SHIPBOARD VENTILATION SYSTEMS AND DESIGN STANDARDS ON BOARD UNITED STATES COAST GUARD CUTTERS

By

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This document is dedicated to my grandfather, Pasquale Rozzi.

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The purpose of this study was to investigate and analyze the current ventilation requirements and standards for shipboard ventilation systems on board U.S. Coast Guard cutters. Shipboard ventilation is a vital system that enables the Coast Guard to perform their everyday mission and maintain a high level of operational readiness. It provides comfort and odor control and is essential in protecting personnel from indoor air quality (IAQ) contaminants and chemical, biological, and radiological (CBR) contaminants. The research was conducted on the following two classes of cutters: 110 foot Island Class Patrol Boat and the 210 foot Reliance Class Cutter. A detailed review of the current standards and regulatory guidance for naval ships and commercial use was conducted. Cooling load calculations were performed to determine the effectiveness of the current ventilation system on board the 210 foot cutter, using the ASHRAE Cooling Load Temperature Difference (CLTD) method and the Society of Naval Architecture and

Marine Engineers (SNAME) method. The two methods of calculations resulted in similar values for total loads.

Temperature, humidity, and carbon dioxide (CO_2) readings were taken on board the 210 foot and 110 foot cutter both underway and inport. The field data taken on the 210 foot cutter indicated a significant problem with condensation and mold/mildew growth in berthing spaces due to varying dew point temperatures and lack of proper cooling of outside air. The field data and observations taken on the 110 foot cutter revealed an inadequate supply of OA to the interior of the vessel, based on excessive CO_2 concentrations. The machinery spaces on board the 110 foot cutter had excessive condensation and rust due to lack of ventilation.

The results of the analysis indicated areas for improvement to the overall ventilation systems, standards, and procedures associated with them. Recommendations include modifications to the 210 foot cutter dehumidification coils to condition the OA air to a state that will lower the dew point temperature and prevent condensation. The 110 foot cutter would benefit from a forced ventilation system (including machinery spaces) to provide OA necessary to maintain acceptable CO_2 concentrations and provide conditioned air to prevent condensation and metal deterioration. Improved filtration systems, including the use of HEPA filters and photocatalytic technologies, will help protect the cutters from IAQ contaminants and CBR agents. An IAQ program should be established for all Coast Guard vessels to include visual inspection, periodic air sampling, and temperature readings. Standards including the Naval Ship Technical Manual and the Navy Shipboard Habitability Manual (OPNAVINST) should be updated to reflect a minimum OA requirement of 20 cfm and maximum CO_2 concentrations.

CHAPTER 1
INTRODUCTION

The Coast Guard's (CG) role has significantly changed in the past few years. As a result of the September 11, 2001, attacks on the World Trade Center, the Coast Guard's traditional missions of boat safety, migrant and drug interdiction, and fisheries enforcement have grown to include boarding and inspecting cargo ships bound for U.S. ports, sharing intelligence about threats and possible efforts to smuggle terrorists or weapons into the country, and conduct surveillance on the high seas. In March 2003, the Coast Guard was moved into the Department of Homeland Security and given the primary responsibility for maritime security in addition to its regular duties. The added responsibilities include patrolling the nation's 361 ports and 95,000 miles of coastline, boarding and inspecting tens of thousands of cargo ships and recreational boats, and reviewing security at the nation's commercial ports. In addition to performing missions within the United States, Coast Guard cutters are also stationed throughout the world including Guam, Puerto Rico, Europe, Asia, and the Middle East.

Despite the increase in responsibilities and missions, the Coast Guard continues to operate with vessels that have well exceeded their service life and with aging equipment that continues to deteriorate. This has had a significant impact on mission readiness and has resulted in an increase in the number of unscheduled maintenance days from 257 in 1999 to 742 in fiscal year 2004, for all major cutters and patrol boats (IDS 2003).

The Coast Guard has over 88 operational cutters, with the majority of the missions performed by the 110 foot and 210 foot cutter fleet. Repairing and replacing these old boats is critical in order to provide a livable and operational environment that will enable crew members to operate at their highest efficiency. Currently of the 49 110 foot cutters the CG operates, only 25% are considered fully mission capable (IDS 2003).

The 210 foot cutter class was built between 1964 and 1969 and underwent a Major Maintenance Availabilities between 1993 and 1996. While some significant changes were made, many of the systems are still operating with the original design and equipment. Currently the CG air conditioning systems are based on outdated design standards and have not been updated to reflect current commercial standards and policy. CDR Steve Bayne, Commanding Officer of 210 foot CG Cutter Decisive, has reported crewmembers suffering from mold-related respiratory problems and routinely faulty air conditioning systems.

Shipboard ventilation systems supply and remove air to and from spaces throughout the ship. In doing so, these systems control quality of breathing air and protect personnel and sensitive equipment from hazardous airborne contaminants, fires, explosions, and excessive heat (Naval Safety Center; ASHRAE 1996). This ensures the maintenance of a crew that is physically and mentally fit (NSTM 2003). Well designed and easily maintained ventilation systems are critical to a safe and comfortable shipboard work environment (Navel Safety Center). Failure to provide effective ventilation systems in the design stage can create costly obstacles to safe and efficient ship operation and maintenance, which ultimately presents a threat to personnel safety and health and to mission readiness (Naval Safety Center).

The most widespread ventilation problem aboard a ship is controlling heat and humidity (Naval Safety Center). High heat and humidity lead to conditions that are both uncomfortable and reduce personnel productivity. This has an indirect, but potentially very significant effect on cost over the life of the ship, because of reduced productivity and the need for additional manpower to perform a given set of tasks (Naval Safety Center). Excessive condensation due to lack of ventilation has led to hull degradation on the 110 foot cutters in their machinery spaces, resulting in 17 hull breeches between FY2001 and FY2003, totaling more than $11M in emergency repairs and an average of 3 months out of service (IDS 2003).

Current design standards for surface ships require a supply of outside air in excess of that required for oxygen renewal of 2 cubic feet per minute (cfm) of fresh air per person (NSTM 2003). All berthing, messing, medical, electronics, and necessary control spaces, on surface ships are to be air conditioned to maintain a maximum of 80°F dry bulb (db) and 62.5°F wet bulb (wb) under external ambient conditions up to 90°F db and 81°F wb and sea water temperatures of 85°F, with personnel on board and normal machinery operating (OPNAVINST 1996). Berthing areas are designed to permit a person to sleep without perspiring. Offices and control spaces provide an environment where personnel can work for an extended period of time without a loss in efficiency (NSTM 2003). For ships located in tropical operations, the external ambient design temperatures are increased to 105°F db, 87.5°F wb, and sea water temp of 95°F. Air to ventilated spaces in these ships shall be precooled to 90°F (OPNAVINST 1996).

Spaces that are not air conditioned are cooled with ventilation air. Ventilation air is brought into the ship from the outdoors, used to cool a space, and then exhausted to the outdoors. In these unairconditioned spaces, other than boiler and machinery rooms, the differences between space and weather temperatures will not exceed 15°F (NSTM 2003).

Normally occupied spaces in surface ships are to be treated to allow temperature rise over external ambient temperatures or required rate of air exchange. The Navy Shipboard Habitability Manual (OPNAVINST 1996) states a minimum OA requirement of five cubic feet per minute per person, which conflicts with NSTM and ASHRAE standards. Ventilation in sanitary spaces shall be specifically designed to minimize high humidity and odor, with a minimum air exchange rate of 15 changes per hour and a minimum of one exhaust terminal located to service each shower group (OPNAVINST 1996).

The focus of this research was to study the current ventilation design standards on board the 210 foot cutter class and 110 foot patrol boat class and to determine the effectiveness of the current systems. Figure 1-1 shows a picture of a U.S. Coast Guard 210 foot Reliance Class Cutter. Figure 1-2 shows a picture of a U.S. Coast Guard 110 foot Island Class Patrol Boat.

Figure 1-1: U.S. Coast Guard 210 foot Reliance Class Cutter

Figure 1-2: U.S. Coast Guard 110 foot Island Class Patrol Boat

Actual field data including temperature, humidity, and CO_2 concentrations and observations were taken on board these cutters both inport and underway, and under normal operating conditions. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Cooling Load Temperature Difference (CLTD) method and Society of Naval Architects and Marine Engineers (SNAME) method of load calculations were completed on a specific ventilation supply system on board the 210 foot cutter to determine the total load and cooling required. The values were compared to determine the accuracy of the SNAME method. The results of the calculations were evaluated with the ship's specifications to determine if the system is equipped to handle the calculated load and the effectiveness of providing ventilation air. The information was compared with an evaluation of current regulating industry standards to determine any disparities and areas for improvement, and recommendations for improved ventilation were also developed.

CHAPTER 2
LITERATURE REVIEW

This research focused on shipboard ventilation systems and their ability to provide acceptable indoor air quality and effective ventilation for thermal comfort and a healthy living and working environment. This is accomplished by evaluating the measures to ensure indoor air quality, and the use of carbon dioxide (CO_2) as an indicator of indoor air quality. This research also looks at conventional technology and new developments to protect ventilation systems against contamination from biological and non biological contaminants in addition to providing protection against the threat of terrorism.

2.1 Ventilation Air

Ventilation is the process of exchanging indoor air with outdoor air to create optimal conditions for humans in indoor environments, with respect to health and comfort, by removing or diluting indoor pollutants, adding or removing moisture, and by providing heating and cooling (Wargocki et al. 2002). Ventilation air can be supplied through mechanical ventilation systems or by infiltration through building envelopes (Seppanen et al. 1999). Ventilation systems on board ships are particularly important because they provide ventilation for occupants 24 hours a day and must accommodate a range of outdoor environmental conditions. There is strong evidence, as shown in previous studies, that the ventilation of buildings and the indoor environment can have significant effects on comfort, health, and worker productivity (Fisk and Rosenfield 1997; Wargocki et al. 2002; Seppanen et al. 1999; Simonson et al. 2002; Persily et al. 2005).

Ventilation systems need to be designed to ensure an acceptable indoor air quality at all times and to prevent reentrainment of exhaust contaminants, condensation, ice formation, and growth of microorganisms. Vent ducts and plenums must also be constructed and maintained to minimize the opportunity for growth and dissemination of microorganisms through the ventilation system. Duct systems on board U.S. Coast Guard cutters are insulated on outside, which enables easier maintenance and cleaning. Air filters and dust collectors may capture microorganisms, dusts, fumes, smoke, and other particulate matter. Figure 2-1 illustrates the flow path of airborne pathogens in relation to a typical air handling unit.

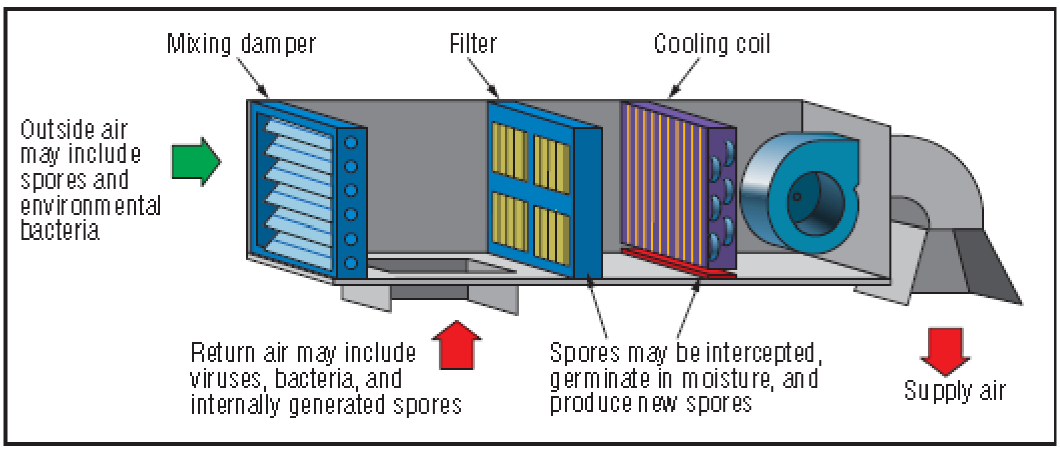

Figure 2-1. Sources and pathways of microbial contamination in typical AHU (Kowalski and Banfleth 1998).

Relative humidity (rh) should be maintained between 30% and 60% in habitable spaces to prevent growth of pathogenic or allergenic organisms. Stagnant water in heating, ventilation, and air-conditioning (HVAC) air distribution systems can also induce microbial contamination. If relative humidity in spaces, low velocity ducts, and plenums exceeds 70% fungal contamination such as mold and mildew can occur (ASHRAE 62 2001). Air handling unit condensate pans must be designed for safe drainage to preclude the buildup of microbial slime, in particular with the pitch and roll of the ship. This has been a particular problem on the 110 foot cutter with drain pans that overflow. A new design with a sloping pan has been prototyped on the 110 foot cutter to minimize this effect. Provisions should also be made for periodic cleaning of cooling coils and condensate pans. Air handling/fan coil units should be constructed for accessibility for inspection and preventive maintenance. Due to lack of space on board the cutters, these units are frequently located in hard to reach areas and small crawl spaces that often become used as additional storage space, preventing accessibility and sometimes precluding proper operation of the equipment.

Indoor air must not contain contaminants that exceed concentrations known to impair health or cause discomfort for occupants, including various gases, vapors, microorganisms, smoke, and other particulate matter. These may be present in make-up air or introduced from indoor activities, furnishings, building materials, surface coatings, and air handling/air treatment components. Deleterious factors include toxicity, radioactivity, and potential to induce infection due to allergies, irritants, extreme thermal conditions, and objectionable odors (ASHRAE 62 2001).

The sense of thermal comfort results from an interaction between temperatures, relative humidity, air movement, clothing, activity level, and individual physiology. Temperature and relative humidity measurements are indicators of thermal comfort (NIOSH 1991). They may also provide indirect indications of HVAC conditions and the potential for airborne contamination from biological or organic compounds. Comparison of indoor and outdoor temperature and humidity readings can indicate whether thermal discomfort might be due to extreme conditions beyond the design capacity of the HVAC equipment or the building envelope (NIOSH 1991). Readings that show large variations within a space may indicate a room air distribution or mixing problem.

2.2 Indoor Air Quality (IAQ)

The health and comfort of crew members reflects the total indoor environment and includes a number of indoor air quality (IAQ) parameters including: lighting, ergonomics, thermal comfort, smoking, noise, vibration, ventilation, and psychosocial or work-organizational factors (Batterman and Peng 1995). IAQ issues should be a considerable concern for the shipboard environment where personnel live and work for weeks and months at a time. There are currently no defined standards regarding indoor contaminants for buildings, although there are some common IAQ indicators that are instrumental in evaluating and solving IAQ problems. Some common indicators include contaminant concentrations, source emission rates, ventilation rates, odor and sensory perceptions, and occupant density. Additional indicators include indoor/outdoor concentration ratios, emission rates per unit floor area or building volume, and material loading factors. There are some contaminants that are frequently measured such as: CO_2, carbon monoxide (CO), total volatile organic compounds (TVOCs), microbial volatile organic compounds (MVOCs), mass and number of concentrations of aerosols and fibers, and total bioaerosol concentrations (Batterman and Peng 1995).

The indoor pollutant generation rate (source strength) is usually not constant and is affected by five major factors: (1) the level and type of pollutants outdoors, (2) possible recirculation of return air, (3) location of outdoor air intake relative to outdoor air pollution sources including exhaust air outlets, (4) pollution sources in the air handling system, and (5) pollutant removal from supply air by filters, sorbents, or deposition on duct surfaces (Seppanen et al. 1999). Indoor air quality may vary significantly due to variations in the quality of the supply air for a given ventilation rate (Seppanen et al. 1999).

The standards developed by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) are considered the lead standards in regulating indoor air quality for workplace environments and apply to all indoor or enclosed spaces that people may occupy, except where other applicable standards and requirements dictate larger amounts of ventilation are required. ASHRAE Standard 62 defines indoor air quality as the amount of outdoor air required to control moisture, carbon dioxide, and odors, which have led to a minimum rate of outdoor air supply per occupant (ASHRAE 62 2001). Table 2-1 summarizes the outdoor air requirements for ventilation for commercial facilities.

The minimum outside air supply per person for any type of space is 15 cubic feet per min (cfm). This minimum rate will maintain an indoor CO_2 concentration below 1000 ppm (or 1%) based on an outdoor concentration of 350 ppm (ASHRAE 62 2001).

Application/Area	**CFM* Per Person**	**L/s** Per Person**
Commercial Laundry	25	13
Dining Rooms	20	10
Kitchen (cooking)	15	8
Cafeteria	20	10
Dormitory Sleeping Areas	15	8
Conference Rooms	20	10
Office Spaces	20	10
* Cubic feet per minute	** Litre per second	

Table 2-1: Outdoor Air Ventilation Requirements (ASHRAE 62 2001).

Two procedures for determining acceptable indoor air quality include the Ventilation Rate procedure and the Indoor Air Quality procedure. The Ventilation Rate procedure defines air quality as acceptable if the concentrations of pollutants in the incoming outdoor air meet the US National Ambient Air Quality Standards (NAAQS) and if the outdoor air supply rates meet or exceed values provided in Table 2-1.

The Indoor Air Quality procedure defines outdoor air supply rate as acceptable if: 1) the indoor concentrations of 9 pollutants are maintained below specified values, and 2) the air is deemed acceptable via subjective evaluations of odor (ASHRAE 62 2001). High rates of ventilation are required to control contaminant levels for areas with high contaminant source strengths; however other methods of control may be more effective, such as filtration.

Comfort and odor criteria (with respect to bioeffluents) are most likely to be satisfied according to the Ventilation Rate procedure, if indoor CO_2 concentrations are less than 700 ppm above the outdoor air concentration. CO_2 concentrations in acceptable outdoor air typically range from 300-500 ppm. High CO_2 concentrations can be an indicator of combustion or lack of proper ventilation (ASHRAE 62 2001).

2.3 Carbon Dioxide as an Indicator of IAQ

CO_2 is a normal constituent of the atmosphere and not a contaminant of IAQ, but indoor CO_2 concentrations are an effective indicator of the adequacy of the ventilation system in providing appropriate ventilation air per occupant, and a surrogate for the indoor concentration of bioeffluents (Apte et al. 2000). Comparison of peak CO_2 readings between rooms, air handler zones, and at varying heights above the floor may also help to identify and diagnose various building ventilation deficiencies (NIOSH 2003).

To effectively use CO_2 as an IAQ indicator, the National Institute of Occupational Safety and Health (NIOSH) recommends that measurements be collected away from any source that could directly influence the readings, and to take one or more readings in “control” locations to serve as baselines for comparisons (NIOSH 2003). Outdoor air samples should be taken near the outdoor air intake and indoor measurements should be collected when the concentrations are expected to peak. If occupant population is fairly stable during normal business hours, CO_2 levels will typically rise during the morning, fall during the lunch period, then rise again mid afternoon. In this case, sampling should take place in the mid to late afternoon (NIOSH 2003). Peak CO_2 concentrations above 1000 ppm in the breathing zone are indicative of ventilation rates that are unacceptable with respect to body odor and bio-effluents. Concentrations of CO_2 below 1000 ppm are not indicators that the ventilation rate is adequate for removal of air pollutants from other indoor sources (Seppanen et al. 1999). Elevated CO_2 measurements may be due to increased occupant population, air exchange rates below ASHRAE guidelines, poor air distribution, and poor air mixing. If CO_2 readings, taken before the occupied period begins, are higher than outdoor readings taken at the same time, there may be a problem with the HVAC system. Outdoor concentrations above 400 ppm may indicate an outdoor contamination problem from traffic or other combustion sources (NIOSH 2003). Seppanen et al. and Apte et al. both found that dose dependent increases of up to a factor of six in the risk of building-related lower respiratory and mucous membrane irritation symptoms when average workday indoor CO_2 concentrations increased by 420 ppm above outdoor levels (Seppanen et al. 1999; Apte et al. 2000).

2.4 Indoor Air Quality Contaminants

Indoor air quality (IAQ) and human health can be affected by exposure to both living and non living biological contaminants. These indoor air contaminants can be grouped into three categories: 1) contaminants generated within the space, 2) environmental contaminants introduced into the space, and 3) organic contaminants that breed within the space (Coad 1999). Contaminants generated with a space may include biological odors and artificial aromas from occupants, CO_2, and volatile organic compounds (VOCs) from building materials within the space. Environmental contaminants include pollutants such as CO, sulfur, industrial chemicals, and other substances that may be found in the outdoor environment. Organic compounds that breed within a space are considered the most harmful, and include microbes, mold, mildew, and microbial volatile organic compounds (MVOCs). This study focused on the third category of contaminants.

2.4.1 Microbial Contamination

Mold and mildew are defined as fungi that grow on the surfaces of objects, within pores, and in deteriorated materials. In addition to causing discoloration and odor problems, mold gives off spores and mycotoxins that may cause irritation, allergic reactions, or disease in immune-compromised individuals (Bahnfleth and Kowalski 2005). The structure of the fungal cell is similar to that of plants and animals. The fungal cell is bounded by rigid wall that contains a material similar to that in insect exoskeletons (Burge 1997). The fungal cells can exist as single cells, but the most common fungal bodies are composed of long chains of cells called hyphae. The hyphal strands secrete enzymes designed to digest substrates so the dissolved nutrients can be absorbed (Burge 1997). Fungi produce new cells by mitosis (nuclear division) and cell division. Most fungi produce several spore forms that are disseminated through the air and remain airborne for long periods of time. Spores are always present in the outdoor air, and in buildings, providing a continuous source of organisms to colonize (Burge 1997). The most commonly found type of mold in the indoor environment is the

Aspergillus species, which has been found to account for 80% of indoor spores (Kowalski and Bahnfleth 1998).

For mold growth to occur on surfaces, the temperature range must be between 40º F to 100º F (NIOSH 1991). Mold spores, a nutrient base, and moisture must also be present. Mold growth does not require standing water to be present, but can occur when high relative humidity or if the hygroscopic properties of building surfaces allow sufficient moisture to accumulate (NIOSH 1991). Water vapor moves in and out of spaces as part of the air that is mechanically introduced to spaces or that infiltrates or exfiltrates through openings in the building's shell. The ability for the air to hold water vapor decreases as the temperature of the air is lowered; thus as the air cools, the relative humidity increases. If the air is saturated (at 100% rh) the water vapor condenses, changing from a gas to a liquid. Air can reach 100% rh without changing the amount of water vapor; rather all that is required is for the air temperature to drop below the dew point. The highest rh in a space is always next to the coldest surface, and is called the "first condensing surface." This type of mold development through condensation is typical on board USCG cutters. For mold growth the humidity level of a space or water source must be maintained long enough for the fungi to become established. Although there is not much data supporting this figure, it has been proposed that at least 48 continuous hours are required for mold to develop (Burge 1997; EPA 2001). As stated above, temperature also plays a direct role in the colonization of fungi. At relatively low temperatures (50º-60º F) spores take longer to germinate and grow than at higher temperatures such as 60º-70ºF.

Mold and mildew can be controlled by reducing the moisture content (vapor pressure) of the air, increasing air movement at the surface, or increasing the air temperature (either space temperature or temperature at building surfaces) (NIOSH 1991). Surface temperature dominated mold and mildew can be reduced by increasing the temperature of the air by raising the thermostat setting or by improving air circulation, or by decreasing heat loss by adding insulation and closing cracks. Vapor pressure dominated mold and mildew can be reduced by source control, dilution of moisture rich indoor air with outdoor air that is at a lower absolute humidity, or by dehumidification (NIOSH 1991).

2.4.2 Microbial Volatile Organic Compounds (MVOCs)

Microbial volatile organic compounds are a product of the decomposition of complex organic compounds into simpler compounds, carbon dioxide, and microbial biomass (Wessen and Schoeps 1996). As a metabolic by-product of bacteria and fungi, they can be detectable before any visible signs of microbial growth appear. These MVOCs are responsible for the unpleasant odors associated with fungal growth and are able to penetrate building materials, such as wallpaper and small clefts, and diffuse into the surrounding air (Schleibinger et al. 2005; Korpi et al. 1998). Thus, identification of MVOCs may indicate microbial contamination when other signs of microbial growth cannot be detected (Korpi et al. 1998; Wilkins and Larsen 1995; Wessen and Schoeps 1996; Black et al. 1998; Fiedler et al 2001). Although their health impact has not been extensively studied, these volatiles have been shown to impact the cilial cells in respiratory airways, and are blamed for a variety of building related health effects (Wessen and Schoeps 1996). Pasanen et al. found that the probability of irritating symptoms caused by microbial contamination in buildings would increase considerably when airborne concentrations of MVOC's are on the level of hundreds of μg/m^3 and mg/m^3 (1998). Analysis of MVOCs in air in addition to fungal spores and mycotoxins, allows for a more precise evaluation of indoor air quality and possible health risks, and is important in determining masked contamination by molds.

Current research has identified unique MVOCs (UMVOCs), substances only produced by fungi or bacteria. These UMVOCs are not a result of sources common in indoor environments such as building materials (Gao et al. 2002). Gao et al. identified a number of UMVOCs produced by the *Aspergillus species*, one of the most commonly found types of mold in indoor environments (2002). These UMVOCs have the potential to be used as markers for indoor mold growth.

It was shown in a study by Wessen and Schoeps that micro-organisms produced different VOCs when grown on different materials (1996). Due to the fact that the production of microbial metabolites is affected by the species and media, it makes it difficult to clearly identify the effect of fungal species and building material on MVOC production (Wilkins and Larsen 1995; Korpi et al. 1998). While several MVOCs may be useful indicators, additional studies are required for better indoor air analysis

Guidelines for public health exposure for limited VOCs are available in the World Health Organization (WHO) Air Quality Guidelines for Europe (1982). These guidelines address noncarcinogenic and carcinogenic effects. Occupational exposure standards exist for many other VOCs but none are endorsed by the EPA or NIOSH (NIOSH 2003).

2.5 Health Effects of Poor Indoor Air Quality

Current evidence indicates the link between health and productivity in relation to the quality of the indoor environment. These links include infectious disease, allergies and asthma, sick building health symptoms, and direct impacts of worker performance

(Fisk and Rosenfield 1997). Some of the effects of indoor air problems can result in sick building syndrome (SBS), building related illness (BRI), and multiple chemical sensitivity (MCS). A study by Wargocki et al. found that reducing the pollution load on indoor air proved to be an effective means of improving the comfort, health, and productivity of building occupants (1991, 2002).

Approximately 20% of the US population has environmental allergies and approximately 10% have asthma (Fisk and Rosenfield 1997). The symptoms of allergies and the portion of asthma caused by airborne allergens can be triggered by a number of allergens in indoor air, including fragments of dust mites, allergens from fungi and insects, contaminants from outdoors, irritating chemicals in indoor air, and moisture and microbiological material (Fisk and Rosenfield 1997). The symptoms of allergies and asthma may include headache, fatigue, shortness of breath, congestion, cough, sneezing, eye/nose/throat irritation, skin irritation, dizziness, and nausea (DOE 2001).

Sick building syndrome (SBS) is used to describe cases where occupants experience acute health and comfort effects that are linked to the time they spend in a building, but in which no specific illness or cause can be identified. Symptoms often include respiratory complaints, irritation, and fatigue. Problems may be caused by the combined effects of multiple pollutants at low concentrations, environmental stressors (overheating, poor lighting), ergonomic stressors, job-related psychosocial stressors, and other unknown factors (OSHA 1999; NIOSH 2003; DOE 2001). Figure 2-2 shows the risk of SBS symptoms as a function of ventilation rate, based on a study of 160 office buildings in Sweden. This study conducted by Sundell and Lindvall involved indoor climate investigations and measurements (outdoor airflow rate) in 540 office rooms and questionnaire reports from 4943 office workers (1993). The symptoms of SBS, documented by the detailed questionnaire report, covered general symptoms (fatigue, headache, etc.), mucous membrane symptoms, and skin symptoms (Sundell and Lindvall 1993). The odds ratio used is a measure of the strength of the association between the symptoms of SBS, health outcome, and exposure factors and is an estimate of the odds, approaching relative risk, of being affected when exposed (Sundell and Lindvall 1993). The OA flow rate of 10 L/s is equivalent to 20 CFM as defined per ASHRAE Standard 62. A study conducted by Apte et al. found that increases in ventilation rates, sufficient to reduce CO_2 concentrations to outdoor levels, would be expected to decrease the prevalence of selected SBS symptoms by 70% to 85% (2000).

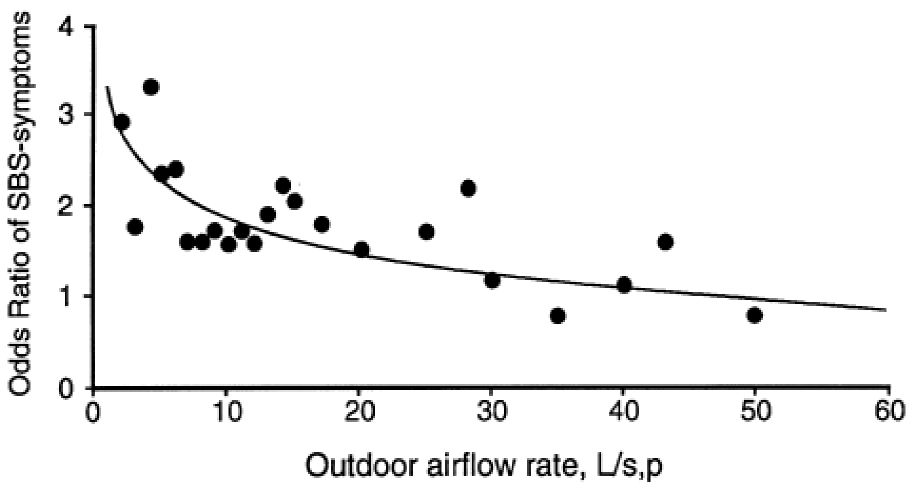

Figure 2-2. The risk of Sick Building Syndrome (SBS) symptoms as a function of ventilation rate in 160 office buildings in Sweden (Fanger 2001).

Building-related illness (BRI) refers to illness brought on by exposure to a building, where symptoms of a diagnosable illness are identified and can be directly attributed to environmental agents in the air. Legionnaire's disease and hypersensitivity pneumonitis are examples of BRI that can have life threatening consequences (NIOSH 2003; DOE 2001). Multiple chemical sensitivity (MCS) is sensitivity to a number of chemicals in indoor air, each of which may occur at low concentrations. Although this condition is not well understood, it is attributed to high levels of exposure to certain chemicals (NIOSH 2003; DOE 2001).

The amount of any allergen that must be inhaled for sensitization to occur is unknown as is the amount of any allergen required to trigger symptoms. This missing information is the reason why standards for safe exposures to allergens have yet to be developed.

Indoor environments have a direct impact on worker productivity and performance, and should be a consideration in providing acceptable indoor air quality. Fisk and Rosenfield reported that productivity increases of just 1% correspond to reduced sick leave of two days per year, reduced breaks from work or increased time at work of 5 minutes per day, or a 1% increase in the effectiveness of physical and mental work (1997). This is particularly important to shipboard military environment where high productivity is demanded and essential, and personnel live and work for weeks and months at a time.

2.6 HVAC System Components

HVAC systems range in complexity and use. Thermal comfort is maintained by mechanically distributing conditioned (heated or cooled) air throughout the building. Air systems can be supplemented by piping systems that carry steam or water to the building perimeter zones. A single air handling unit can serve more than one area if the areas served have similar heating, cooling, and ventilation requirements, or if the control system compensates for differences in heating, cooling, and ventilation needs. Areas regulated by a common control are called zones. Thermal comfort problems can result if the design does not adequately account for differences in heating/cooling loads between rooms in the same zone (NIOSH 1991). Multiple zone systems can provide each zone with air at a different temperature by heating or cooling the air stream in each zone. Alternative design strategies involve delivering air at constant temperature, while varying the volume of airflow, or modulating room temperature with a supplementary system, such as perimeter hot water piping (NIOSH 1991). Constant volume systems deliver a constant airflow to each space. Temperature changes in spaces are made by heating or cooling the air, or switching the air handling unit on or off. These systems operate with a fixed minimum percentage of outdoor air (NIOSH 1991). Demand control based ventilation systems use sensors, typically CO_2, to determine the instant requirement (demand) of fresh air in that space, and regulate the airflow accordingly.

2.6.1 Filters

Air filters are primarily used to remove particles from the air. The type and design of filter determine the efficiency at removing particles of a given size and the amount of energy needed to pull or push air through the filter. Figure 2-2 shows some common air contaminants and their relative size.

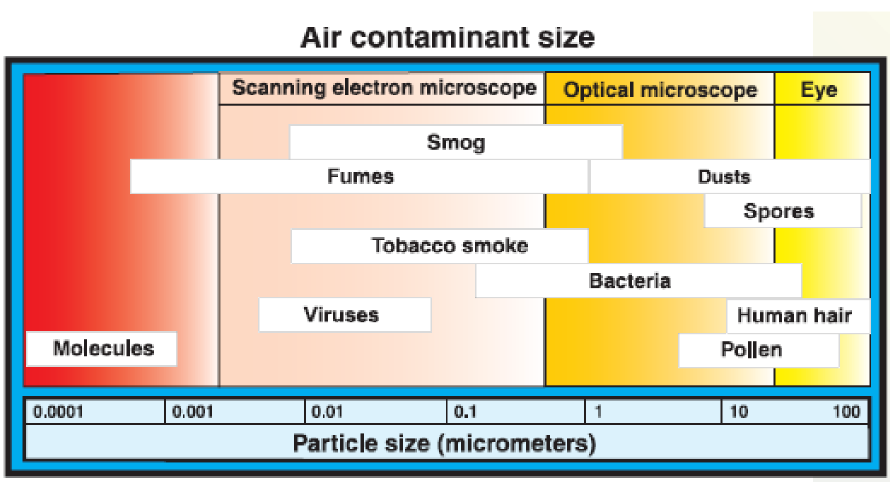

Figure 2-3. Common air contaminants and their relative size (NIOSH 2003).

Low efficiency filters (ASHRAE Dust Spot Rating of 10% to 20% or less) are used to keep lint and dust from clogging the heating and cooling coils of a system. Filters must also remove bacteria, pollens, insects, soot, dust, and dirt with an efficiency suited for the use of the building. Medium efficiency filters (ASHRAE Dust Spot rating of 30% to 60%) can provide much better filtration than low efficiency filters, but require more airflow and additional energy to move air through them. High efficiency extended filters (ASHRAE Dust Spot rating of 85%) can be used with a medium efficiency pre-filter or alone (NIOSH 2003). Filters are also available to remove gases and volatile organic contaminants from ventilation air. Permanganate oxiders and activated charcoal may be used for gaseous removal filters. Partial bypass carbon filters and carbon impregnated filters may also be used to reduce volatile organics in the ventilation air (NIOSH 2003).

One of the most crucial aspects of air filters is regular maintenance, cleaning, or replacement. As a filter loads up with particles, it becomes more efficient at particle removal but this also increases the pressure drop through the system, therefore reducing airflow. If dirt accumulates in ductwork and if the relative humidity reaches the dew point, so that condensation occurs, then the nutrients and moisture may cause the growth of microbiologicals (NIOSH 2003).

2.6.2 Heating/Cooling Coil

Heating and cooling coils are used to regulate the temperature of the air delivered to a space. In the cooling mode cooling coils provide dehumidification as water condenses from the air stream; this can only take place if the chilled water fluid is maintained at a temperature generally below 45 degrees. Condensate collects in the drain pan under the cooling cool. If the drain pan has been not properly designed according to ASHRAE standards, the standing water can accumulate and mold and bacteria can develop. In the heating mode, if the hot water temperature in the heating coil has been set too low, the air may not be heated sufficiently to maintain thermal comfort or adequately condition the outdoor air (NIOSH 2003).

Condensation on insulated piping can occur when ‘two pipe’ systems are used. These systems provide heating and cooling via two pipes with a common heating/cooling coil (Ecker 2005). This is particularly common with shipboard systems due to space restrictions. The piping system carries chilled water for cooling in the summer and hot water in the winter for heating. Due to thermal expansion and contraction, the seams of the insulation may loosen and humid air may become trapped between the insulation and piping and condense causing the insulation to become wet, and a potential source for mold growth (Ecker 2005).

2.7 Chemical, Biological, Radiological (CBR) Protection

Since the September 11, 2001 attacks on the World Trade Center, the emerging threat of a chemical, biological, and radiological (CBR) attack is a real and present danger. It is essential to provide protection to the military, which are providing the security to ensure the safety of our nation. Without effective protection, they are limited in their ability to perform their missions and are put at an unnecessary risk.

There are several ventilation based strategies that have been proposed to protect building occupants from the accidental and intentional release of airborne CBR contaminants, which can be applied to marine applications. Ventilation can provide both positive and negative impacts with respect to CBR agents. Ventilation can reduce the levels of agents through dilution with outside air, and can also provide effective filtration and removal of contaminants through use of air cleaning equipment and filters (Persily

2004). Ventilation can negatively influence the dispersion of CBR agents through outdoor air intakes or envelope pressures in the building.

One strategy to protect against outdoor releases of CBR agents is through space pressurization. This would require enough outdoor air so that the indoor pressure increases above the outdoor pressure at all air leakage sites. This is only effective if the filtration system is equipped to block the effective agents. However there is also the issue of contaminant entry through leakage. To prevent this from occurring, the building envelope must be kept sufficiently tight to ensure the airflow rate for pressurization is maintained. Another strategy is to design ventilation systems with installed agent detectors that trigger damper and fan operation to isolate zones and provide safe areas on the ship. Such systems are considered costly and there is a limitation in the number of agents that can be detected.

2.8 Alternative Technology

New engineered alternatives to IAQ contamination control may include purging with outside air, filtration, ultraviolet germicidal irradiation (UVGI), photocatalytic technologies, and isolation through pressurization control. IAQ goals, energy consumption, replacement cost, and lifecycle analysis should dictate the economic choice for a particular alternative (Kowalski and Bahnfleth 2003).

Pressurization control, as described in the above section, is often used in biohazard facilities and isolation rooms to prevent migration from one area to another, but inherent costs and operational instability at normal air flow rates limit feasibility for other applications (Kowalski and Bahnfleth 2003).

HEPA filters, which are highly efficient at removing IAQ contaminants, can be used alone or in combination with ASHRAE rated filters. High or medium efficiency filters are also capable of removing airborne pathogens, such as spores, without high operation or replacement costs. To increase efficiency, these filters should be placed in the recirculation loop or downside of the cooling coil (Kowalski and Bahnfleth 2003). Electrostatic filters and biocidal filters can limit or prevent fungal growth on the filter media, in addition to carbon adsorbers, which are effective at removing VOC's produced by some fungi and bacteria (Kowalski and Bahnfleth 2003). HEPA filters are only effective at removing particles up to 3 microns in size, which limits their ability to remove contamination by microorganisms such as viruses.

UGVI systems for air disinfection are an emerging and very efficient method for controlling microbial growth on cooling coils and deactivating airborne viruses and bacteria (Bahnfleth et al. 2005). It has been successfully used for disinfection of small areas, but has not been proven to work well in central ventilation systems. UGVI is not effective at degrading chemicals such as formaldehyde, styrene, and toluene (Goswami 2003). Despite promising developments in this area, there is no consensus guidance on the design, installation, commissioning, and certifications of UVGI systems (Bahnfleth et al. 2005). Without this guidance, there is no method to ensure the performance and reliability of these systems.

Photocatalytic technology is an emerging area that is proving to be effective at decontaminating air and reducing indoor air pollution in ventilation systems. It has been demonstrated successful at removing microorganisms, VOCs, bacteria, and spores, while providing protection against bioterrorism agents. According to D.Y. Goswami, the photocatalytic process involves the action of low energy UV light on a catalyst in the presence of water vapor, which generates hydroxyl radicals that destroy microbes and airborne VOCs. It has most recently been shown capable of destroying species similar to *anthrax* (Goswami 2003). Relative humidity (rh) is an important factor in the effectiveness of photocatalytic technology. Goswami found that the optimum rh to achieve 99% disinfection of air by photocatalysis was between 40%-70%, with the best performance being around 50% (2003). This technology, when combined with the use of a HEPA filter, becomes an effective answer to the indoor air quality problem and can be integrated into central air conditioning systems or used in stand alone units (Goswami 2003).

The use of liquid and dry desiccants in HVAC systems are an alternative to mechanical refrigeration systems. Desiccants are materials which attract and hold water vapor through absorption or adsorption. According to Daou et al, the outside air is dehumidified by forcing it through a desiccant material and then drying the air to the required indoor temperature (2006). The water vapor that is adsorbed/absorbed must then be removed from the desiccant (regeneration), which is accomplished by heating the desiccant to its temperature of regeneration (Daou et al. 2006). Once the desiccant is dried enough to adsorb water, it will be recycled through the process. In the case of Coast Guard cutters, use of a desiccant system with a conventional cooling system could remove the entire latent load and part of the sensible load from the supplied outdoor air, while the internal FCUs handle the rest of the sensible load (Liu et al. 2006). Waste heat from the ship service generators and main diesel engines can be used in the regeneration of the desiccant. By removing the humidity from the air, the air conditioning requirements are reduced, indoor air quality is improved, and the coefficient of performance (COP) is increased.

2.9 Current Ventilation System Design for Ships

HVAC design for shipboard use depends on the ship's mission. Factors such as weight, size, corrosion resistance, and tolerance for pitch/roll, and vibration are important considerations. On board military ships, HVAC systems must provide an environment in which personnel can live and work without heat stress, in addition to providing reliability of electronic and other critical equipment, as well as weapons systems (ASHRAE 2003) Ventilation must meet requirements of ASHRAE Standard 62, unless otherwise stated in ship's specification. Design outside ambient conditions for naval vessels are 90ºF db and 81ºF wb, with 85°F seawater conditions. Heating season temperatures are 10ºF for outside air and 28º F for seawater. Naval ships are typically designed for space temperatures of 80º F db with maximum of 55% rh for most areas requiring air conditioning. Current naval ship design requires air conditioning systems replenish air in accordance with damage control classifications, as specified in USN (1969):

- Class Z systems: 5 cfm OA per person
- Class W systems for troop berthing areas: 5 cfm per person
- All other Class W systems: 10 cfm per person. The flow rate is increased only to meet either a 75 cfm minimum branch requirement or to balance exhaust requirements.

The ventilation onboard the CGC VENTUROUS (WMEC 210) consists of supply, exhaust, and recirculation systems. See Appendix A for the ventilation diagrams. The ventilation exhaust and supply system for living quarters, mess deck, ship's office, and I.C. gyro room supplies air to satisfy the fresh air requirement for personnel. Steam preheaters, dehumidification coils, and electric reheaters are fitted in these systems and are thermostatically controlled. The supply systems are fitted with thermostatically controlled steam preheat coils only. The supply system for the steering gear room is provided with a single speed fan, only for ventilation purposes. The supply and exhaust system for the machinery spaces are fitted with two speed fans for the purpose of ventilation only.

The air conditioning on the 02 deck is accomplished by a ducted recirculation system (02-82-2). A two speed fan is fitted in the system and operates at high speed during cooling season and low speed during heating season. The fan discharges through an electrostatic precipitator, duct mounted cooling cools, and duct mounted electric reheaters. Each electric reheater is thermostatically controlled. The exhaust from each zone is ducted via the return side of the recirculation system back to the inlet side of the fan. A portion of the air equal to the replenishment quantity is exhausted through the door and passageway, to the exhaust terminal system. Replenishment air is drawn from the fan room, which serves as a supply plenum and is fitted with a steam operated and thermostatically controlled preheater in the exterior air supply. The cooling coil is a hydronic type supplied from the air conditioning chilled water system. The flow of water to the coil is controlled by thermostatically operated (Navy type 2PD) solenoid valves, which are located in each of the zones serviced by the system. The electric reheaters in the system are thermostatically controlled and serve as supplemental heat during the heating, cooling, and ventilation operations. The thermostats are duct mounted and sense and control the air temperature on the discharge side. The Navy type 2PD space thermostats only operate at the times the space requires additional heat.

Steam operated preheaters are installed in the weather air supplies to the galley, laundry, flammable stores, auxiliary machinery room, sewage space, and refrigeration equipment space. The steam supply lines are fitted with thermostatically controlled valves which have thermostats that are adjustable and sense and regulate the temperature of the air leaving the heater. Electric duct reheaters are installed in the supply ducts to the three zones on the 02 Level recirculation system, the 01 level berthing areas, and main deck berthing areas. The thermostats controlling the heaters are duct mounted and sense and control the air temperature on their discharge side. Fan electric space heaters are installed in all toilet and shower spaces, the engineer's workshop, helo room, I.C. gyro room, and bosun storeroom to supply heat to these rooms.

Fan coil type air conditioning units are furnished to provide heating and cooling for all quarters and control spaces. The units are equipped with three-speed fans and bulkhead mounted speed control switch. Bulkhead mounted thermostats are provided in the spaces served and control the flow of water to the coil of the unit. For spaces with more than one fan coil unit, all units are controlled by a singe thermostat and fan speed switch. Gravity cooling coils are furnished to provide cooling for the magazine and handling room. Solenoid valves, located in the handling room, controls the flow of water to the units. Remote type thermostats are furnished to sense the compartment temperature and actuate the solenoid valves.

Cleanable type air filters are installed in the weather deck supply openings for the galley, the replenishment air supply intakes for the living spaces, 02 deck recirculation system, 2nd deck storerooms, and auxiliary machinery spaces.

The chill water circulating system is split into three zones: forward, aft, and control space zone. The forward and aft zones are each serviced by 25 ton units that are operated in parallel. The control space chilled water zone is serviced by two 5 ton units. The systems' supply and return is through manually operated, 3- way, 3- port valves, located in the sewage disposal compartment. The valves are installed to provide a designed rate of water flow to each unit. Seasonal changeover of this system is accomplished by setting the four 3-way valves to their required positions and stating the applicable heating or chilling units.

The ventilation/air conditioning system on board the CGC DRUMMOND (WPB 110) consists of 5 air handling units (AHUs) that operate independently and are positioned throughout the ship to provide conditioned air for its associated compartments (zones). See Appendix A for the 110 foot cutter ventilation system drawings. The air handling units consist of an evaporator coil, electric strip heater, blower fan, inlet and outlet valves, an expansion valve, and a liquid solenoid valve. The air handling units are capable of removing or adding heat to the air being circulated by the blower. The evaporator coil and strip heater are controlled by local control switches. A 10 ton capacity chill water system supplies all 5 AHUs.

Zones 1, 3, 4 AHUs, which supply air to aft berthing, CPO quarters, main passageway, fwd quarters, and pilot house, are each 2 ton units, fitted with an 800 cfm blower and a 3.5 kW strip heater. The Zone 2 AHU services the galley and messdeck, and has a 4 ton capacity. It is fitted with a 1600 cfm blower and 10 kW strip heater. Zone 5 AHU, which services the bridge, CO and XO’s berthing space, and electronics space, has a 3 ton capacity and is fitted with a 1200 cfm blower, and 7 kW strip heater. The 4 heads on board are fitted with 50 cfm exhaust blowers that discharge into the naturally vented void space between the joiner work and the side shell.

CHAPTER 3
ANALYSIS METHODOLOGIES

This chapter outlines the analytical procedure used to find the expected energy requirements and air conditioning cooling load on board the 210 and 110 foot cutters. A number of factors and variables affect cooling load calculations, and cooling load components vary greatly during a 24 hour period making it difficult to have precise values. Cooling load calculations are particularly challenging for shipboard design, due to a constantly changing weather and sea conditions, ship orientation, and ship structure.

Space heat gain is the rate at which heat enters into and or is generated within a space at a given instant of time. Heat gain in a space is classified by: (1) the mode in which it enters the space, and (2) whether it is sensible or latent heat gain. Heat gain can occur in the form of: (1) solar radiation through transparent surfaces, (2) heat conduction through exterior walls and roofs, (3) heat conduction through interior partitions, ceilings, and floors, (4) heat generated within a space by occupants, lights, and equipment, (5) energy transfer as a result of ventilation and infiltration, and (6) miscellaneous heat gains. The type of heat gain is essential for correct selection of cooling equipment. Sensible heat gain is when there is direct addition of heat to the conditioned space by any or all mechanisms of conduction, convection, and radiation. Latent heat gain is when moisture is added to the space. Cooling equipment must be able to provide adequate sensible heat removal capacity and latent heat removal capacity to meet the space cooling load.

The space cooling load is the rate at which heat must be removed from the space to maintain room air temperature and humidity at a constant value. Heat extraction is the rate at which heat is removed from an air conditioned space by the cooling and dehumidification equipment. The space cooling load at a given time does not necessarily equal all the instantaneous space heat gains due to radiation effects, thermal storage, and thermal lag.

Current standards for building cooling load calculations follow procedures as defined by the ASHRAE Fundamentals Handbook, which defines several methods that can be used to perform the calculations (2005, 1997, 1981). The most recent edition, 2005 Handbook Fundamentals, describes the Heat Balance (HB) in detail as the primary method of load calculation. The HB method involves calculating a surface-by-surface conductive, convective, and radiative heat balance for each room surface and a convective heat balance for the room air (ASHRAE 2005). The HB method uses no arbitrarily set parameters and solves the calculations directly instead of introducing transformation based procedures (ASHRAE 2005). The HB method involves complex iterative calculations that require the use of computers. The Radiant Time Series (RTS) method is a more simplified method derived from the HB method. It is suitable for peak design load calculations, and although it is simple in concept, it involves too many calculations to be used as a manual method (ASHRAE 2005). ASHRAE 2005 recommends the Cooling Load Temperature Difference/Cooling Load Factor (CLTD/CLF) method in 1997 ASHRAE Handbook Fundamentals for manual cooling load calculations. The CLTD/CLF method, other wise known as the Transfer Function Method (TFM) uses regression data of computer generated transfer function solutions, with cooling load temperature differences (CLTD) and cooling load factors (CLF) for each component of the space cooling load. These values include the effect of time lag due to thermal storage. For this research, the 1981 ASHRAE Handbook of Fundamentals CLTD/CLF procedure was used, based on the applicability to perform manual calculations. Manual calculations allowed for a more detailed look at the various cooling load components on board the cutter and the ability to compare the results with the current shipboard method of calculation. Although there are updated versions of this procedure, the 1981 tables correlated more closely with the materials and conditions found on board the cutters. The calculations were completed for July 21, at1800 for St Petersburg, Florida (28 N Latitude) based on the information found in the 2001 ASHRAE Climatic Design Information, Handbook Fundamentals. . The calculations were completed manually using a Microsoft Excel Spreadsheet.

Current Navy standards for shipboard cooling load calculations use general recommended practices defined by the Society of Naval Architecture and Marine Engineers (SNAME) in Technical and Research Bulletin 4-16, Recommended Practices for Merchant Ship Heating, Ventilation, and Air Conditioning Design Calculations. This manual was last updated in 1980. The calculations do not consider a time lag due to thermal storage. The calculations also do not consider a specific day, time, or location; instead they are a general calculation using base values for any given time. The calculations were completed manually using a Microsoft Excel Spreadsheet.

For this research, the ventilation supply system 1-65-1 on CGC VENTUROUS was evaluated using the CLTD and SNAME method. This system was chosen because it supplies the majority of the 210 foot cutter’s living, working, and eating spaces. This system supplies 24 compartments on board the cutter. Each compartment serviced by this system was analyzed and evaluated to determine the internal room loads due to transmission across boundaries, glass, solar, equipment, and personnel; and the ventilation load due to outside air. The total system load was calculated as a sum of the loads from each compartment. Appendix B shows the detailed breakdown of the compartment calculated loads using the CLTD method. Appendix C shows the detailed breakdown of the compartment calculated loads using the SNAME method. The results were compared using the two methods, and compared to the values listed on the ship's drawings. Appendix D contains the summary of results.

Field data measurements and visual observations were taken on board the USCGC VENTUROUS (210 foot cutter) and USCGC DRUMMOND (110 foot cutter). The recorded data included CO_2 concentration, temperature, dew point, and relative humidity. A hand-held Testo 535 CO_2 infrared absorption sensor, with an accuracy of +/- 50 ppm, was used to measure CO_2 concentrations. A hand-held Thermo-Hygro temperature and humidity sensor was used to measure dry bulb and wet bulb temperatures, and relative humidity. These readings were taken while the cutters were underway and inport, under normal operating conditions, and with full crew complement. The readings were taken mid day during the months of May and June in each of the spaces supplied with ventilation air. The underway data for the VENTUROUS and DRUMMOND were taken approximately 30 miles off the coast of Key West, while the inport data was taken at USCG Sector Key West. Carbon Dioxide (CO_2) was measured to evaluate the outdoor air (OA) supplied to each space. The optimum carbon dioxide level was based on ASHRAE Standard 62, which states that the allowable buildup of CO_2 concentration should not exceed a difference of 700 ppm between space and outdoor conditions. The recorded temperature, dew point, and relative humidity were taken as per prcocedure defined in ASHRAE 55 and compared to design requirements and ship specifications. They were evaluated to determine if the ventilation air was being effectively treated to provide acceptable indoor air quality (IAQ).

CHAPTER 4
ANALYSIS AND DISCUSSION

The ASHRAE Cooling Load Temperature Difference (CLTD) method and Society of Naval Architecture and Marine Engineering (SNAME) method of load calculations were performed to determine the effectiveness of the current ventilation system on board the 210 foot cutter class. Like many of the Coast Guard vessels, these ships are operating with old systems that have not been updated or modified to reflect today's current commercial standards and policy.

Both methods of calculations were performed to determine the total space cooling load (Btu/h) and cooling required (Btu/h, tons) for the main operating system on the ship, which services all the major working, eating, and living spaces. These values were compared to determine the accuracy of the SNAME method as compared to a more conventional land based method. The results were then compared to the ship's specifications to determine if the system is equipped to handle the calculated load, and its effectiveness of providing ventilation air.

To complete both methods of calculations, a detailed study of the ship's plans and drawings was conducted. This provided the baseline for the values used in the calculations, although a number of assumptions and interpretations were required, due to lack of specifics in the drawings and plans. The following paragraphs describe the results of the two methods of calculations and the assumptions made.

4.1 U-Value Determination

The Design Heat Transfer Coefficients (U-Value) for the cutter envelope components were an important parameter in both the CLTD method and SNAME method load calculations. Both methods used SNAME Technical and Research (T&R) Bulletin No. 4-7, Thermal Insulation Report, to determine the required U-values for the calculations. SNAME T&R 4-7 designates separate U values for boundary conditions including: solar radiation, weather air to inside air, inside air to inside air, and seawater to inside air. The envelope construction was determined by the ship's drawings. Typical exterior bulkhead construction is shown in Figure 4.1 and typical interior watertight bulkhead construction is shown in Figure 4.2.

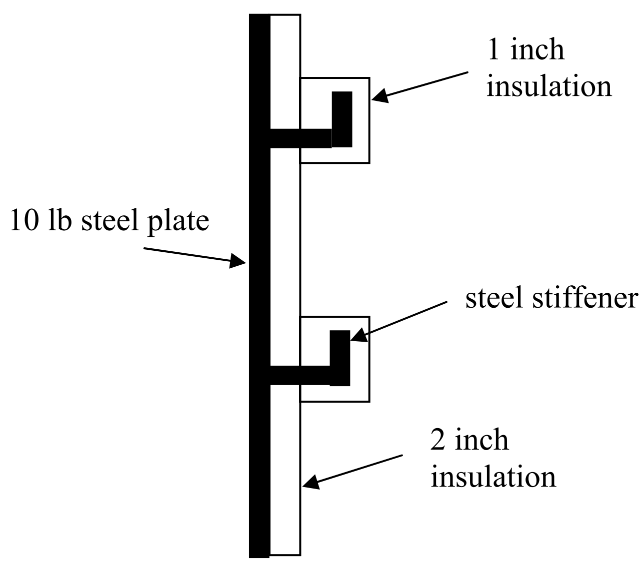

Figure 4-1: Typical exterior bulkhead construction

In places on the ship where 7/8 inch thick (3/4 inch cell) non metallic honeycomb Nomex is used, the U-value for 7/8 inch Marinite 36# was substituted. The thermal conductivity for 7/8 inch Marinite 36# is 0.760 (Btu-in)/(h-ft^2-°F). Figure 4-3 shows the thermal conductivity of 7/8 inch (3/4 inch cell) Nomex to be approximately 0.760 (Btu-in)/(h-ft^2-°F).

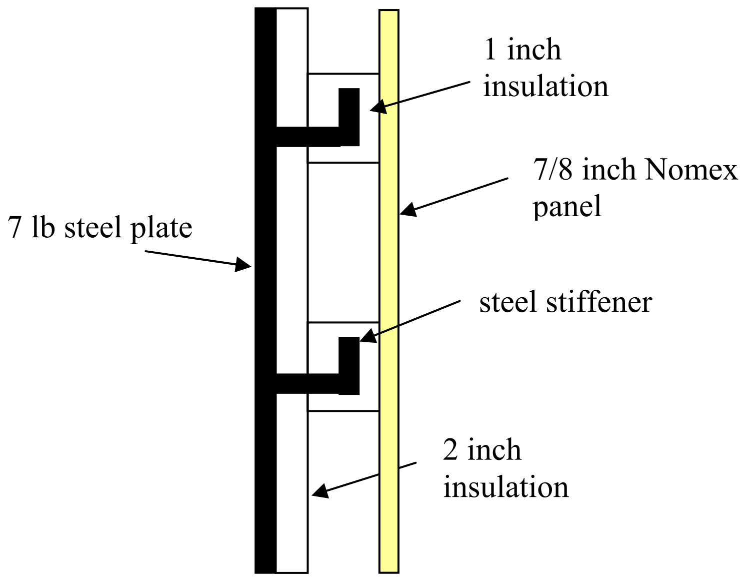

Figure 4.2: Typical interior watertight bulkhead construction

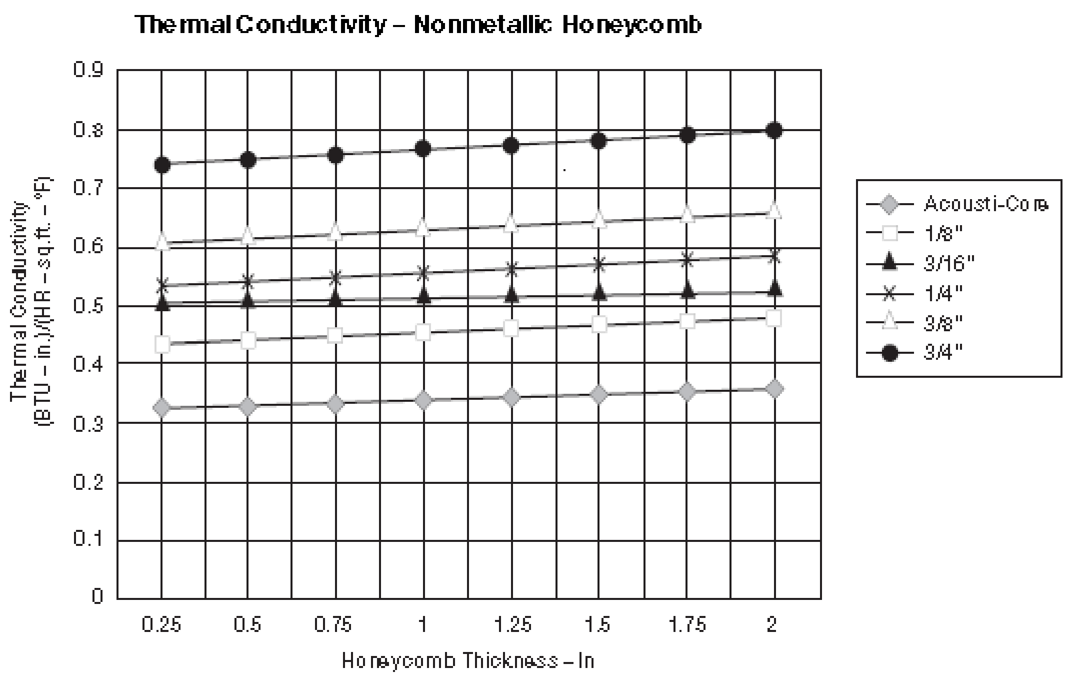

Figure 4-3: Thermal Conductivity of Nomex Honeycomb (Hexcel Corporation)

4.2 CLTD Method Calculation Assumptions

Table 4-1 lists the equations used for the CLTD method of calculations, as found in the 1981 ASHRAE Fundamental Handbook.

LOAD	EQUATION
CLTD	CLTD cor= [(CLTD+LM)*K+(78-T_R)+(T_O-85)
ROOF	q= U*A*CLTD cor
OUTSIDE WALL	q= U*A*CLTD cor
PARTITION	q= U*A*TD
GLASS	q= U*A*CLTD cor
SOLAR	q= A*SC*SHGF*CLF
LIGHTING	q= Input*CLF
EQUIPMENT	q(sens)= HGs*CLF
	q(lat)= HGl
PEOPLE	q(sens)= Pers*HGs*CLF
	q(lat)= Pers*HGl
VENTILATION	q(sens)= CFM*1.08*TD
	q(lat)= CFM*4.5*Δh - q(sens)

Table 4-1: Summary of CLTD Equations

The CLTD method calculations were completed for July 21, at 1700 in Saint Petersburg, Florida. The ship's orientation was based on a maximum CLTD value for the boundary with the greatest area of outside exposure. As a result, the port (left) side of the ship was designated as east, and the starboard (right) side of the ship was designated as west. This orientation was held constant for all calculations.

The roof was specified as Roof No.1 from Table 5A in 1981 ASHRAE Fundamentals Handbook, Chapter 26, which describes the roof construction as steel sheet with 1 or 2 inch insulation. This was assumed for all CLTD roof calculations.

The outside wall boundaries were selected as Group G from Table 6 in 1981 ASHRAE Fundamentals Handbook, Chapter 26, which describes the wall construction as a frame wall with 1 to 3 inch insulation. This was assumed for all CLTD wall calculations.

The glass was determined as single pane from Table 13 in 1981 ASHRAE Fundamentals Handbook, Chapter 27. This value was assumed for all glass load calculations.

The maximum solar heat gain factor (SHGF) was chosen from Table 11A in the1981 ASHRAE Fundamentals Handbook, Chapter 26, for Saint Petersburg (28° N Latitude), and east/west orientation. The cooling load factor (CLF) was designated from Table 13 in 1981 ASHRAE Fundamentals Handbook, Chapter 26, for east /west orientation and light room construction. The shade coefficient (SC) was determined from Table 28 in 1981 ASHRAE Fundamentals Handbook, Chapter 27, which assumes 3/8 inch clear glass.

The lighting on the ship was assumed to be on from 0600 (reveille) until 2200 (taps.) The cooling load factor (CLF) for lights was specified from Table 17A in the 1981 ASHRAE Fundamentals Handbook, Chapter 26, when lights are on for 16 hours. An *a* coefficient of .55 was chosen assuming ordinary furnishings, medium to high ventilation rates, and recessed light fixtures. A *b* classification of “A” was chosen assuming light room air circulation, and a mass floor area of 10 lb/ft2. Both these designations were taken from Table 15 and Table 16, respectively, in 1981 ASHRAE Fundamentals Handbook, Chapter 26.

The cooling load factor (CLF) for people was selected from Table 18 in 1981 ASHRAE Fundamentals Handbook, Chapter 26. Crew berthing spaces were assumed to be occupied for 14 hours, from 1700 to 0700. Work spaces and mess areas were assumed to be occupied for 10 hours, from 0700 to 1700. Officer and chief petty officer staterooms were assumed to be occupied for 18 hours from 2400 to 1800. The rates of sensible and latent heat gain (HG) for occupants were determined from Table 16 in 1981 ASHRAE Fundamentals Handbook, Chapter 26. Full compartment occupancy (100%) was assumed for berthing areas and work spaces; messing areas were assumed to be 2/3 of the total compartment occupancy.

The sensible heat cooling load factor (CLF) for equipment and appliances was selected from Table 23 in 1981 ASHRAE Fundamentals Handbook, Chapter 26, assuming 14-16 total operational hours for all spaces. The sensible and latent heat gains (HG) for equipment were determined based on Table 6 in SNAME T&R 4-16; Table 20 in 1981 ASHRAE Fundamentals Handbook, Chapter 26; Table in 1997 ASHRAE Fundamentals Handbook, Chapter 28, and ship's drawing No 627WMEC_085.

Table 4.2 lists a summary of the assumptions made for the CLTD method load calculations.

4.3 SNAME Method Calculation Assumptions

Table 4-3 lists the equations used in the SNAME method of calculation as found in SNAME T&R Bulletin 4-16, Recommended Practices for Merchant Ship Heating, Ventilation, and Air Conditioning Design Calculations.

For boundaries exposed to weather but no sun exposure, the load was treated as a standard transmission load using the outside air temperature. For outside boundaries with sun exposure, effective surface wall temperatures were used from Table 4 in SNAME T&R 4-16, for vertical and horizontal weather boundaries. Separate values were given for compartments with multiple boundary exposures. These effective temperatures are based on an ambient dry bulb temperature of 95°F. For compartments with multiple exposures to the sun, separate heat gain calculations were performed for each combination of boundaries to determine the greatest simultaneous heat gain. Spaces below the waterline with outside boundary exposure assumed a water temperature of 85°F db as per SNAME T&R 4-7.

LOAD	PARAMETER	ASSUMPTIONS	TABLE	REFERENCE
ROOF	CLTD	Roof 1	Table 5A	Chap 26, 1981 ASHRAE Fundamentals
WALL	CLTD	Group G	Table 6	Chap 26, 1981 ASHRAE Fundamentals
GLASS	CLTD	Single pane	Table 13	Chap 26, 1981ASHRAE Fundamentals
SOLAR	SHGF	28 N Latitude, East/West orientation	Table 11A	Chap 26, 1981 ASHRAE Fundamentals
	SC	3/8 in clear glass	Table 28	Chap 27, 1981 ASHRAE Fundamentals
	CLF	East/West, light room construction	Table 13	Chap 26, 1981 ASHRAE Fundamentals
LIGHTING	CLF	0600-2200, 16 operational hours	Table 17A	Chap 26, 1981 ASHRAE Fundamentals
	a, b	Ordinary furnishings, medium ventilation rates	Table 15, Table 16	Chap 26, 1981 ASHRAE Fundamentals
EQUIPMENT	CLF	14-16 operational hours	Table 23	Chap 26, 1981 ASHRAE Fundamentals
	HG (lat/sens)		Table 6	SNAME T&R 4-16
	HG (lat/sens)		Table 20	Chap 26, 1981 ASHRAE Fundamentals
	HG (lat/sens)		Table	Chap 28, 1997 ASHRAE Fundamentals
PEOPLE	HG (lat/sens)		Table 16	Chap 26, 1981 ASHRAE Fundamentals
	CLF	Crew Berthing Spaces: 1700-0700, 14 hours	Table 18	Chap 26, 1981 ASHRAE Fundamentals
	CLF	Work Spaces/Mess Areas: 0700-1700, 10 hours	Table 18	Chap 26, 1981 ASHRAE Fundamentals
	CLF	Officer Staterooms: 2400-1800, 18 hours	Table 18	Chap 26, 1981 ASHRAE Fundamentals

Table 4-2: Summary of CLTD Load Calculation Assumptions

The glass factor (GF) was used from Table 4 of SNAME T&R 4-16, for single boundary and multiple boundary sun exposure. For glass exposed to a weather boundary but no sun exposure, no GF was used, instead it was treated as a standard transmission load and the U value is determined from SNAME T&R 4-7.

LOAD	EQUATION
ROOF	q= U*A*TD
WALL	q= U*A*TD
PARTITION	q= U*A*TD
GLASS	q= GF*A
SOLAR	q= U*A*TE
LIGHTING	q= Input*3.412*BF
EQUIPMENT	q(sens)= HGs*UF*HF
	q(lat)= HGl*UF
PEOPLE	q(sens)= Pers*HDs
	q(lat)= Pers*HDl
VENTILATION	q(sens)= CFM*1.08*TD
	q(lat)=CFM*4.5*Δh - q(sens)

Table 4-3: Summary of SNAME Equations

The ballast factor (BF) was determined from SNAME, T&R 4-16, Section 3.3.1, for fluorescent bulb wattage. The installed lighting was specified from ship's drawing 627WMEC_ 331.

The use factor (UF) and hood factor (HF) were chosen from Table 7 in SNAME T&R 4-16 and Section 3.4.1. The sensible and latent heat gain (HGl and HGs) for the equipment were the same used in the CLTD calculations.

The sensible heat dissipation factor (HDs) and latent heat dissipation factor (HDl) were selected from Table 9, SNAME T&R 4-16. The occupancy was assumed the same as used in the CLTD calculations.

Table 4-4 summarizes the assumptions and references used in the SNAME method load calculations.

4.4 CLTD and SNAME Ventilation Load Calculation Assumptions

The ventilation loads using the CLTD method were calculated assuming outdoor conditions of 93° F db/81°F wb for St. Petersburg, Florida and indoor conditions of 80°F db/67°F wb, as designated by 2001 ASHRAE Fundamentals Handbook and ship's information book. St. Petersburg, Florida was chosen because the temperature conditions for that location were the closest to the conditions defined by the SNAME method. This different in dry bulb temperature can be later attributed to the slight difference in calculated loads. The ventilation loads using the SNAME method were calculated assuming outdoor conditions of 95°F db/82°F wb and indoor conditions of 80°F db/67°F wb, as designated by SNAME, T&R 4-16 and ship's information book. Table 4-5 summarizes the conditions used for the calculations.

LOAD	PARAMETER	ASSUMPTION	TABLE	REFERENCE
ROOF	TD	Exposed to weather, no sun	Table 3	SNAME T&R 4-16
GLASS	TD	Exposed to weather, no sun	Table 3	SNAME T&R 4-16
GLASS	GF	Exposed to sun	Table 4	SNAME T&R 4-16
SOLAR	TE	Exposed to sun	Table 4	SNAME T&R 4-16
LIGHTING	BF		Section 3.3.1	SNAME T&R 4-16
EQUIPMENT	UF		Table 7	SNAME T&R 4-16
	HF	No hood	Section 3.4.1	SNAME T&R 4-16
	HGs, HGl		Table 6	SNAME T&R 4-16
	HGs, HGl		Table 20	Chap 26, 1981 ASHRAE Fundamentals
	HGs, HGl		Table	Chap 28, 1981 ASHRAE Fundamentals
PEOPLE	HDs		Table 9	SNAME T&R 4-16
	HDl		Table 9	SNAME T&R 4-16

Table 4-4: Summary of SNAME Load Calculation Assumptions

	db (°F)	wb (°F)	dp (°F)	h (Btu/lb dry air)
CLTD Outside	93	81	77.2	44.8
SNAME Outside	95	82	77.9	45.9
CLTD Indoor	80	67	60.4	31.7
SNAME Indoor	80	67	60.4	31.7

Table 4-5: Summary of Air Conditions for SNAME/CLTD Methods

A Trane psychometric chart was used to determine the enthalpy of the outdoor and indoor conditions for the conditions in Table 4-5. The flow rate of outside air into each compartment was determined from ship's drawings No. 627WMEC-512.

The OA ventilation load internal to the space was calculated using the following equation:

$$q\ (total) = OA\ CFM*4.5*(\Delta\ h)$$

where Δh is the difference between the enthalpy of the air entering the space through the ventilation system at conditions of 86°F db/76.5°F wb and the enthalpy of the steady state air in the room at conditions of 80°F db/67°F wb.

4.5 Load Calculation Results and Comparison

Both methods of calculations resulted in similar values for total latent and sensible loads. The CLTD method calculations completed on the 210 foot USCGC VENTUROUS determined that the total internal load (sensible and latent) for supply ventilation system 1-65-1 was 234,870 Btu/h (20 tons). The SNAME method calculations determined the total internal load (sensible and latent) to be 223,350 Btu/h (19 tons). The CLTD method ventilation load (sensible and latent) for supply ventilation system 1-65-1 is 219,880 Btu/h (18 tons). This difference in loads can be attributed to the slight variation in entering dry bulb temperatures. The SNAME method ventilation load (sensible and latent) is 233,220 Btu/h (19 tons). The total combined system load is 454,750 Btu/h (38 tons), based on the CLTD method; and 456,570 Btu/h (38 tons), based on the SNAME method. These values are also similar to the space total cooling loads listed in ship dwg No. 627WMEC_512_001, for FCUs. The loads listed for space FCUs also considers the additional ventilation load resulting from the mixing of outdoor air and supply ventilation air discharged by the FCUs in the space. Table 4-6 summarizes the results of the load calculations.

	CLTD vent	SNAME vent	CLTD tot	SNAME tot	DWG tot
SYSTEM LOAD (Btu/h)	219880	233220	234870	223350	226140
TONS	18	19	20	19	19

	CLTD	SNAME
TOTAL LOAD (Btu/h)	454750	456570
TOTAL TONS	38	38

Table 4-6: Summary of Load Calculations

Appendix A shows the layout of the chilled water system on board the 210 foot cutter. The plant is equipped with two 25 ton chillers which are operated in parallel, and supply the dehumidifiers for system 1-65-1 and system 01-96-1, the FCUs for the spaces serviced by both systems, and the gravity coils for the four magazine spaces. The plant is also equipped with two five ton units which are operated in parallel to supply the cooling coils for system 01-101-2 and 01-103-2 which service the engine room, engine room control booth, and IC gyro. The calculated loads from the CLTD and SNAME method show that the current installed units are sized to handle the load demand, with additional reserve if needed.

4.6 Actual Field Data

Field data were taken on the 210 foot and 110 foot cutters to determine the actual working conditions of the vessels. There is no prior documentation of such data that has been reported on these vessels. Temperature control, humidity, and fresh air requirements were identified as existing problems on the vessels. These issues can lead to conditions that are both uncomfortable and reduce personnel productivity. The field data provided real information on the current operating condition of the ventilation systems on board the vessels. The data were then evaluated and compared to current ASHRAE standards and requirements to determine if the standards for temperature, humidity, and fresh air were being met.

The recorded data were taken underway on CGC VENTUROUS on May 24, 2005. The outside conditions were 80°F db, 76.38°F wb, 75.09°F dp, and 85% rh. The recorded data on CGC VENTUROUS indicated a number of areas in which the installed ventilation system is not operating as per specifications. Ship drawings and Navy standards specify design temperatures for living area and common spaces of 80°F db and 65°F wb. Measurements taken in these spaces ranged from five to twelve degrees below the design dry bulb temperature, and ranged from 3°F wet bulb above and below the design wet bulb temperature. Relative humidity for the living and common spaces ranged from space to space reaching 72% on the messdeck, and 71% in crew and deck berthing. Both operations berthing area and engineer berthing area had relative humidity readings around 65%. ASHRAE and NAVY standards indicate that relative humidity should be maintained between 30% and 60% to prevent growth of mold and mildew. Operations berthing, crew berthing, and engineer berthing had visible signs of mold and mildew growth on the insulation of the upper and lower bulkheads. Condensation was also visible on the FCUs, on piping insulation, and upper bulkheads. Crew members expressed symptoms of fatigue, sinus and nasal problems, and thermal discomfort from their living spaces. It was also observed that stand-alone dehumidifiers (not part of the ship's compliment) were placed in deck, 1st class, and operations berthing areas, to reduce the moisture in the space, although the presence of mold and mildew was still observed in these spaces.

Carbon dioxide (CO_2) readings taken throughout the ship varied greatly. Underway, the measured outdoor CO_2 concentration for CGC VENTUROUS was 380 ppm. ASHRAE defines acceptable CO_2 concentration as within 700 ppm of the measured outdoor concentration. With the exception of the dispensary and main control, all measured spaces were within the acceptable limits. The average measured CO_2 concentration in main control was 2835 ppm. This space is the main control booth for monitoring all of the engineering equipment. A three to four person watch is always on duty in this space while underway, and requires the highest degree of alertness and vigilance to maintain the integrity and operation of the ship. This space is supplied with 75 cfm of OA and 470 cfm of air supplied from two FCUs. Although, research has indicated that CO_2 has little effect on health until concentrations exceed 5,000 ppm, the most important use of CO_2 is as an indicator of ventilation efficiency, showing whether the supply of outdoor air is sufficient to dilute airborne contaminants (Batterman and Peng 1995). ASHRAE 55 specifies a CO_2 ceiling of 1000 ppm to maintain odor-free environments and levels of human bioeffluents.

The underway recorded data for CGC DRUMMOND were taken on May 27, 2005. The outside conditions were 82°F db, 76.46°F wb, 74.46°F dp, and 78% rh. The inport data were taken on May 26, 2005. The outside conditions were 91.4°F db, 80.89°F wb, 77.51°F dew point, and 64% relative humidity. Temperature and humidity readings on CGC DRUMMOND, both inport and underway, were fairly consistent and on average fell within the acceptable limits. Inport temperature and humidity readings were all below 60% relative humidity, with the exception of the forepeak space and all machinery spaces, including the engine room, battery space, and aft steering. These spaces are not supplied with installed ventilation inport or underway. According to ship's policy and weather permitting, during inport periods the access hatches to the space are left open to 'air out' the space This is not possible while underway due the maintenance of watertight integrity. Humidity readings in these spaces were 85%, 79%, 84%, and 79% respectively. Visible condensation and rust covered the bulkheads and decks in these spaces, in addition to insulation failure. The 110's have undergone significant metal replacement work, as a result of rusted metal in the hull of the ship. This has resulted in numerous casualties and billions of dollars spent to repair the aging fleet. The effects of the condensation and humidity not only are detrimental to the integrity of the ship, but also deteriorate the operating machinery, such as pumps, motors, and steering gear.

The outdoor CO_2 concentration on CGC DRUMMOND, while underway, was 402 ppm. The recorded data were on average greater than 700 ppm over the outdoor recorded concentration. Aft berthing had an average CO_2 concentration of 1786 ppm. The bridge had an average concentration of 1718 ppm, followed by the communications space with an average concentration of 1663. The messdeck and galley had recorded average concentrations of 1373 and 1351 respectively. These values were significantly different than the recorded inport values. None of the inport readings exceeded 700 ppm above the outside recorded CO_2 concentration. This may be a result of the ship's adopted policy of opening the watertight doors and hatches while inport, introducing fresh outside air to the interior of the ship. While underway, the only outside air that is introduced into the ship is from 5 natural vents that are located on the main deck of the ship. The use of the natural vents while underway has created water intrusion issues on 110's, which has led to severe rust and metal deterioration requiring hull plating replacement. It was observed that some of the natural vents were stuffed and covered with cloths to prevent air/water from entering the ship.

4.7 Marine and Military Environment Considerations

Ventilation air specific to military and marine environments has challenges that are different from land based applications. Temperatures and environmental conditions are constantly changing on a daily basis. Sea water particle intrusion can damage ventilation ducting and equipment. Condensate drain pans must be specially designed to handle the ship's motion.

Other considerations for marine ventilation are fire control and chemical, biological, and radiological (CBR) protection. Fire suppression systems are installed on both the 110 foot and 210 foot cutters in the machinery spaces. To prevent the spread of fire and smoke through the ducting system, manual dampers can be closed. 110's do not have an installed ducting supply system that takes fresh outside air and distributes it to the spaces. On the 210 foot cutter, part of the fire casualty response is to close the supply and exhaust dampers to the space and ensure positive ventilation surrounding the space to prevent fire and smoke from spreading to other parts of the ship.

CBR has become an increasing concern for our nation's seagoing fleet. Neither the 210 foot nor 110 foot cutters have a ventilation system that is equipped to handle an airborne attack. On the 210 foot cutter, Class W fittings are closed in the event of an attack, which prevents any outside air from being introduced into the ship. These fittings shut off the air supply and exhaust for each system. The effectiveness of the dampers depends on the maintenance upkeep of the system, which includes regular cycling of the valves and dampers. The filters used on both vessels are Navy Standard replaceable filters. These filters are ineffective at limiting a number of contaminants from entering the ship. This does not prepare the ship from an unknown attack, and is purely a reactive measure. This ultimately yields a loss of effectiveness in performing mission essential capabilities. With the emerging threat of airborne attacks, it is essential to prepare the nation's first line of defense with the necessary tools to perform this mission.

4.8 Indoor Air Quality Results

While there are currently no defined standards regarding indoor contaminants, there are some common IAQ indicators that are instrumental in evaluating and solving IAQ problems. Concentrations of microbial volatile organic compounds (MVOCs) can be an indicator of IAQ issues, such as mold and mildew. Although no MVOC samplings were taken on the ship, it is recommended that readings be taken to determine baseline values. Mold and mildew were visually observed on the 210 foot cutter, but visual inspection alone should not be the sole indicator. Spores can be present without visible signs, and growth can be in places that are not observable, such as behind insulation or equipment.

Thermal comfort is a continual problem on ship. Common berthing areas accommodate as many as 24 people, making it difficult to meet individual needs. Temperatures are often much colder than required, and work spaces are drafty.

Based on the field data and observations, the indoor air quality varied between spaces on a ship. In some cases, effective fresh air requirements were being met and temperature conditions were acceptable, while in others mold and mildew was observed and adequate fresh air was not supplied. This was a pronounced issue on the 110 foot cutter, which does not have an installed outside air supply system.

4.9 Current Procedures on 210 and 110 foot Cutters

Ventilation supply system 1-65-1, which services the majority of the 210 foot cutter's work and living spaces, has two installed dehumidifier coils and electric re-heaters. Figure 4-3 depicts the ventilation diagram of system 1-65-1.

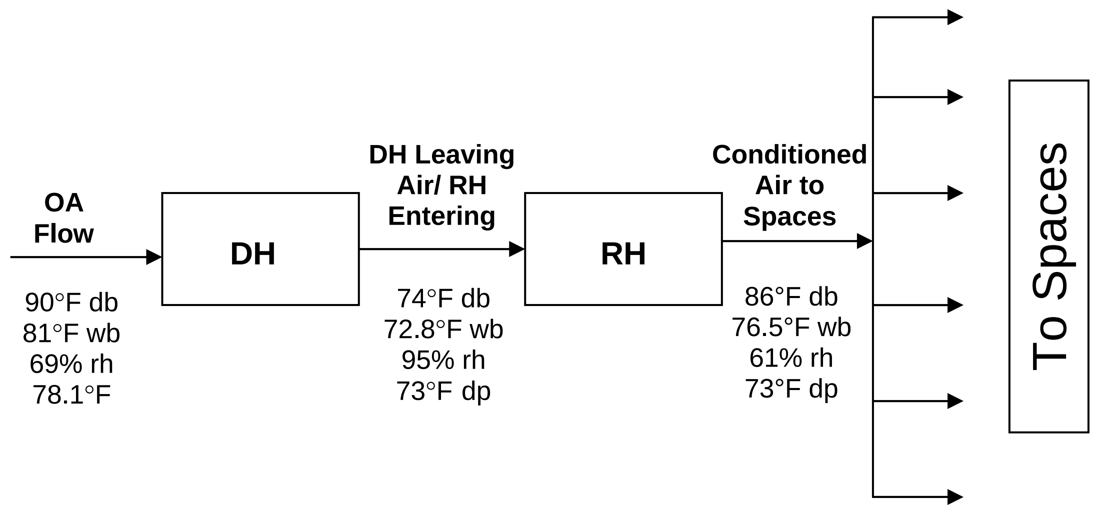

Figure 4-3: Ventilation system 1-65-1

The supply ventilation system 1-65-1 is designed for OA conditions of 90°F db, 81°F wb, 69% rh, and 78.1°F dp. The supply air enters a dehumidifier at these conditions and leaves at 74°F db, 72.8°F wb, 95% rh, and 73°F dp. The air then passes through an electric re-heater, which warms the air to 86°F db, 76.5°F wb, 61% rh, and 73°F dp before being dispersed in the ductwork to the individual spaces. The high dew point temperature of the air that is dispersed in the spaces is a significant concern based on the observations that were taken in the spaces. When the air in the space hits a surface that is below this temperature, such as the FCU casings, the moisture in the air will condense and water will be formed.

On the 110 foot cutter, fresh air is introduced through natural ventilation and infiltration. The five air handling units on the ship take recirculation air and recondition it to meet the room air requirements of 80°F db and 67°F wb. A 10 ton chiller supplies the chill water to coiling coils of these air handling units.

4.10 Documentation

During the course of research, it was observed that there were a number of conflicts between specifications and guiding documents. Specifications for OA requirements in spaces varied between NIOSH, ASHRAE, NSTM, NAVY, and the ship's specifications. The range of specifications varied from 5 to 20 cfm per person. Although Navy regulations reference ASHRAE standards, they need to be updated to account for changes that have been made in the newer published standards.

SNAME guidance has not been updated to reflect the current status of the marine community. The Thermal Insulation Report (T&R 4-7) has not been updated since 1974 and does not contain information for newer materials such as Nomex. The Calculations for Merchant Ship Heating, Ventilation, and Air Conditioning (T&R 4-16) does not contain updated values for equipment HGs.

CHAPTER 5
CONCLUSIONS

This thesis was undertaken to determine the effectiveness of the current ventilation systems installed on board the 110 and 210 foot Coast Guard cutters. An analysis of the cooling load required on the 210 foot cutter was performed using the CLTD method and SNAME method of load calculations. Actual field data were taken on both the 110 foot and 210 foot cutters to determine the actual operating conditions, in addition to a detailed study of the ship's plans and drawings.

- The results of the load calculations performed on the 210 foot cutter, supply system 1-65-1, show that the CLTD method and SNAME method produce very similar results, and the assumptions made in the CLTD method are comparable to the generalizations used in the SNAME method. The chiller units on board are sized to handle the total load with additional cooling available. The internal loads of the spaces, which are handled by the FCUs in the space, are adequate, not considering the additional load required to cool the outside supply air from the conditions leaving the reheater to the room's steady state conditions. In order to accommodate this additional load, additional FCUs would need to be installed or modifications would need to be made to the existing ventilation supply air system.

- The ventilation drawings for supply system 1-65-1 on board the 210 foot cutter indicate that all spaces are maintained at neutral pressurization.

- The field data taken on the 210 foot cutter indicated a significant problem with moisture and mold/mildew growth as a result of the room air conditions and the dew point temperatures that are maintained. According to the ship's ventilation drawings, the OA ventilation supplied by system 1-65-1 does not effectively treat the air to maintain the dew point temperature at a level that will prevent moisture build up and condensation from forming. The OA is being supplied to the spaces at a dew point of 73° F, while the FCUs are supplying air at 55°F-60°F. Since air supplied by the FCUs is cooler than this dew point temperature, this results in condensation on the FCU casings and on wall surfaces.

- The CO_2 concentrations taken on board the 210 foot cutter were on average well within the required allowable concentration, with the exception of the main control booth, due to lack of adequate fresh outside air supplied to the space.

- The field data taken on board the 110 foot cutter indicate that dry bulb and dew point temperatures are being maintained in the living and berthing spaces to prevent excessive moisture. Due to the lack of an installed ventilation system, conditioned ventilation air is not supplied to machinery spaces. As a result the machinery spaces had recorded relative humilities around 80%, and 82°F dp temperatures, with significant observable condensation and rust. These spaces do not get effective ventilation to maintain temperatures that will prevent condensation on the framing and machinery.

- The CO_2 concentrations recorded on board the 110 foot cutter were on average above the 1000 ppm threshold designated by ASHRAE. This result is due to the lack of an OA ventilation supply system on board the cutter. The only outside air introduced into the ship is through vents that supply fresh air. This is particular challenging on this type of vessel due to the nature of its mission and the consequent effects of the sea conditions on the ship.

- The current ventilation systems on both 110 and 210 foot cutters are not adequate to provide effective protection in the case of a CBR attack or provide effective filtration of indoor air contaminants. This is due to the lack of an advanced filtration system and significant building envelope leakage.

CHAPTER 6
RECOMMENDATIONS

This thesis evaluated the ventilation effectiveness of shipboard ventilation systems on board two classes of U.S. Coast Guard cutters and their ability to provide adequate indoor air quality. The results and analysis indicate several areas of improvement regarding the installed ventilation systems, and the standards and specifications that are associated with them.

- The FCUs installed on the 210 foot cutter in the following spaces: deck berthing, wardroom, CPO mess, ship's office, messdeck, operations berthing, engineer berthing, lower officer staterooms (3), and armory workshop are not adequate to handle the ventilation load of the outside air supplied to the spaces through the installed supply system 1-65-1. To accommodate this load, modifications should be made to the installed coiling coil which will reduce the OA ventilation load in the space.

- Visible mold growth and condensation in living spaces on board the 210 foot cutter indicate IAQ problems and improper treatment of ventilation air. OA entering the 210 foot cutter through ventilation system 1-65-1, is cooled and then reheated before entering the spaces at 86°F db, 76.5°F wb, 61% rh, and 73°F dp. To provide conditioned air at a lower dew point temperature to prevent condensation, the air should be treated by cooling it to 55°F db and 53° F wb before being reheated. This would require an additional 35 tons of cooling, 22 tons in excess of the current cooling load. This would necessitate the installation of an additional chiller. It would cost approximately $22,000 per cutter to install a water cooled, semi hermetic chiller unit of this size and requires an extra 22 kW electrical load to be handled by the two ship service generators.

- Adequate OA must be provided to the main control booth on the 210 foot cutter to maintain CO_2 concentrations below 1000 ppm. This can be accomplished by increasing the existing duct work that is serviced by supply ventilation system 01-103-1 (which supplies the engine room ventilation). Because this system does not currently supply filtered and conditioned air, the best option is to alter the duct work to the space by branching off from supply system 1-65-1 or supply system 1-160-2 (which services the galley). The benefit from this option would be the ability to provide properly filtered and conditioned air to the space. As one of the most critical spaces on board the cutter, it is essential that ample conditioned and filtered

OA is supplied to the main control space, to ensure personnel maintain the highest level of alertness and vigilance.

- Recorded CO_2 concentrations and lack of OA supply on board the 110 foot cutter signifies poor IAQ. The 110 foot cutter should be outfitted with a forced ventilation system throughout the ship to effectively maintain the CO_2 indoor air concentration in living, working, and eating spaces below 1000 ppm. The installed system should also service the machinery spaces including: the forepeak, battery space, and aft steering. Pre-conditioned air should be supplied to these spaces to maintain conditions necessary to prevent condensation and metal deterioration of the framing and machinery, insulation failure from water intrusion, and mold growth. It would cost approximately $15,000 per boat to install a 3 ton water cooled, semi hermetic chiller with duct work.

- Better designs for the air intakes and natural vents on board the 110 foot cutters need to be evaluated to ensure the vessel is receiving appropriate OA without allowing water intrusion. This can be accomplished by installing air intakes above the 02 deck and using an installed duct work system to distribute the air through out the cutter. High performance intake designs that provide protection from water penetration (i.e. double drain gutters in each blade), along with ducting systems that include a drain area with a water/air separation unit (trap) will provide additional protection from water intrusion.

- Both the 210 and 110 foot cutter need ventilation designs to protect against IAQ and CBR contaminants. Improved filtration should include the use of HEPA filtration systems, which have the ability to provide protection against particles larger than 3 µm in size, along with the installation of a pre-filter and gas filter using activated carbon. The cost for installation of a HEPA filtration system would be approximately $19,000 for the 210 foot cutter, and approximately $5,000 for the 110 foot cutter. For higher levels of protection against smaller biological agents including viruses, modifications should include the use of photocatalytic technology, in addition to the use of HEPA filters. Additional research needs to be conducted to evaluate the use and effectiveness of photocatalytic technology for shipboard use.

- Space pressurization on the 210 and 110 foot cutter will provide additional protection in regards to the entrainment of IAQ contaminants and airborne CBR contaminants. An air balance should be conducted to determine the effective rate of supply and exhaust ventilation needed to provide approximately .2 ACPH to maintain the necessary space pressurization.

- The use of a liquid/dry desiccant system on board the 210 and 110 foot cutter should be considered. The installation of this type of system would enable humidity/moisture to be directly removed from the incoming outdoor air, preventing problems with condensation and mold/mildew growth. Waste heat from ship service generators and main diesel engines can be used in the regeneration of the desiccant. This type of system reduces the energy needed to cool the OA to temperatures below dew point and then reheat the air to room temperatures. Due to the cost and space requirements for this type of system, additional research should be conducted to evaluate the application of this type of system for shipboard use.

- A Coast Guard wide IAQ program for cutters should be established. This should include updated maintenance standards and IAQ monitoring. IAQ monitoring should include air sampling (spores, MVOCs, CO_2), visual inspection, and documentation. Periodic temperature and humidity readings should be taken to ensure ventilation systems are operating according to specifications. Preventive Maintenance Standards (PMS) should be updated to reflect these changes. The IAQ monitoring program can be managed by the local land based Naval Engineering Support Units along with the equipment necessary to perform the testing. It would cost approximately $3,000 to set up an IAQ program with the purchase of a portable CO_2 gas analyzer, air sampling equipment, and portable temperature/humidity recorder.

- HVAC systems and components should be commissioned by qualified companies in accordance with ASHRAE standards following major maintenance availabilities (dry-docks and docksides) and prior to ship commissioning. This will ensure systems are operating as per specifications and prevent failure due to system modifications.

- Standards such as OPNAVINST, NSTM, Naval Engineering Manual, and Navy Design Criteria Manual need to be modified to reflect HVAC standards defined in ASHRAE 62, ASHRAE 55, and ASHRAE 26. This includes an OA requirement of 20 cfm/person and maximum CO_2 concentrations based on ambient conditions. Although ASHRAE defines a minimum rate of 15 cfm/person, the environment of the ship and the activity level of personnel dictate a higher rate. Inherent odors from shipboard personnel, diesel oil, JP-5, and other sources, can combine to create sensitivities despite being at low concentrations and require a higher ventilation rate to control.

- While the CLTD method and SNAME method of load calculations produced very similar results, SNAME publications need to be updated to reflect current conditions. Modifications should include updated equipment lists, HGs, and updated U values for newer composite materials such as Nomex.

APPENDIX A
SHIP DRAWINGS FOR 110 AND 210 FOOT CUTTER CLASS

The following objects include the drawings for the 210 foot and 110 foot cutters. Included are the outboard and inboard profiles, compartment layout, and the ventilation system diagrams and components.

APPENDIX B
DETAILS OF CLTD LOAD CALCULATIONS

Object 12 contains the Excel Spreadsheet calculations that were used to determine the cooling load on board the U.S. Coast Guard Cutter VENTUROUS (210 foot) for ventilation supply system 1-65-1 using the ASHRAE Cooling Load Temperature Difference (CLTD) method. The spreadsheet is organized by each compartment/space and the loads associated with them.

Object 12. Details of CLTD Load Calculations.

APPENDIX C
DETAILS OF SNAME LOAD CALCULATIONS

Object 13 contains the Excel spreadsheet that was used to calculate the cooling load on board the U.S. Coast Guard Cutter VENTUROUS (210 foot) for supply system 1-65-1 using the Society of Naval Architects and Marine Engineers (SNAME) method. The spreadsheet is organized by compartment/space and the loads associated with them.

Object 13. Details of SNAME Load Calculations

APPENDIX D
SUMMARY OF LOAD CALCULATION RESULTS

Object 14 contains the Excel spreadsheet summarizing the results for the load calculations completed on the 210 foot cutter VENTUROUS for supply ventilation system 1-65-1. It contains the results from the CLTD method, SNAME method, and the load values extracted from the ship's drawings.

Object 14. Summary of Load Calculation Results

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BIOGRAPHICAL SKETCH

Jessica Appollonia Rozzi-Ochs was born on October 13, 1978, in Reading, Pennsylvania. She is the first daughter of William F. Ochs, ESQ, and Luciana A. Rozzi-Ochs. She has two younger sisters, Elizabeth and Katherine. Jessica received her BS in mechanical engineering from the United States Coast Guard Academy, New London, CT, in 2000. Upon graduation she received an officer commission in the United States Coast Guard and currently has the rank of LT (O-3). Her first duty station was on the USCG Cutter TAHOMA, a 270 foot cutter stationed in New Bedford, MA, as an Engineer Officer in Training and the Damage Control Assistant. Following this tour, she served as a Port Engineer at the Naval Engineering Support Unit in Miami, FL, and was responsible for the maintenance and operation of six 110 foot patrol boats home-ported in San Juan, Puerto Rico. Jessica was then assigned to the University of Florida to pursue a Master of Science in mechanical engineering. After graduation in May 2006, Jessica will be assigned to the USCG Cutter VALIANT, a 210 foot cutter home-ported in Miami Beach, FL, as the Chief Engineer Officer.