

The suggested test scenario in the ship's fan has a total area of 2,000 thousand cubic feet. We are concerned about dirty COVID-19 diseased air being drawn into the ship's ventilation and infecting the crew while at sea. By using commercially available UVC air purifiers, the devices are moved into the desired space. The wheels can be removed, then the unit is bolted to the deck and connected to ship's power. There may need to be some additional consideration of protecting the device, due to sea spray but this can be mitigated with some covering material. This type of UVC air purification can be operated with personnel in the room, since the UVC lamps are all internal. Installation could be extremely fast and implemented almost immediately with the appropriate approving authority. The example air purifier can treat a 20,000-cubic-foot room at six-room air changes per hour, which is significantly more than the amount needed, ensuring proper disinfection capability. The device in Figure 14 demonstrates one of the larger COTS stand-alone UVGI air purifiers and this one measures 70.875" x 33" x 31" in height, length and width.



Figure 14. Sanitaire RSM2680 Mobile Air Sanitizer can be secured to the deck or bulkhead. This model provides 6 air exchanges per hour for 20,000 cubic feet using UVC lamps and is safe for occupants. Source: BuyUltraviolet.com (n.d.)

F. UVGI IN-DUCT SYSTEMS

UVGI lamps can be installed in duct systems located in the air handling units or further downstream of the AHUs to disinfect ventilated air as it passes through the ductwork. There are many factors that determine the successful inactivation of viruses and microorganisms traveling through the ducting systems. Among these are air temperature, flow rate, lamp design, and ballast design (VanOsdell and Foarde 2002). The benefits of UVGI installed in the ductwork are improved air quality, increasing the life of the HVAC filters, and decreasing the transmission of airborne pathogens throughout the ship.

There are several configurations for UVC lamps within in-duct systems. Lamps can be mounted in parallel or perpendicular to the air stream. Higher velocities of air traveling through the duct system reduces exposure time for pathogens. Design engineers or the commercial vendor need to take this into consideration to achieve proper effective

inactivation. It should be noted that an access door may be required for in-duct systems to provide support and maintenance. A safety switch can be installed to turn the UVGI lamps off when there is a maintenance operation for inspecting or replacing the UVGI equipment or lamps.

For example, a 2 to 3 meter/ second airflow might be able to achieve 99% inactivation but an 8 to 9 meter/second air velocity rate through the ductwork may require a significant level of effort to ensure proper irradiation of the disease. Figure15 shows a typical installation design for in-duct UVGI lamps providing air disinfection of airborne pathogens traveling through the ductwork.

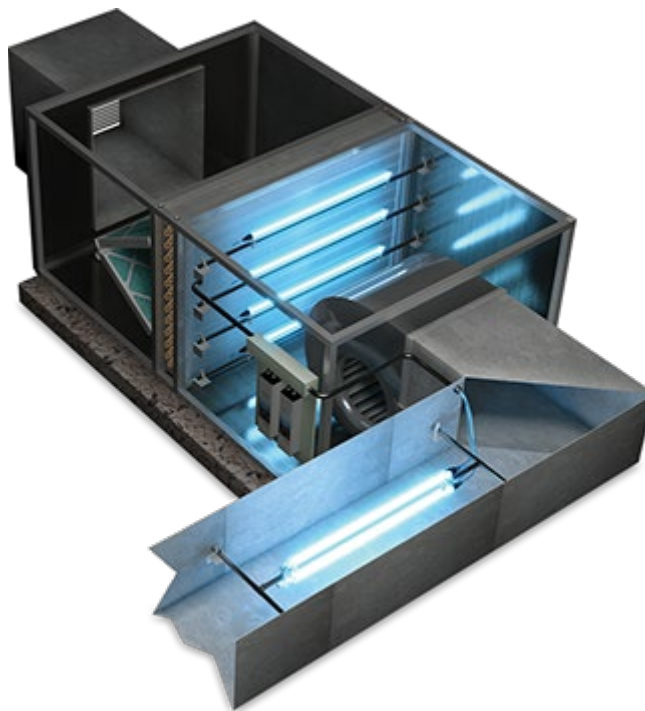


Figure 15. Illustration of UVGI lamps inside an air-duct system. Source: Edison Air Purifiers (n.d.)

How well the UV air disinfection performs depends on the dosage of the UVGI light in the airstream. In order to quantify the dosage, the exposure time of the microorganism and the average irradiance of the ventilation duct needs to be considered. To calculate exposure time, the dimensions of the ductwork will be calculated with the

airflow measurements. Ships design engineers must consult all appropriate authoritative references to determine correct coefficients for the specific equipment and ventilation configuration of interest. Numbers such as 10 % per hour or better would be an excellent outcome. Other future designs might include characteristics as necessary deliverables for contracted equipment. Of related note is that all ships already have excellent estimates for how much time is required to remove smoke and contaminants from the ship's atmosphere. Such calculations can be used as a cross-check confirmation for estimated effectiveness for COVID-UVGI removal. The formula and methodology from (Kowalski 2009) are used to calculate the UVGI removal rate inside ductwork:

$$E_t = \frac{Vol}{Q} = \frac{WHL}{Q}$$

where:

E_t = exposure time in seconds
 Vol = volume of the UV Chamber, m³
 Q = airflow m³/s
 W = width, m
 H = height, m
 L = length, m

$$RR = 1 - e^{-kI_mE_t}$$

where:

RR = removal rate, fraction or %
 k = UV rate constant, m²/J
 I_m = mean irradiance, W/m²

For the above example, it estimated that volume of the ducting is 100 m³. The airflow velocity is 50 m³/s which gives an E_t of 2 seconds. The UV constant rate k for a type of Coronavirus is 0.377, the mean irradiance I_m is 7.5 watts. The removal rate would yield:

$$0.996 = 1 - e^{(-0.377)(7.5)(2)}$$

If a filter is used in combination with a UV system, the removal rate increases significantly. For example, if a filter removal rate is 0.95 and the UV system removal rate is 0.996, the increased removal rate percentage would be as follows:

$$R_T = 1 - (1 - R_F)(1 - R_U)$$

$$0.9998 = 1 - (1 - 0.95)(1 - 0.996)$$

where:

R_T = Total Removal Rate

R_F = Removal Rate of Filter

R_U = Removal Rate of UV system

The Kowalski *UVGI Handbook* states that mean irradiance is the “key to estimating UV air performance” (Kowalski 2009, 178). Figures 16 and 17 are graphs demonstrating mean irradiance in relation to three power levels and the reflectivities of two common types of ducting material, polished aluminum, and galvanized steel. Table 5 gives the mean irradiance for duct length. The “p” values in Table 5 indicate three reflectivity values and UVP is UV power as measured in watts. By using Table 5, the mean irradiance for ducting systems can be calculated based on the measured length of the ductwork. An example, adapted from Kowalski 2009), is given that a mercury lamp rated at 100 W is installed in 10 meters of ductwork, with an air velocity of 500 fpm, what would be the UV dosage needed? To solve this, the efficiency of the UV lamp needs to be known. Kowalski states that a typical UV lamp is about 31% efficient. By multiplying 100 W by a 31% efficiency rate, this gives a value of 31 W. The ducting in our example uses untreated surface aluminum with p=50% value. By using Table 5, it is determined that 10 meters of duct length at 20 W equals 10.9 J/m² and 40 W at 10 meters equals 21.9 J/m². To find out the value for 30 UV power (UVP), 10.9 J/m² and 21.9 J/m² are averaged to yield a value of 16.4 J/m² of UV energy needed.

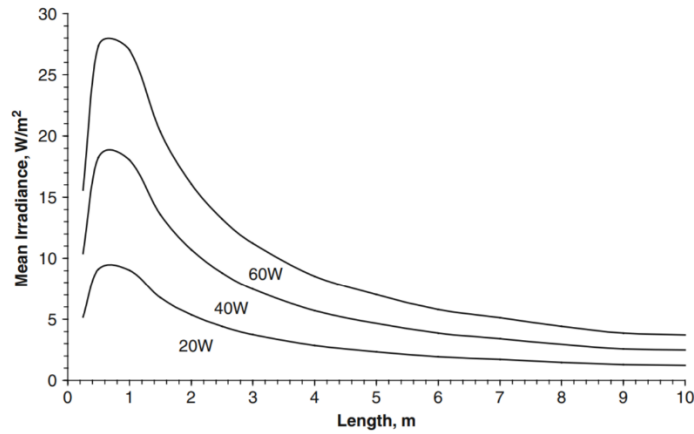


Figure 16. Mean irradiance vs. length, at three power levels, for a one square meter duct, 0% reflectivity. Source: Kowalski (2009).

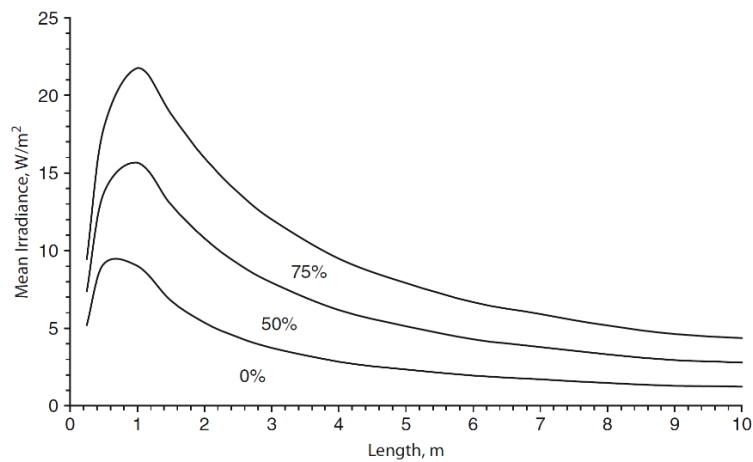


Figure 17. Mean irradiance vs. length, for polished aluminum 75% reflectivity, galvanized steel 50% at three different power levels. Source: Kowalski (2009).

Table 5. UV exposure dose for a square duct (face area = 1 m²), with a ventilation system operating at 2.54 m/s (500 fpm). Source: Kowalski (2009).

Table 8.3 UV exposure dose for a square duct
unitary square-sided duct, Face Area = 1 m²

Duct length		E _t sec	UVP W	D, J/m ² ρ = 0%		D, J/m ² ρ = 50%		D, J/m ² ρ = 75%	
m	ft			URV	URV	URV	URV		
0.5	1.6	0.20	20	1.8	8	2.7	9	3.5	9
1	3.3	0.39		3.5	9	6.2	10	8.6	10
1.5	4.9	0.59		4.0	9	7.7	10	11.1	11
2	6.6	0.79		4.2	9	8.5	10	12.6	11
2.5	8.2	0.98		4.3	9	9.0	10	13.5	11
3	9.8	1.18		4.4	9	9.4	10	14.2	11
4	13.1	1.57		4.5	9	9.7	10	14.9	11
5	16.4	1.97		4.6	9	10.1	11	15.6	12
6	19.7	2.36		4.6	9	10.1	11	15.8	12
7	23.0	2.76		4.7	9	10.5	11	16.3	12
8	26.2	3.15	40	4.6	9	10.4	11	16.3	12
9	29.5	3.54		4.6	9	10.5	11	16.5	12
10	32.8	3.94		4.9	9	10.9	11	16.9	12
0.5	1.6	0.20		3.6	9	5.4	10	7.0	10
1	3.3	0.39		7.1	10	12.3	11	17.1	12
1.5	4.9	0.59		8.0	10	15.4	12	22.2	13
2	6.6	0.79		8.4	10	17.0	12	25.2	13
2.5	8.2	0.98		8.7	10	18.0	12	27.1	13
3	9.8	1.18		8.8	10	18.7	12	28.4	13
4	13.1	1.57		9.0	10	19.5	12	29.9	13
5	16.4	1.97	9.2	10	20.2	13	31.2	14	
6	19.7	2.36	60	9.1	10	20.3	13	31.6	14
7	23.0	2.76		9.4	10	20.9	13	32.6	14
8	26.2	3.15		9.3	10	20.9	13	32.7	14
9	29.5	3.54		9.3	10	20.8	13	32.7	14
10	32.8	3.94		9.7	10	21.9	13	34.4	14
0.5	1.6	0.20		5.4	10	8.1	10	10.5	11
1	3.3	0.39		10.6	11	18.5	12	25.7	13
1.5	4.9	0.59		12.0	11	23.0	13	33.3	14
2	6.6	0.79		12.6	11	25.5	13	37.7	14
2.5	8.2	0.98		13.0	11	27.0	13	40.6	15
3	9.8	1.18	13.3	11	28.1	13	42.6	15	
4	13.1	1.57	13.4	11	29.2	13	44.8	15	
5	16.4	1.97	80	13.8	11	30.3	14	46.8	15
6	19.7	2.36		13.8	11	30.4	14	47.4	15
7	23.0	2.76		14.0	11	31.4	14	48.9	15
8	26.2	3.15		13.9	11	31.3	14	49.0	15
9	29.5	3.54		14.0	11	31.2	14	49.1	15
10	32.8	3.94		14.3	11	32.9	14	51.5	16
0.5	1.6	0.20		7.2	10	10.8	11	14.1	11
1	3.3	0.39		14.2	11	24.7	13	34.3	14
1.5	4.9	0.59		16.0	12	30.7	14	44.4	15
2	6.6	0.79		16.9	12	34.0	14	50.3	16
2.5	8.2	0.98	17.3	12	36.1	14	54.1	16	
3	9.84	1.18	80	17.7	12	37.5	14	56.8	16
4	13.12	1.57		17.9	12	38.9	14	59.8	16
5	16.4	1.97		18.4	12	40.4	15	62.4	17
6	19.7	2.36		18.3	12	40.6	15	63.1	17

Determining lamp strength in relation to the UVGI disinfection goal is at times difficult to determine due to multiple variances, including pathogen resilience, temperature, humidity, reflective values of materials and the shadowing effect where microorganisms may be partially hidden by other organisms or structures. In an air stream,

moving pathogens must have enough exposure and intensity to a UVC light source(s) to be inactivated. One way to increase germicidal UV lighting inside ducting systems is by using reflective materials. Table 6 provides the reflectance values of certain materials inside ducting systems which can improve UVC success in destroying microorganisms (VanOsdell and Foarde 2002).

Table 6. Reflectance Values for Common In-Duct Materials

Material	Reflectance
Aluminum, untreated surface	40- 60%
Stainless steel plate	25-30%
Typical duct liner	1%

G. UVGI VENTILATION STUDY

In a 2003 study (Menzies et al. 2003), 771 participants took place in a double-blind, crossover trial. The purpose of the research was to see if UVGI lights installed in office ventilation systems contributed to worker's health and well-being. The methodology consisted of a 48-week trial with UVGI being turned on and off several weeks at a time with health questionnaires given to active participants.

The results indicated a 99% surface reduction of microbial and endotoxins on the surfaces irradiated within the ventilation systems with UVGI turned on, compared to UVGI turned off. It was estimated in the study that 25–30% of airborne pathogens were reduced. This may seem like a modest reduction but there was a noticeable decrease in worker symptoms. The reasons for UVGI being successful, even though the airborne disinfection rates were not high were presumed as follows:

In view of the modest reduction in worksite airborne concentrations, how could UVGI have led to decreased symptoms? UVGI reduced the growth of fungi and bacteria previously associated with sinusitis, asthma, humidifier fever, and hypersensitive pneumonitis. Also, endotoxin

production was eliminated almost entirely, which has been associated with influenza-like or respiratory symptoms and changes in lung function. An alternate explanation is that UVGI reduces the aerosolization of microbial antigenic proteins. Unfortunately, these were not measured, but this hypothesis is lent support by the greater benefit from UVGI in non-smokers and workers with an atopic history (who have a greater risk for an immune reaction to such antigens) than in others. (Menzies et al. 2003, 1790)

Table 7. Effects of UVGI in office ventilation system on workers' health.
Source: Menzies et al. (2003).

	No symptoms either setting	Symptoms with both settings	Symptoms only with UVGI off	Symptoms only with UVGI on	Odds ratio for UVGI on:off
Work-related*					
Total for all trials†					
Any	614 (40%)	434 (28%)	283 (18%)	212 (14%)	0.74 (0.6–0.9)
Systemic	927 (60%)	171 (11%)	223 (14%)	222 (14%)	0.99 (0.8–1.2)
Mucosal	806 (52%)	301 (20%)	246 (16%)	190 (12%)	0.77 (0.6–0.9)
Respiratory	1429 (93%)	17 (1%)	56 (4%)	41 (3%)	0.73 (0.5–1.1)
Musculo-skeletal	1347 (88%)	37 (2%)	94 (6%)	65 (4%)	0.69 (0.5–0.9)
Before work					
Total for all trials†					
Any	887 (58%)	190 (12%)	205 (13%)	242 (16%)	1.18 (0.98–1.4)
Systemic	1306 (86%)	25 (2%)	86 (6%)	107 (7%)	1.24 (0.9–1.6)
Mucosal	1045 (69%)	113 (7%)	162 (11%)	204 (13%)	1.26 (1.03–1.5)
Respiratory	1415 (93%)	10 (1%)	47 (3%)	52 (3%)	1.11 (0.7–1.6)
Musculo-skeletal	1345 (88%)	35 (2%)	68 (4%)	76 (5%)	1.12 (0.8–1.6)

Data are number (%) or odds ratio (95% CI). *Defined as a symptom that began after arrival at work. †Pairs of responses within each trial judged to be independent observations.

The results in Table 7 indicate that UVGI systems installed in the HVAC system produced tangible results when the UVGI lights were on. Even though the UVGI air disinfection rates for pathogens were relatively low in this trial, testing data proved a positive correlation in the improved workers' health and well-being. If only 25–30% UVGI air disinfection rates provided noticeable results in this office environment, a well-engineered UVGI system, with high air ventilation rates, would provide increased protection for crewmembers aboard ships.

H. EMERGING TECHNOLOGIES

Recent work on far-UVC lighting has shown promise for the potential development of new UV light sources equipment that avoids human exposure hazards. In a Columbia University article, researchers using 222 nm light believe that at this wavelength, the far-UVC light is not able to penetrate the outer dead cell-cell skin layer or damage eyes (Brenner 2020). The study's lead author stated, "Based on our results, continuous airborne

disinfection with far-UVC light at the current regulatory limit could greatly reduce the level of airborne virus in indoor environments occupied by people” (Brenner 2020).

As the value of UVGI equipment becomes apparent during the pandemic, further options may become available. Such progress needs to be actively considered as part of ship’s life-cycle improvement. UVGI technology is continuously being used in new and inventive ways. During the conduct of this thesis, circular rotary ceiling fans that added UVGI lighting shining upward away from people below became available. Figure 18 shows an example of an 8–14 ft. diameter UVGI fan that draws air upward and into its UVGI disinfection zone to help reduce airborne pathogens within a room.



Figure 18. UVGI Rotary Fan. Source: Big Ass Fans (2020).

These innovative ideas may also improve the deployability of UVGI disinfection. For example, the following image shows how UVGI lighting can be used to disinfect shoes. Placing the shoe on top of the post energizes the light; removing the shoe turns off the light, so that no human exposure occurs. The technology could be used to disinfect boots as well. Further surprising changes in new-equipment availability are likely. Figure 19 shows the device being used to sanitize a shoe using UVC LED lights.



Figure 19. UVGI Shoe Sanitizer. Source: Sterishoe (2020).

These are new technologies with no proven record of effectiveness. Because of the technical risk associated with their low maturity, they were not considered for shipboard use or in cost analysis.

I. CHAPTER SUMMARY

There are several recommended areas for applying UVGI in HVAC systems to clean the air of pathogens, including within the air handling units, ductwork, and in open room areas wherever high densities of personnel congregate. In addition to air disinfection, UVC lamps can kill bacteria and mold, building up on the coil.

IV. NEAR-TERM AND LIFE-CYCLE SYSTEM DESIGN CONSIDERATIONS FOR SMALL AND LARGE NAVY SHIPS

A. INTRODUCTION

This chapter investigates the application of UVGI methods to a small Navy ship and a large Navy ship to determine the feasibility of fleet-wide installations. Ultraviolet germicidal irradiation (UVGI) systems can provide supplemental disinfection to current methods of air cleaning. It must be noted that any long-term change or modification to the life-cycle design of a ship's HVAC system needs to be ultimately approved through NAVSEA or through the appropriate naval approval process. For this analysis, the author visited USS *Hurricane* (PC 3) in Bahrain and USS *Tripoli* (LHA 7) in San Diego and was also provided information regarding each ship's HVAC systems. Good systems engineering practice provides useful system design considerations to evaluate the many characteristics necessary for the proper modification of ship ventilation. A preliminary assessment is needed to guide future near-term and long-term installation decisions.

B. SHIPS VISITED

The larger ship studied was the America-amphibious assault ship, USS *Tripoli* (LHA 7). USS *Tripoli* is 844 ft long, has a displacement of 45,000 tons (USNI News 2020), and has a crew of 65–100 officers, 994–1,000 enlisted men, and a Marine detachment of approximately 1,800 Marines (NavSource 2020). The smaller ship studied was the Cyclone-class patrol ship, USS *Hurricane* (PC 3). USS *Hurricane* is 179 feet long, has a displacement of 288 tons, and a crew of 4 officers, 23 enlisted personnel (SURFLANT n.d.).

USS *Hurricane* is equipped with several small air handling units that supply ventilated air to various areas of the ship. Each air handling unit has a filter to prevent dust and dirt from going into the AHU and into the ventilation system. There are no HEPA grade filters installed in the ventilation system to protect the crew, but room air exchange rates are adequate. Accommodations are relatively small but manageable for a ship with a crew of approximately 30 sailors. Airborne transmission of the disease is possible if a crew

member became sick, and aerosolized pathogens might easily travel throughout the ship. Potential installation of UVGI devices inside the air handling units and the ductwork appears difficult since the ducting is relatively small and does not afford much space for installation of UVGI devices.

For USS *Tripoli*, there are multiple HVAC systems that provide air-conditioned and heated air throughout the numerous spaces and rooms aboard the ship. It may require cutting, welding, and modification of components to make the use of UVGI devices feasible. It is worth noting that ventilation systems on larger Navy surface ships are highly decentralized and redundant. There are multiple systems that supply treated air to many different areas of large ships, so UVGI implementation likely needs to be engineered for each HVAC system.

C. GENERAL SYSTEM DESIGN CONSIDERATIONS

HVAC systems aboard both vessels were inspected to determine the feasibility of applying current commercial UVGI methods, including implementation into the air handling units (before or after the cooling coils), installation into the ship's ducts, as well as considerations for upper-room versus deck-mounted air purification units. Tasks relating to general design considerations are provided in Figure 20.

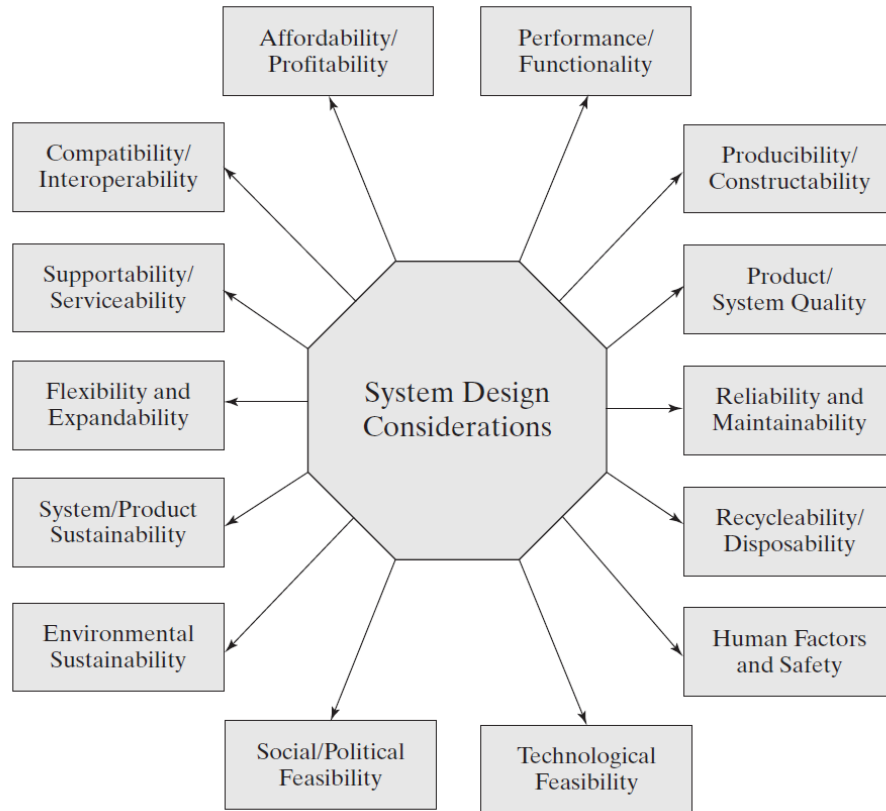


Figure 20. General System Design Considerations cover numerous aspects of interest for any system. Adapted from Blanchard and Fabrycky (2011).

Descriptions for key design considerations are as follows:

- **Affordability:** Besides the unit cost, which may be relatively low, the price for engineering, labor, replacement costs, preventative and corrective maintenance, initial installation, subject matter experts, drawings, updates to existing diagrams, and ship manuals need to be calculated for total costs.
- **Performance/Functionality:** Device performance claims need to be validated. For example, if the manufacturer states that their device can provide air disinfection for 20,000 cubic feet of space, how was their testing done? Were the test and evaluation procedures sufficiently presented? Some UVGI COTS manufacturers might submit exaggerated

claims regarding the effectiveness of their device against certain bioweapons such as anthrax. Manufacturer claims will require scrutiny for accuracy and truthfulness.

- **Producibility/ Constructability:** This is the ease in which COTS components can be manufactured and constructed.
- **Product System Quality:** This refers to how well the systems are constructed. An example of quality could be the decibel rating for stand-alone or upper-room systems. If these devices are placed into the sleeping berths, it will be necessary to choose quieter models.
- **Reliability / Maintainability:** The systems should be reliable and durable to withstand ship environments. If the device constantly malfunctions or breaks, HVAC personnel will need to spend time and resources on repairing or replacing the device. Another consideration is if the system breaks, how does the system or UV lamps get properly disposed of.
- **Recyclability/ Disposability-**Although the UVGI lamps may contain small amounts of mercury, recyclability and disposability should not be a concern.
- **Human Factors and Safety:** The primary safety considerations for UVGI devices is UVC exposure to personnel. Upper-room and stand-alone devices will not expose ship HVAC technicians to UVC light. If the UVGI contains a mercury lamp, this could present some safety concerns due to mercury vapor or ozone.
- **Technological Feasibility:** UVGI technology in commercial applications is well researched and documented. The technological feasibility of UVGI is not a primary concern.
- **Social/Political Feasibility:** Social concerns are primarily centered on Navy personnel, concerned about health and safety. For example,

operational personnel needs to be able to execute their mission with confidence or else they are rightfully hesitant to deploy or reenlist. Political concerns primarily involve a higher-level chain of command and the perception of the general public. Families need to know that the Navy is taking all necessary steps to protect their loved ones during long-term deployments at sea.

- **Environmental Sustainability:** Although produced artificially, UVGI is an environmentally safe way of inactivating viruses and killing germs. There are no harsh, environmentally produced chemicals in UVGI. The small amounts of mercury used in mercury UVGI lamps do not cause any long-term environmental problems during disposal.
- **System/Product Sustainability:** Design considerations include the anticipated life cycle for operational use of the UVGI systems. It will be necessary to understand the expected years of service life that these systems are expected to last.
- **Flexibility and Expandability:** Design considerations include whether UVGI systems can be increased or modified to produce more UV light. For example, it may be discovered through device trials that higher wattage lamps may be required for deployments at sea. Devices may need to change or adapt as requirements dictate.
- **Supportability/Serviceability:** This concerns logistics and repair of UVGI systems for long term deployments. If additional manpower is not provided to support these systems at sea, current ship HVAC personnel will need to perform any supportability or serviceability requirements. UVGI systems should be very low maintenance items to support and repair.
- **Compatibility/ Interoperability:** This consideration relates to how compatible and interoperable the UVC system is for a sea-going vessel.

Some COTS UVGI systems may not require much testing. These devices still need to be analyzed for compatibility with existing ship systems.

Another concern is due to the photodegradation effect of UVC light on petroleum-based products. Is the device compatible with specific room installations with rubber gaskets, seals, or wiring that could degrade and crack over prolonged periods of exposure?

Due to the immediate benefit to sailor health and risk reduction of COVID-19 exposure, one additional category is added.

- **Deployment Readiness:** This describes how long before the system is most likely ready for production use aboard ships.

D. ADDITIONAL SHIPBOARD DESIGN CONSIDERATIONS

UVGI ventilation modifications must be integrated into the existing ship's systems. Due to limited space aboard Navy ships, there may be significantly less room where some of the HVAC components can be installed as opposed to a commercial air handling unit. Less space may make serviceability or replacement of the devices more difficult. If devices fail or become inoperable, regular ventilation system operation cannot be inhibited. If the UVGI devices require more time for ships-force personnel to support preventive or corrective maintenance, such problems are severe due to the already-high workload required of the crew. For device installations within the ship's air ventilation systems, considerations for additional manpower may be required to support maintenance tasks. Some components may require little or no support. For example, the Sanitaire systems for deck and upper-room UVGI may just need to be "turned on" then set it and forget it.

Software to control UVGI devices will probably require additional crew training. For example, if there are multiple UVGI devices installed in the ductwork and the temperature or humidity changes, some calculations in the software may be required to allow the UVGI devices to operate at their peak efficiency. Software required to run the UVGI devices might need to be periodically updated during ashore maintenance periods. Other integration considerations may include how much subject matter knowledge experts are required to know about the systems and how they operate.

E. PRELIMINARY ASSESSMENT OF SYSTEM DESIGN CONSIDERATIONS FOR SMALL SHIPS AND LARGE SHIPS

The following tables provide a preliminary assessment for UVGI installation aboard a ship, comparing different potential locations. Table 8 is for small ships; Table 9 is for large ships. Note that columns for portable standalone units and upper-room devices are suitable for near-term use (and possibly long-term use). These columns are followed by installation inside existing equipment, which is only an option for long-term use. These assessments are based on the author's visits to the ships mentioned earlier.

Table 8. System Design Considerations Comparing UVGI Device Types for Small Ships

UVGI Device Types	Portable standalone units	Upper-room devices	Within Air Handling Units	In-duct Installed Devices
<i>Deployment Readiness</i>	<i>Near Term</i>	<i>Near Term</i>	<i>Long Term</i>	<i>Long Term</i>
Affordability	Excellent Risk-Benefit Tradeoff	Excellent Risk-Benefit Tradeoff	Equipment Redesign Difficult	Excellent Risk-Benefit Tradeoff
Performance/Functionality	Hospital Proven	Hospital Proven	Evaluation Needed	Evaluation Needed
Producibility/Constructability	Excellent	Excellent	Prototype Test	Prototype Test
Product/System Quality	Excellent	Excellent	Prototype Test	Prototype Test
Reliability/Maintainability	Untested at sea	Untested at sea	Necessary	Necessary
Recyclability/Disposability	Untested	Untested	Necessary	Necessary
Human Factors and Safety	Ozone, Mercury (if used)	Ozone, Mercury (if used)	Ozone, Avoid Mercury	Ozone, Avoid Mercury
Technological Feasibility	Excellent	Excellent	Excellent	Excellent
Social/Political Feasibility	Essential	Essential	Essential	Essential
Environmental Sustainability	Hospital Proven	Hospital Proven	Evaluation Needed	Evaluation Needed

UVGI Device Types	Portable standalone units	Upper-room devices	Within Air Handling Units	In-duct Installed Devices
<i>Deployment Readiness</i>	<i>Near Term</i>	<i>Near Term</i>	<i>Long Term</i>	<i>Long Term</i>
System/Product Sustainability	Hospital Proven	Hospital Proven	Evaluation Needed	Evaluation Needed
Flexibility/Expandability	As Needed	As Needed	As Designed	As Designed
Supportability/Serviceability	Replacement Afloat/Ashore	Replacement Afloat/Ashore	Replace, Repair Ashore	Replace, Repair Ashore
Compatibility/Interoperability	Excellent	Excellent	Excellent	Excellent

Table 9. System Design Considerations Comparing UVGI Device Types for Large Ships

UVGI Device Types	Portable standalone units	Upper-room devices	Within Air Handling Units	In-duct Installed Devices
<i>Deployment Readiness</i>	<i>Near Term</i>	<i>Near Term</i>	<i>Long Term</i>	<i>Long Term</i>
Affordability	Excellent Risk-Benefit Tradeoff	Excellent Risk-Benefit Tradeoff	Excellent Risk-Benefit Tradeoff	Excellent Risk-Benefit Tradeoff
Performance/Functionality	Hospital Proven	Hospital Proven	Evaluation Needed	Evaluation Needed
Producibility/Constructability	Excellent	Excellent	Prototype Test	Prototype Test
Product/System Quality	Excellent	Excellent	Prototype Test	Prototype Test
Reliability/Maintainability	Untested at sea	Untested at sea	Necessary	Necessary

UVGI Device Types	Portable standalone units	Upper-room devices	Within Air Handling Units	In-duct Installed Devices
<i>Deployment Readiness</i>	<i>Near Term</i>	<i>Near Term</i>	<i>Long Term</i>	<i>Long Term</i>
Recyclability/Disposability	Untested	Untested	Necessary	Necessary
Human Factors and Safety	Ozone, Mercury (if used)	Ozone, Mercury (if used)	Ozone, Avoid Mercury	Ozone, Avoid Mercury
Technological Feasibility	Excellent	Excellent	Excellent	Excellent
Social/Political Feasibility	Essential	Essential	Essential	Essential
Environmental Sustainability	Hospital Proven	Hospital Proven	Evaluation Needed	Evaluation Needed
System/Product Sustainability	Hospital Proven	Hospital Proven	Evaluation Needed	Evaluation Needed
Flexibility/Expandability	As Needed	As Needed	As Designed	As Designed
Supportability/Serviceability	Replacement Afloat/Ashore	Replacement Afloat/Ashore	Replace, Repair Ashore	Replace, Repair Ashore
Compatibility/Interoperability	Excellent	Excellent	Excellent	Excellent

F. CHAPTER SUMMARY

The purpose of this chapter is to consider near-term and life-cycle system design considerations for small and large Navy ships. Two ships were visited to consider UVGI installation possibilities for both small and large Navy vessels. Good systems engineering practice provides excellent criteria for assessing numerous systems design characteristics,

which is essential when integrating new capabilities into complex systems that must operate over long periods of time. Some adjustments to general criteria were provided to adapt for shipboard requirements especially when considering short-term deployability versus long-term integration into life-cycle ship design. Initial assessments for all criteria and all primary installation alternatives are provided to expedite rapid decision-making and response for deploying these critical capabilities.

After careful consideration of all cases, no blocking factors or limitations have yet been noted that prevent rapid adoption and execution of the recommendations for this thesis.

V. COST ANALYSIS

A. INTRODUCTION

This chapter performs a preliminary cost analysis. Following an emphasis on design considerations, example parameters and costs are provided for portable standalone units, upper-room devices, within air handling units (AHUs), and in-duct systems.

B. DESIGN CONSIDERATIONS

While there are many ways to apply these systems, the result is always similar: recirculated air is disinfected at a rate proportional to airflow through UVGI equipment. It cannot be forgotten that the cost of a ship's force personnel getting sick, or a ship being unable to conduct its mission, far exceeds any possible cost comparison. Nevertheless, due-diligence design, good stewardship of public resources, and repeatable life-cycle sustainability requires meaningful estimates of cost for any large-scale system.

This chapter examines approximate costs for feasible approaches including portable standalone units. Only material procurement costs are presented; labor for installation and detailed design is not included. These COTS devices can be portable or preferable mounted to the deck. Other cost analyses are provided for upper-room devices that are mounted to the bulkhead, HVAC UVGI which are positioned inside air handling units and in-duct systems that provide for air disinfection through the ductwork. In-duct UVGI lamps are usually positioned just downstream of the air handling units.

C. PORTABLE STANDALONE UNITS

This study encountered several commercial-off-the-shelf (COTS) equipment possibilities that might be adapted for shipboard use. An example of a standalone device is shown in Figure 21 with wheels that can be removed, and the device can be bolted to the deck. The primary market segment of interest that demonstrates capabilities suitable for shipboard use is found in hospitals and health care facilities. Such sites tend to use high-powered equipment (with possible eye- and skin-exposure hazards) when personnel are not present to ensure 100 % disinfection. Such gear provides immediate opportunities for

shipboard deployment if it can be stably secured to avoid damage from ship motion, placed in a safe location that includes excellent air recirculation, and avoids personnel exposure to harmful UV light.



Figure 21. Sanitaire RSM2680 Mobile Air Sanitizer can be bolted to the deck. This model can provide 6 air changes for 20,000 cubic square feet using UVC lamps and is safe for occupants. Source: BuyUltraviolet.com (n.d.).

A large deck-mounted UV air purifier by Sanitaire was considered for this cost analysis. This device can draw in large quantities of air for room air disinfection purposes. Specifications and approximate costs are listed in Table 10. Ventilation engineers need to compute how many units are necessary according to the number of ventilation zones that are present on a ship. Depending on circulation rates, the period necessary for complete air changes (and corresponding reduction by UVGI equipment) is a straightforward calculation.

Table 10. Portable Standalone Unit Example Specifications and Approximate Costs. Adapted from BuyUltraviolet.com (n.d.).

Item	Values
Model	Sanitaire RSM2680
Size	79"x33"x31"
Power	120 volts AC x 12 Amps = 1.2 Kilowatts (maximum)
Maximum Room Size	20,000 cubic feet (approximately 40'x40' room, 12' ceiling)
Corresponding Replacement Rate	6 air changes/ hour
Approximate cost	\$17,000 per unit

D. UPPER-ROOM DEVICES

Upper-room devices are UV light sources that can be mounted high on the wall (or ship's bulkhead) that shine upwards towards the ceiling to prevent UV light exposure to human eyes. See Figures 10 and 11 as examples. For indoor building use, such devices are typically recommended to be at least 7 feet above the deck. Thus, such devices might be useful in shipboard locations with a high overhead (such as high-bay compartments or hangar decks) but might be impractical in other compartments. Note that the air flow in overhead zones is likely limited due to the many pipes, cables, ventilation ducts, and frame dividers that can be found in the overhead. Nevertheless, upper-room devices are worth considering on a case-by-case basis. Figure 22 provides an example of a bulkhead or deck-mounted unit that draws in air internally for UVGI purposes.

A simple upper room cost analysis can be provided by dividing an area of a room by the square footage that the device cleans. An example of commercial-grade unit is the Sanitaire RSA760 UV air sanitizer. Prices and specifications are listed in Table 11.

Table 11. Cost of a smaller UVGI device

Item	Values
Model	Sanitaire RSA760
Size	61"x14"x12"
Power	5.65 Amps 110V, 60 Hz, single phase 110 volts AC x 5.65 Amps = 0.6215 Kilowatts (maximum)
Maximum Room Size	3,800 cubic feet (approximately 15'x20' room size with 12' overhead)
Corresponding Replacement Rate	6 air changes/ hour
Approximate cost	\$4,000 per unit



Figure 22. Sanitaire RSA760 ultraviolet air sanitizer draws air into the system using a fan, then passes the air over UVC lamps, which irradiates the air providing air disinfection for 3,800 cubic feet of space at 6 room air exchanges per hour. Source: BuyUltraviolet.com (n.d.).

The cost could then be multiplied by the size of the room needed. For example, the berthing area on a ship may be 20,000 cubic feet, $(20,000 / 3,800)$ yields 5.26, and to be on the conservative side of estimation, rounding up would require six devices for a total of \$24,000. If using one upper-room device for each air handling unit, for a USS *Hurricane* size the cost would be approximately $7 \times \$24,000$ for a total of \$168,000 excluding labor.

E. WITHIN AIR HANDLING UNITS (AHUS)

Air handling units (AHUs) include ventilation fans, ventilation assemblies, adjacent filters, adjacent heating, and cooling coils, as well as adjacent empty plenums that

might be used for atmospheric monitoring or installation-spacing purposes. AHUs tend to be considered as a single composite unit even when they contain multiple components. As a result, larger AHUs may have sufficient unused volume to permit the internal installation of UVGI equipment.

The cost-estimation example for Table 12 gives an idea of the approximate cost for each UVGI installation. Electrical ballasts are used to limit the electrical current so that there is a controlled amount of power being applied to the lamps. Coil cost estimates are multiplied by the number of systems needed for each individual ship. Labor, consultant, engineering design, and installation costs can vary widely and are not included in this cost estimate (Larson Electronics 2021). These UVC lamps can be installed downstream of the air filter to provide air disinfection or mounted on the coil to prevent bacterial build-up.

Table 12. Example Unit Coil Costs for a Single UVGI Installation

Coil size	Price	Number of UVC Lamps	Number of Ballasts
72"x52"	\$5,000	4	2
60"x36"	\$2,500	2	1
48"x24"	\$1,800	1	1

The difference in equipment layout and atmospheric volume varies significantly for every Navy ship. Thus, these tables provide simple approximations of unit costs. For every near-term installation, variations in the number of devices installed are not a controlling factor since the only resulting change is the overall time to filter ship's atmosphere. Therefore, shipboard installation costs are easily computed for every ship eligible for a near-term installation.

F. IN-DUCT INSTALLED DEVICES

In-duct installed devices are placed within ventilation ducts and thus do not require any special modification of existing shipboard ventilation equipment. Because huge

amounts of empty (but active) ventilation ducting are available aboard ships, numerous installation locations are possible. Modifying empty ventilation ducting is perhaps the simplest ship alteration to consider and possibly the least expensive to accomplish as well. Typically, all equipment associated with ventilation systems tends to be grouped together in each ventilation zone to simplify monitoring and maintenance. The exact placement of installed in-duct devices is likely to vary on a ship-by-ship basis since every Navy ship (even in the same ship class) has its own characteristics.

As shown in Appendix B, custom in-duct installed devices can be produced for ventilation systems of interest. Because so many factors pertaining to the creation of such custom equipment, and because any such long-term design must be specialized for all ship classes of interest, no-cost analysis is performed in this thesis. Such analysis is a straightforward task for designers of future ship systems.

G. CHAPTER SUMMARY

The costs for implementing UVGI airborne disinfection on a Navy ship is necessary, when compared to the alternative of severe pandemic outbreaks at sea. The initial procurement costs for several typical COTS devices for two different Navy ships were presented. Detailed life-cycle costing to include design, testing, operations, and sustainment are beyond the scope of this thesis but can be accomplished as part of a longer-term effort.

VI. ACTIONS, CONCLUSIONS AND RECOMMENDATIONS

A. IMMEDIATE ACTIONS

Reducing COVID-19 exposure at sea is crucial for both sailor health and operational mission requirements. Two immediate actions are necessary:

- Following a rapid assessment of safety concerns, commercial-off-the-shelf (COTS) ultraviolet germicidal irradiation (UVGI) ventilation equipment needs to be installed aboard all deploying Navy and Coast Guard ships.
- Develop detailed designs for the installation of ship alterations based on a multi-disciplinary approach with disciplined systems engineering to sustainably deploy UVGI ventilation equipment aboard all Navy and Coast Guard ships and submarines across their full life cycles.

B. CONCLUSIONS

The application of UVGI for U.S. Navy and Coast Guard ships is feasible, necessary, and cost-effective. Both immediate and long-term actions for UVGI air disinfection should be utilized by Navy stakeholders. Immediate implementation of UVGI devices can be installed with a relatively low level of effort since they would not be installed in HVAC systems.

Rapid implementations of UVGI include the installation of stand-alone and upper-room devices. These systems would require low effort for installation since they would not be installed in HVAC systems. An example of a stand-alone deck-mounted UVGI device can provide air disinfection for a 20,000 cubic feet area at six-room air exchanges per hour for approximately \$17,000. An upper-room, bulkhead-mounted device can treat a 3,800 cubic feet room at six air exchanges per hour for approximately \$4,000. The costs do not include labor or peripheral considerations

These devices can provide air purification for areas where personnel are in close-quarter environments such as in sleeping berths, mess halls, meeting rooms, gyms, medical and dental spaces.

UVGI application within the ventilation systems for Navy ships is possible but will require long-term planning and multi-disciplinary systems engineering approach to be successful. Navy ships have multiple, decentralized HVAC systems and are considerably different than HVAC systems in a commercial office building. The level of effort needed for installation, plus the use of mercury vapor lamps inside HVAC systems, would require additional testing and evaluation by NAVSEA. Monitoring systems would also need to be installed to make sure that UVC light sources are properly working and making sure that no ozone, although unlikely, is introduced into the ventilation system.

Labor and manpower need to be part of the equation whenever new systems are introduced aboard ships. Additional personnel may be required to support new UVGI systems. Maintainability, supportability, warranty tracking, and support will be required even if additional UVGI devices are advertised as self-contained, low-maintenance items.

Smaller Navy ships, such as patrol boats, have far fewer HVAC components and may have less than ten air handling units that provide treated air through the ship. Although less level of effort would be required on smaller U.S. Navy ships for UVGI implementation into the HVAC systems, long-term planning and engineering would still be required. Upper-room and stand-alone UVGI devices for smaller ships would also provide an immediate solution to provide air purification for the ship's crew.

HEPA grade filters with high MERV values, in conjunction with UVGI systems, would provide an extremely robust air purification system for Navy ships. Again, it should be noted that the introduction of UVGI for Navy ships is not meant to take away from any current air filtration processes in current use.

Long-term UVGI planning and implementation for Navy ships could have defensive value against a possible bioweapon attack. Many ships do not have a CBR system and the ships which do have the CBR system only have certain areas or zones where the CBR system would supply clean, filtered air. Other areas of the ship would still be vulnerable. UVGI that is engineered into future HVAC systems could reduce the level of effectiveness that a bioweapon attack would have on a ship's ventilation system and room spaces.

Real-world events may require Navy ships to bring aboard civilians in distress. It is possible that disease or sickness could be introduced aboard a ship, even with the Navy's strict quarantine protocols for such events. The air in the spaces where the civilians are housed and waiting could be cleaned with UVGI devices in the room.

There are safety concerns with UVC lights, primarily due to accidental prolonged exposure incidents. Upper-room and stand-alone UVGI units are designed to be used in rooms where personnel are present. Another safety concern with UVGI devices is that some UV light sources, such as mercury vapor lamps, contain small amounts of mercury. Mercury poses both health hazards and the potential for severe corrosion. Exposure to mercury would only occur if a mercury lamp source was somehow broken, with the mercury exposure. It should be noted that many commercial manufacturers have a protective shield coating over the quartz glass of the mercury lamp. Even if the mercury lamp was broken and bent at various angles, the mercury or mercury vapor would not escape. Navy ships also carry mercury spill kits, which could also help mitigate any potential risk of exposure. An alternative to UVGI mercury lamps could be the use of powerful UVC LED lights.

It is certain that future global pandemics such as the current COVID-19 outbreak will repeat again. The topic of UVGI use for Navy vessels was mentioned in 2003 but was not acted upon. An article in the *Military Medicine* journal mentioned UVGI for ships after a TB outbreak occurred on a Navy ship in 1998. The article stated:

A promising engineering control is the use of ultraviolet germicidal irradiation (UVGI). Not only the would installation of ultraviolet lamps lower the transmission risk of other viral, bacterial, and fungal respiratory pathogens, while also controlling fungal growth in the ventilation systems. Viruses are more susceptible to UVGI than bacteria, while bacterial spores are more resistant. Considering the huge expenditure of resources associated with this outbreak and the emerging threat of attack with biological agents, the potential for UVGI systems to decrease respiratory disease rates and the feasibility of their installation aboard ships should be investigated by the Navy. (Lamar and Malakooti 2003, 527)

In conclusion, the Navy should act now to implement UVGI for Navy ships. Non-HVAC UVGI systems can be installed immediately. A long-term planning and multi-

disciplinary systems engineering approach should be started for UVGI HVAC implementation.

C. RECOMMENDATIONS FOR FUTURE WORK

Conduct a rapid assessment of the health of certain Navy ship ventilation systems and conduct air quality samples. This will provide a health data point as to current air quality.

Investigate the use of far-UVC (207-222 nm) light, which has lower wavelengths in the electromagnetic spectrum. Far-UVC devices may be equally effective at inactivating viruses and killing microorganisms. Studies have shown that far-UVC wavelength of light does not penetrate skin or cause damage to eye tissue lowering health risks associated with exposure (Welch et al. 2018). Research is still ongoing in medical trials, but the International Ultraviolet Association warns that “there is a lack of protocols to govern the safe construction and operation of such devices” (IUVA 2020). If these devices are proven safe for human exposure, then they could be installed into the overhead lighting fixtures and provide disinfection in areas such as on handrails and common surfaces that are touched by crew members frequently.

UVGI could be applied to U.S. naval transport aircraft. Currently, airborne pathogens can be spread through aircraft cabins and be transmitted to passengers and flight crews. By applying UVGI to aircraft ventilation systems (far-UVC should also be considered), airborne infections could be reduced significantly.

This thesis provided preliminary estimations for UVGI implementation. A more detailed analysis of UVGI costs could benefit the Navy. The research would calculate not only the labor costs, hardware, and software but also attempt to calculate the UVGI savings by preventing a major disease outbreak aboard a ship.

APPENDIX A. PROJECT PRESENTATION



Feasibility and Assessment of Applying Ultraviolet Germicidal Irradiation (UVGI) to U.S. Navy Ships

Jonathan Burnette
Systems Engineering Thesis

Advisors: Don Brutzman
Gregory Miller
16 December 2021



Airborne Disease Transmission aboard Navy Ships

BLUF: Reducing COVID-19 exposure at sea is crucial for both sailor health and operational mission requirements. Two immediate actions are necessary.

1. Following a rapid assessment of safety concerns, Commercial -Off-The-Shelf (COTS) ultraviolet germicidal irradiation (UVGI) ventilation equipment needs to be installed aboard all deploying Navy and Coast Guard ships.
2. Develop detailed designs for installation of ship alterations based on a multi-disciplinary approach with disciplined systems engineering to sustainably deploy UVGI ventilation equipment aboard all Navy and Coast Guard ships and submarines across their full life cycles.



2



Droplets versus Aerosolization

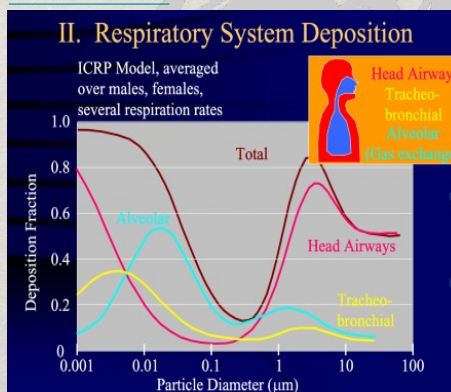
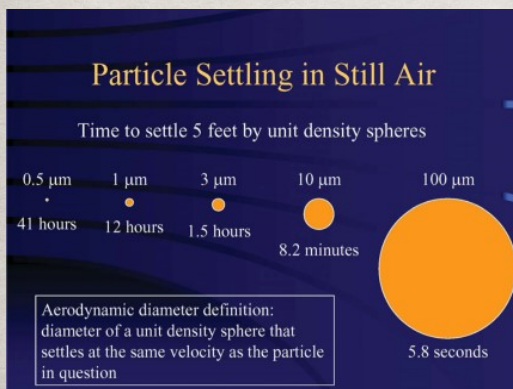
Yahhalation of air carrying very small Jne droplets and aerosol particles that contain infectious virus. Risk of transmission is greatest within three to six feet of an infectious source where the concentration of these very Jne droplets and particles is greatestX

YPeople release respiratory Huids during exhalation (e.g., quiet breathing, speaking, singing, exercise, coughing, sneezing) in the form of droplets across a spectrum of sizes.19 These droplets carry virus and transmit infection.X

YThe largest droplets settle out of the air rapidly, within seconds to minutes.

The smallest very Jne droplets, and aerosol particles formed when these Jne droplets rapidly dry, are small enough that they can remain suspended in the air for minutes to hours.X

<https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/sars-cov-2-transmission.html>



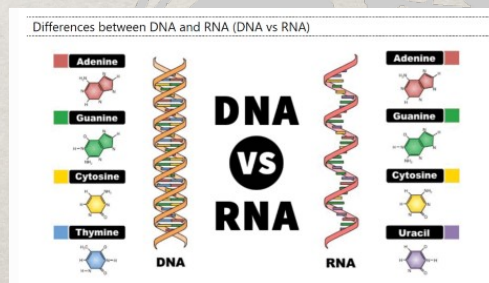
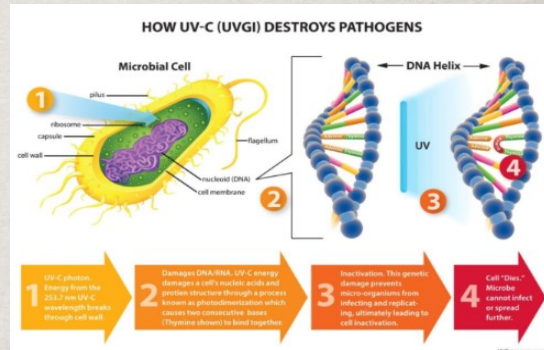
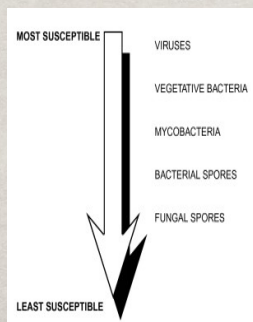
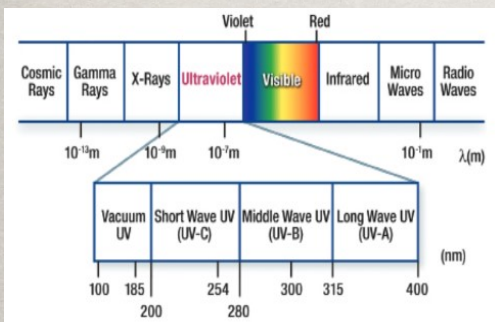
Diamond Princess Incident

- February 2020 (initial month of pandemic, pre -lockdown)
- 700 crew and staff infected with COVID-19 during several week at sea, then everyone quarantined on board
- 7 fatalities due to virus (WebMed 2020)
- Led to disease transmission modeling. (Azimi et al. 2021)





UVC Light Effects on Airborne Virus



(Mackenzie 2021)

5



UVC Hazards

Risks: UVC lamps used for disinfection purposes may pose potential health and safety risks depending on the UVC wavelength, dose, and duration of radiation exposure. The risk may increase if the unit is not installed properly or used by untrained individuals.

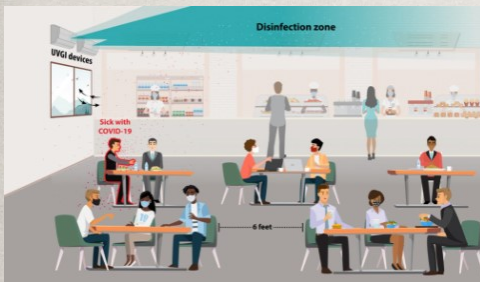
- Direct exposure of skin and eyes to UVC radiation from some UVC lamps may cause painful eye injury and burn-like skin reactions. Never look directly at a UVC lamp source, even briefly. If you have experienced an injury associated with using a UVC lamp, we encourage you to [report it to the FDA](#).
- Some UVC lamps generate ozone. Ozone inhalation can be irritating to the airway.
- UVC can degrade certain materials, such as plastic, polymers, and dyed textile.
- Some UVC lamps contain mercury. Because mercury is toxic even in small amounts, extreme caution is needed in cleaning a lamp that has broken and in disposing of the lamp. (FDA 2021)



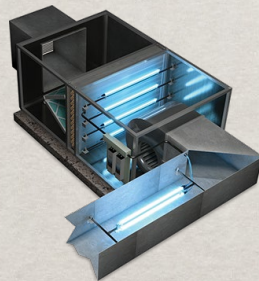
6



UVGI Implementation Methods



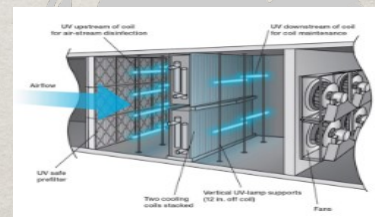
Upper-Room UVGI



In-Duct UVGI



Floor Mounted UVGI Systems



UVGI Prevention of Bacterial Growth on Coil in Air Handling Units

7



UVGI Adoption aboard Cruise Ships



Currently there is no published guidance for UVGI shipboard installation. Carnival Cruise Lines Chief Maritime Officer VADM William Burke USN (Ret.) and Senior HVAC Engineer Julien Prodhomme provided NPS with information about Carnival's UVGI design and implementation methods, confirming our investigations. Carnival is currently deploying UVGI onboard their ships for passenger and crew safety.



Windstar Cruises: "The Beyond Ordinary Care program is a multi-layered strategy with key hospital-grade elements: HEPA filters and **UV-C ultraviolet germicidal irradiation to filter and disinfect the air**, plus electrostatic sprayers to sanitize all surfaces throughout the yacht. (Windstar Cruises 2020)."



"MSC Cruises will be the first cruise line in the world to install a new and advanced innovative technology sanitation system called 'Safe Air' to improve further the quality and cleanliness of the onboard air for its guests and crew. The 'Safe Air' next-generation sanitation system is based on the technology of **UV-C lamps** which are type C ultraviolet rays applied in combination with the ship's air conditioning system, whereby air flow is radiated at source with a short wavelength light that hits organic particles and prevents the circulation of **air pollutants such as viruses, bacteria and mold** (MSC Cruise 2020)."

8



UVGI Disinfection for Bioweapons

Research has shown that ultraviolet germicidal irradiation, when the appropriate dosage is applied, can have some success at destroying or inactivating all microorganisms including those used for bioweapons, including anthrax, botulism, plague, smallpox, tularemia, and viral hemorrhagic fever (Brickner et al. 2003).

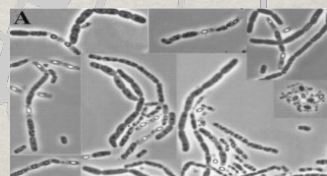
Airborne, surface -borne and waterborne biocontamination can be remediated effectively with UV systems (Kowalski 2009).

Bioweapon agents that are thought to be desirable as terroristic weapons are those which cause a high rate of fatality and that can be easily disseminated. Airborne contamination is by far the most serious type of biological weapons threat since an airborne agent can be spread faster and more widely than would a foodborne or waterborne agent. Chief among such airborne agents are anthrax, influenzas, hantavirus and smallpox (Kowalski 2009).

Following a 1998 tuberculosis incident at sea, the potential use of UVGI for shipboard protection of Naval vessels was formally recommended by medical research published in 2003.

“Considering the huge expenditure of resources associated with this outbreak and the emerging threat of attack with biological agents, the potential for UVGI systems to disease respiratory disease rates and the feasibility of their installation aboard ships should be investigated by the Navy” (Lamar and Malakooti 2003).

This thesis investigation found no Navy activity applying UVGI aboard ships.



Anthrax

9



Carnival Cruise Line UVGI Implementation



Main air handling unit (AHU) pushing air with UV system on.



Main air handling unit (AHU) as seen from exhaust side.

10



Carnival Cruise Line UVGI Implementation



Inspection of a public-area fan coil unit.
100% recirculation suction is at the bottom,
with exhaust flow at the top.



Deck-mounted public-area
fan coil unit with 100%
recirculation and UV off.

11



Conclusions and Immediate Actions

UVGI protection against Covid is feasible and necessary to prevent illness and save lives.

- a. Already being used in cruise ships, office buildings, schools, hospitals
- b. Cost effective: COTS equipment is available and compatible with shipboard systems.
- c. Systems engineering methodology is essential for properly solving this cross disciplinary problem. If a system engineering hybrid solution is not pursued, piecemeal approaches will fail.

Reducing COVID-19 exposure at sea is crucial for both sailor health and operational mission requirements.

Two immediate actions are necessary:

1. Commercial -Off-The-Shelf (COTS) ultraviolet germicidal irradiation (UVGI) ventilation equipment needs to be installed aboard all deploying ships.
2. Develop execution plans based on the Systems Engineering Methodology to sustainably deploy UVGI ventilation equipment aboard all Navy and Coast Guard ships and submarines across their full lifecycles.

12



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APPENDIX B. MARITIME INDUSTRY EXEMPLAR SHOWING UVGI EQUIPMENT INSTALLATION ABOARD SHIP

Carnival Cruise Line supported this feasibility study by providing information relating to their UVGI implementation methods. The goal for Carnival Cruise Lines is to provide safe, clean air for their passengers and crew. Figures 23 through 29 show the implementation of UVGI components for some Carnival Cruise ships.

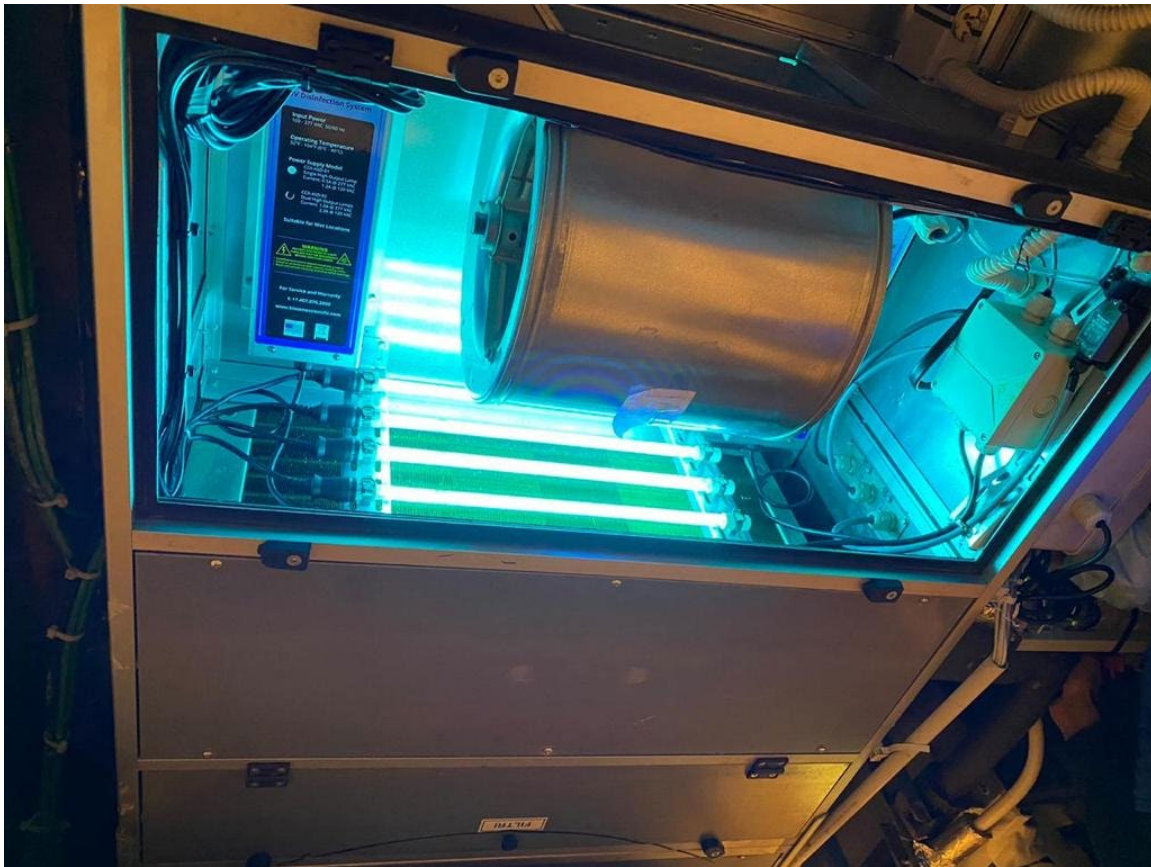


Figure 23. Inspection of a public-area fan coil unit, with 100% recirculation suction at the bottom, and exhaust flow at the top back to a perforated ceiling. Source: Carnival Corporation HVAC Working Group (2021).



Figure 24. This image shows an operator's hand testing the limit-switch functionality, namely a safety test that the UV light stops automatically if the cover door opens. Source: Carnival Corporation HVAC Working Group (2021).



Figure 25. Deck-mounted public-area fan coil unit with 100% recirculation and UV off. Source: Carnival Corporation HVAC Working Group (2021).



Figure 26. Main air handling unit (AHU) with Sorption wheels (for energy recovery) and modulating recirculation damper, as seen from exhaust side. Source: Carnival Corporation HVAC Working Group (2021).



Figure 27. Main air handling unit (AHU) with Sorption wheels (energy recovery) and modulating recirculation damper-exhaust side MERV 13 pleated filters. Source: Carnival Corporation HVAC Working Group (2021).



Figure 28. Main air handling unit (AHU) pushing air with UV system on.
Source: Carnival Corporation HVAC Working Group (2021).



Figure 29. Main air handling unit (AHU) pushing air with UV system off.
Source: Carnival Corporation HVAC Working Group (2021).

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