



**BIOFILTRATION AS A VIABLE
ALTERNATIVE FOR AIR POLLUTION
CONTROL AT DEPARTMENT OF DEFENSE
SURFACE COATING FACILITIES**

THESIS

David M. Hudock, Captain, USMC

AFIT/GES/ENV/07-M3

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
*AIR FORCE INSTITUTE OF TECHNOLOGY***

Wright-Patterson Air Force Base, Ohio

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David M. Hudock, BS

Captain, USMC

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David M. Hudock, BS
Captain, USMC

Approved:

-- signed --

16 Mar 07

LtCol David A. Smith, USAF (Chairman)

date

-- signed --

13 Mar 07

LtCol Ellen C. England, USAF (Member)

date

-- signed --

16 Mar 07

Dr. Charles A. Bleckmann (Member)

date

Abstract

Surface coating operations at aircraft depot facilities are common throughout the Department of Defense (DoD). During paint application processes at Navy and Marine Corps Fleet Readiness Centers (FRCs), spray paints emit volatile organic compounds (VOCs) known to have harmful effects on human health and the environment. FRC East at Marine Corps Air Station Cherry Point, does not control the emissions of VOCs from any of its paint booths. The purpose of this research is to determine if FRC East and its surrounding area can benefit both economically and environmentally from a biofiltration system for air pollution control (APC) rather than the current conventional method of dry filtration. Dry filtration reduces only particulate matter in waste air streams and though there was no regulatory requirement to control VOC emissions at FRC East, the possibility exists that such legislation may be enacted in the future, affecting this facility and other similar DoD facilities. Three biofilters were designed for this study. The cost of each was analyzed using a net present value calculation and compared to potential monetary savings amongst the local population should VOC emissions from FRC East be controlled. Results show that FRC East and similar DoD facilities can benefit environmentally and economically from VOC control using biofiltration technologies.

To the aircraft maintenance Marines for their countless, thankless, and tireless hours spent keeping Marine aircraft off the ground and in the fight.

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Table of Contents

	Page
Abstract.....	iv
Acknowledgements.....	vi
List of Figures.....	x
List of Tables.....	xi
I. Introduction	1
1.1 Background.....	1
1.2 Fleet Readiness Center (FRC) Concept.....	3
1.3 Volatile Organic Compounds (VOCs).....	5
1.4 Biofiltration Technology	6
1.5 FRC East (NADEP), Cherry Point Regulatory Issues.....	8
1.6 Problem Statement.....	10
1.7 Research Objectives / Questions	10
1.8 Methodology.....	11
1.9 Assumptions / Limitations.....	12
1.10 Significance	14
II. Literature Review.....	15
2.1 Background.....	15
2.2 History	15
2.3 Biofiltration Technologies.....	18
2.3.1 Biofilter.....	18
2.3.2 Biotrickling Filters.....	19
2.3.3 Bioscrubbers	21
2.3.4 Rotating Drum Biofilter.....	22
2.3.5 Membrane Bioreactors.....	24
2.4 Biofiltration Application.....	25
2.4.1 Appropriate Contaminants.....	25
2.4.2 Conventional Treatments and Economic Benefits.....	27
2.5 Biofilter Design and Sizing	29
2.5.1 Filter Media.....	30
2.5.2 Design Parameters	34
2.6 Laws and Regulations.....	42
2.6.1 Federal.....	43
2.6.2 State.....	44
2.6.3 Executive Orders.....	45
2.6.4 Military Regulations and Orders.....	48
2.7 Harmful Effects of VOCs	51

	Page
2.8 Economics.....	52
2.9 Summary.....	54
III. Methodology.....	55
3.1 Introduction.....	55
3.2 Procedures.....	55
3.2.1 Case Studies.....	55
3.2.2 Design of the Biofilter.....	57
3.2.3 Contractor Design of the Biofilter.....	60
3.3 Net Present Value Calculations.....	60
3.4 Assumptions.....	63
IV. Results and Discussion.....	65
4.1 Overview.....	65
4.2 Study Design.....	65
4.2.1 FRC VOC Emissions.....	66
4.2.2 Paint.....	67
4.2.3 Hangar D0129 Airflow and Contaminant Concentration.....	68
4.2.4 Design Results.....	69
4.2.5 Biofilter Cost.....	72
4.3 Design Presented by Commercial Biofilter Vendor.....	78
4.4 Cost Comparison: Study vs. Vendor.....	83
4.5 Case Study One.....	83
4.5.1 Background and Design.....	83
4.5.2 Relevance.....	86
4.6 Case Study Two.....	87
4.6.1 Background and Design.....	87
4.6.2 Relevance.....	90
4.7 Discussion.....	92
4.8 Summary.....	94
V. Conclusion and Recommendations.....	96
5.1 Conclusion.....	96
5.2 Research Questions Answered.....	96
5.3 Research Limitations.....	98
5.4 Suggested Improvements.....	99
5.5 Recommendations for Follow-on Studies.....	100
5.6 Significance.....	101
Appendix A: Case Study Questions.....	103
Appendix B: Net Present Value Calculations.....	105

	Page
Appendix C: Study Schematic	106
Appendix D: FRC Plan with Proposed Biofilters	106
Appendix E: Enlarged FRC Plan with Proposed Biofilters	108
Appendix F: Conversion Factors	109
Bibliography	110
Vita.....	119

List of Figures

	Page
Figure 1.1 VOC emissions sources	2
Figure 1.2 Biofilter Schematic	7
Figure 2.1 Drawing of soilbed filter	16
Figure 2.2 How temperature affects microbial metabolic activity	39
Figure 3.1 Example cash flow diagram	61
Figure 4.1 BIOREM Technologies, Inc. up-flow biofilter design.....	80
Figure 4.2 Construction phase of Rothsay Recycles biofilter.....	85
Figure 4.3 The Plum Creek Timber Company, Inc., biofilter.....	88
Figure 4.4 Schematic drawing of Columbia Falls biofiltration system	89

List of Tables

	Page
Table 1.1 VOCs released to the atmosphere from select states and the U. S.	5
Table 2.1 Comparative parameters of selected filter media	32
Table 4.1 PTE values and actual emissions of VOCs at hangar D0129	66
Table 4.2 Summary of biofilter design parameters.....	72
Table 4.3 Biofilter design results presented by BIOREM Technologies, Inc.	82
Table 4.4 Study and vendor biofilter design results.	83
Table 4.5 Characteristics of Rothsay Recycles, biofilter.....	84
Table 4.6 Characteristics of Plum Tree Timber Company, Inc., biofilter.	91

BIOFILTRATION AS A VIABLE ALTERNATIVE FOR AIR POLLUTION CONTROL AT
DEPARTMENT OF DEFENSE SURFACE COATING FACILITIES

I. Introduction

1.1 Background

Though not listed by the Environmental Protection Agency (EPA) as one of the six criteria pollutants, volatile organic compounds (VOCs) present a multitude of problems when released into the atmosphere. These compounds are not of environmental concern on their own, however, they have been labeled by the EPA as “ozone precursors” due to their proclivity to react with sunlight, heat and nitrogen oxide (NO_x) compounds to produce ozone at the ground level. As a result of this behavior, VOCs are regulated at the federal, state and local levels.

Ozone at the ground level is responsible for numerous debilitating health and environmental effects. People with bronchitis, emphysema, and asthma experience heightened severity of their conditions when exposed to ground-level ozone. Even those individuals with healthy lungs are subject to chest pain, coughing, throat irritation and congestion as a result of ozone exposure. In some severe cases of exposure, permanently scarred lung tissue may develop (EPA, 2006a). Environmentally, ground level ozone can damage crops, plants, vegetation and entire ecosystems. Reductions in agricultural crop yield, reductions in survivability of tree seedlings, and increased susceptibilities of vegetation to diseases, pests, and harsh weather have all been linked to ground level ozone (EPA, 2006a).

Control of VOC emissions presents a challenge to air quality control. Due to the proliferation of VOCs in a wide variety of solvents and chemicals designed for home and commercial use, the control of their emission is extremely difficult. VOCs are present in

chemicals used at home in relatively small quantities, i.e. paints, cleaners, pesticides, and even liquid white-out. Controlling emissions at these miniscule levels is neither practical nor suitable. This, combined with the fact that their use—particularly at the home level—can be in extremely small quantities, presents even further challenges to their control. Major sources of atmospheric VOCs include motor vehicle emissions, petroleum vapors, industrial emissions and chemical solvents (EPA, 2006a).

A more reasonable method of controlling VOC emissions is at the macro level, specifically in industrial processes and manufacturing processes. Figure 1.1 shows that 50% of VOC emissions in the United States today are the result of industrial / commercial processes.

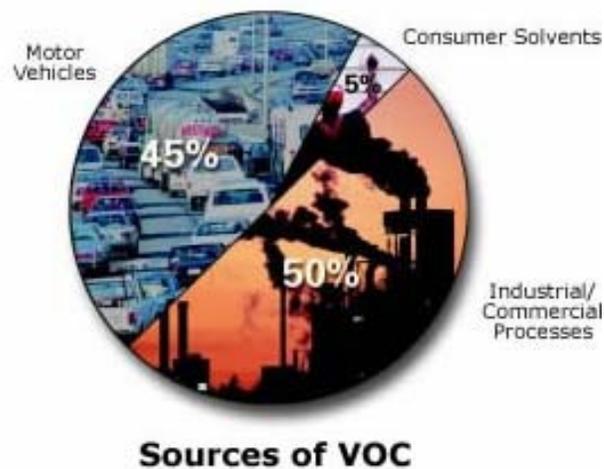


Figure 1.1. VOC emissions sources. (EPA, 2006a).

One component of the industrial / commercial processes shown in Figure 1.1 is the surface coating industry. The military represents a portion of this industry and as a result, emits its share of VOCs into the atmosphere. Though all military services in varied capacities are emitting VOCs to the atmosphere (Park, 2004), this study will focus on the Navy and Marine Corps and their use of surface coating processes during depot-level aircraft maintenance. These facilities,

several of which are in operation throughout the United States serving the needs of Navy and Marine fleet aircraft, are critical to aircraft mission capability. Though there is no current regulation in effect requiring FRC East to control its emissions of VOCs, the possibility exists that such legislation could be passed in the future. If the facility is not prepared for this eventuality and intends to continue operations while not controlling VOCs, the government's likely reaction would be to subject FRC East to heavy fines until it is within compliance of any new regulations. A possible shut-down of operations due to non-compliance is less likely, however, such an action would severely affect aircraft readiness levels at the FRC and in the fleet and is therefore not an option. The continuous operation of these facilities is essential to achieving maximum fleet aircraft readiness.

1.2 Fleet Readiness Center (FRC) Concept

Aircraft maintenance in the United States Marine Corps (USMC) is regulated by the Department of the Navy (DoN). In these most recent times of transformation, reduction, and consolidation within the Department of Defense (DoD), the Marines utilize much of the Navy's aircraft maintenance infrastructure for their own maintenance needs. The largest and most sophisticated of these "shared" structures are the six Fleet Readiness Centers (FRCs, formerly Naval Air Depots or 'NADEPs') located throughout the United States. Until October, 2006, there were three NADEP facilities being utilized by the Navy and Marine Corps for depot-level maintenance. In compliance with the 2005 Base Realignment and Closure (BRAC) Commission Report, which became law with Congressional approval in October 2005 (BRAC, 2007), these three facilities, such as the one chosen for this study aboard Marine Corps Air Station (MCAS) Cherry Point, have been aligned and combined with other aircraft maintenance facilities under

the FRC program to create six FRC facilities. The three FRCs that were once NADEPs still operate exactly as they did previously while the three additional “new” FRCs are the result of the integration of various intermediate-level aircraft maintenance facilities.

Marine and Naval aircraft maintenance is structured into a three-level concept. The lowest level, organizational, occurs on a day-to-day basis at the squadron where the aircraft operate in support of the Marine Corps aviation mission. Only limited on-aircraft maintenance such as inspections, servicing, or on-equipment corrective and preventative maintenance is authorized at the organizational level (DoN, 2005a). More intricate and detailed aircraft repairs such as maintenance on removed components, calibration, and the incorporation of technical directives occur at the middle level of aircraft maintenance, or intermediate level (DoN, 2005a). The highest level of maintenance occurs at the depot, the only facility authorized to perform major structural aircraft repairs, install aircraft modifications, and completely strip and paint entire aircraft (DoN, 2005a). As a result, the six FRCs (in particular the original three NADEP facilities) are considered industrial establishments and as such, have hangar-sized paint facilities large enough to accommodate various Naval and Marine aircraft.

Large paint facilities housing industrial surface coating operations present challenges in air pollution control. Paint booth emissions consist primarily of volatile organic compounds including, but not limited to, toluene, xylene, methyl ethyl ketone (MEK) and n-butyl acetate (McFarland et al, 2003; Webster et al, 1998). Though VOC emissions represent known health and environmental hazards, their current regulation in the coastal region of North Carolina is not strict. For example, FRC Southwest located at Naval Air Station North Island in San Diego, California operates a painting facility similar to FRC East and is subject to an 8-hour ozone non-attainment standard of 0.07 parts per million (ppm) while the EPA’s national standard for 8-hour

ozone is 0.08 ppm (ARB, 2007). The closest 8-hour ozone non-attainment zone to FRC East in North Carolina is approximately 140 miles away in Fayetteville (EPA, 2006e). Accordingly, many facilities—particularly those in attainment zones—are at best controlling VOCs with carbon filter bed adsorption units or worse, releasing these gases directly into the atmosphere unchecked.

1.3 Volatile Organic Compounds (VOCs)

VOCs are not only found in industrial surface coating operations. Other sources include commercial and residential applications such as solvents, cleaners, refrigerants, and glues. These sources individually account for small percentages of atmospheric VOC levels, however, all sources in combination produce a formidable toxic problem; approximately 70% of the 188 chemicals listed by the Clean Air Act as “toxic” can also be classified as VOCs (Suh et al, 2000).

Table 1.1. Amount of VOCs released to the atmosphere, in tons per year, from select states and the U. S., (EPA, 2006b). All VOC sources in combination produce a formidable toxic problem.

	1997	1998	1999	2000	2001
California	1,329,790	1,279,177	1,321,352	1,310,467	1,213,537
New York	907,185	878,051	815,285	785,559	782,815
North Carolina	705,179	658,667	650,493	634,969	638,961
Ohio	781,046	742,643	668,725	656,740	658,690
United States	19,530,287	18,781,546	18,775,885	17,512,394	17,117,700

Amounts of VOCs released to the atmosphere by select states and the U. S. over a 5-year period are shown in Table 1.1.

Once in the atmosphere, VOCs undergo photochemical reactions that contribute to the formation of ozone (EPA, 2006a). Ozone is an innocuous substance in the stratospheric level of the Earth's atmosphere where it is necessary to prevent harmful ultra-violet (UV) rays from reaching Earth's surface. However, ozone near ground-level is known to cause damage to lung tissue, particularly in infants, the elderly and those individuals sensitive to atmospheric irritants (EPA, 2006a). For this reason, the release of VOC emissions must be controlled, if not prevented.

1.4 Biofiltration Technology

Biofiltration for use as a VOC-reducing air pollution control technology is not a new concept. Its effective use at sewage treatment plants for odor control has been studied and documented in this country as early as the 1950s (Wani et al, 1997). Other successful uses of the technology since then include air remediation at a boat manufacturing facility (Lackey et al, 1998), VOC control at a fish processing plant, and odor control in the tobacco (Dragt and van Ham, 1992) and cocoa roasting industries (van Groenestijn and Hesselink, 1993). While some studies have been published regarding the success of biofiltration when applied to VOC removal, fewer studies exist that have examined VOC removal specifically at industrial-sized surface coating operations. One such study showed a 99% removal rate of VOCs from laquer thinner and reducer mixtures (containing variable amounts of toluene, methyl isobutyl ketone, methyl ethyl ketone, xylene, acetone, diacetyl alcohol, and isopropyl alcohol) from an effluent air stream at a coating company (Stewart and Thom, 1996). An experiment conducted at Hill Air Force Base showed a 100% removal rate of VOCs from air streams designed to replicate effluent produced by an industrial surface coating operation (McFarland et al, 2003). Other biological

treatment processes such as a biotrickling filter and a hybrid biofilter were shown to have 90% and 80% surrogate paint VOC mixture removal rates at bench- and lab-scale levels, respectively (Webster et al, 1998; Song et al, 2002).

The concept of biofiltration is simple; contaminated air is forced through a media populated by microorganisms which biologically degrade the undesired contaminant (see Figure 1.2). Contaminant degradation occurs when the microorganisms metabolize the carbon-based contaminant (VOC) molecules to their primary components, usually carbon dioxide, water, and other harmless substances (Wani et al, 1997). Clean, uncontaminated air is then released to the atmosphere from the filter. This process does not generate any additional waste; transfer of pollutants to another media does not occur and, therefore, an additional environmental problem is avoided, saving potential disposal costs. Other immediate benefits include low system maintenance and, consequently, low maintenance and operating costs (Wani et al, 1997).

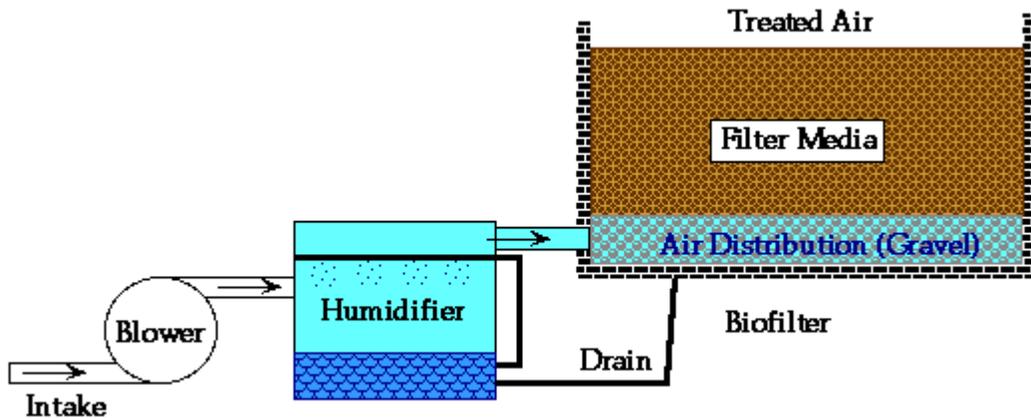


Figure 1.2. Biofilter Schematic. Drawing taken from the Cornell composting website and used by permission of Tom Richard (trichard@psu.edu) and the Cornell Waste Management Institute (<http://compost.css.cornell.edu/science.html>). Contaminated air is forced through a media populated by microorganisms which biologically degrade undesired contaminant.

Despite these advantages, biofiltration technology did not gain a strong foot hold in the United States until after the passage of the Clean Air Act (CAA) amendments in 1990. During the 1970s and 1980s, while biofiltration technology was largely overlooked in the United States, Europe—in particular the Netherlands and Germany—gained research and development momentum to make great progress in the refinement of this technology (Devinny et al, 1999). Portions of the CAA focus on the control and removal of VOCs from contaminated air streams (Wani et al, 1997) and these regulations, along with a new found public interest in air pollution control issues spawned a renewed interest in the technology in the United States that has carried through to today.

1.5 FRC East (NADEP), Cherry Point Regulatory Issues

FRC East is located in an ozone attainment zone, meaning the local quality of the air is “good” by EPA standards and does not require close scrutiny (EPA, 2006c). Paint overspray is currently controlled only by particulate filters, leaving organics free to be released to the atmosphere. According to this facility’s environmental engineer, Mr. Clifton Game, “NADEP could benefit from significant emission reductions if they can be achieved at a reasonable cost” (Game, 2006). Challenges in controlling VOC emissions from this facility lie in the fact that the surface coating operation is not a full-time endeavor. Instead, aircraft and aeronautical parts are painted on an “as-needed” basis and the paint booths produce minimal waste air streams with relatively low levels of contamination; a situation aptly suited for biofiltration techniques.

There is one published order regulating environmental practices and policies within the Marine Corps. Marine Corps Order (MCO) P5090.2A, the *Environmental Compliance and Protection Manual*, is clear in its deferment of the regulation of stationary-source air quality

issues to applicable authorities (DoN, 1998). Though the FRC's primary customer is the Marine Corps, the Marine Corps does not have controlling authority over the FRC. This responsibility formerly rested with the Naval Air Systems Command (NAVAIR) but as of October, 2006 lies with Commander, Naval Air Forces (CNAF). Several documents drafted and disseminated by NAVAIR establish environmental responsibilities and obligations to be observed by subordinate commands such as the NADEP. NAVAIRINST 5090.1, NAVAIR's *Environmental Program* is the most comparable document available to MCO 5090.2A. Several other instructions have been published by NAVAIR that affect the operation of the NADEP none of which, however, mention the control of harmful air emissions to the environment. These military documents have left the scientific aspects of air quality to the government agencies responsible for emissions control and therefore reference the appropriate documents that do so. There is no indication at the present time showing the intent of CNAF to change this policy when it realigns NAVAIR documents under the new CNAF heading. The Department of the Navy has published an instruction detailing the Navy's environmental policy. This document, OPNAVINST 5090.1A, the *Environmental and Natural Resources Protection Manual*, is the Navy's standing order regarding environmental affairs. In much the same way state and local governments can establish and enforce stricter environmental laws than those provided by the federal government, NAVAIR and the Marine Corps can establish their own environmental guidance within the spirit of the presiding OPNAV document. MCO P5090.2A and NAVAIRINST 5090.1 are such examples.

Environmental regulations beyond those within the DoD must also be followed by industrial operators such as the FRC. At the Federal government level, the Clean Air Act amendments of 1990 must be observed. Further, the North Carolina Department of Environment

and Natural Resources has published “Air Quality Rules”, effective January, 2007 (NCDENR, 2007). These rules are separate from North Carolina’s State Implementation Plan (SIP) which is a federally approved plan detailing how North Carolina will enforce Federal environmental regulations. Additional regulations are in the form of Executive Orders (EOs) disseminated by the President of the United States. Many EOs exist to protect the environment, the more pertinent of them to the facility at Cherry Point being EO 12088, “Federal Compliance with Pollution Control Standards”; EO 13101, “Greening the Government Through Waste Prevention, Recycling, and Federal Acquisition”; EO 13123, “Greening the Government Through Efficient Energy Management” and EO 13134, “Developing and Promoting Biobased Products and Bioenergy” (OFEE, 2006).

1.6 Problem Statement

Air pollution control of fugitive VOCs is required under federal law in varying areas within the U. S., is implied with executive orders, and is beneficial to the environment. Currently, the FRC at Cherry Point discharges approximately 26.4 tons of VOCs into the atmosphere per year (Game, 2007). An inexpensive technology is needed to control releases of VOCs from VOC-generating surface coating operations. Biofiltration may be a cost-effective and efficient air pollution control (APC) technology for use at FRC facilities—in particular the Cherry Point facility—for control of these emissions.

1.7 Research Objectives / Questions

The purpose of this research was to determine if FRC East and the surrounding area can benefit both economically and environmentally from a biofiltration system for air pollution

control rather than the current conventional method of dry filtration. Research questions explored included:

1. What is the anticipated reduction in VOC emissions from the paint facilities if a biofiltration unit is installed?
2. Will conventional biofiltration be a satisfactory air pollution control method for use at FRC East, given their low levels of VOC emissions, intermittent operations, and varied aircraft / aircraft component throughput?
3. What is the best packing media for the appropriate size of a conventional biofilter for the FRC facility?
4. Will biofiltration be a cost effective method for reducing FRC East VOC release to the atmosphere, i.e., will a net present value calculation show conventional biofiltration is cost effective for this facility?

1.8 Methodology

Literature was reviewed for cases where biofilters were used successfully to treat similar emissions from like-facilities. A brief case-study analysis was completed on two such facilities. Limitations of biofiltration were obtained from the literature and discussed. FRC East provided the types and amount of VOC emissions from the installation's current air pollution inventory, Toxic Release Inventory (TRI) Report or Title V permit, as applicable. Dimensions of the paint facility under study were provided. With this information, a biofilter was designed using principles and design equations outlined in Devinny (1999). Appropriate residence times, packing materials and other parameters were determined from lab-scale studies found in the literature. A conventional biofilter manufacturer was contacted to determine the sizing, material

recommended and estimated maintenance and operation costs for a conventional unit. The costs of the biofilters were then compared to health and environmental costs associated with not controlling VOC emissions using a net present value calculation.

1.9 Assumptions / Limitations

In order for a fair evaluation to be presented on the feasibility of biofiltration at FRC East, limitations in such a study must be discussed. As this is the first study performed with the intent of recommending an innovative APC technology to the Cherry Point facility, unexpected roadblocks and outcomes were inherent. Attempting to predict and account for these possibilities during the study allowed for more accurate analyses and conclusions to be drawn.

This study was conducted for only one facility. This presents a limitation because every FRC facility currently operated by the Navy and Marine Corps is different. While aircraft maintenance processes and operational practices among the facilities do not vary greatly with location, differences in parameters such as facility infrastructure, work load, and applicable environmental rules and regulations do exist. Therefore, applying the results of this study to another like-facility may present some challenges. Application of a successful study to a comparable facility in a military service other than the Navy and Marine Corps or to a commercial facility may present even further challenges and would require meticulous and careful analysis of that facility's procedures, processes, emissions, and infrastructure prior to such application.

Laboratory tests or pilot-scale installations were not part of this study. The absence of adequate facilities to conduct laboratory-sized experiments and the expense and time constraints involved with installing a pilot-scale system have relegated this study to rely upon lab- and pilot-

scale studies conducted previously. There is no shortage in the literature of studies that have examined the performance and behavior of lab-, pilot-, and full-scale biofilters.

Though there are multiple manufacturers of commercial, industrial-sized biofiltration units, only one unit from such a manufacturer was analyzed for this study. A full study of every industrial-sized biofilter on the market is well beyond the scope of this study. Choosing only one manufacturer, however, presented a limitation because there quite possibly are other vendors and distributors on the market with products or processes containing better, more economical, or more efficient solutions. This fact must be taken into consideration if this study is to be applied to an industrial facility other than that at Cherry Point.

Finally, there is the matter of policy change at the Cherry Point facility should this study prove to be successful and should the facility decide to install a biofiltration unit for its APC needs. Limitations in this area come in the form of maintenance and training issues and what entity will provide each. Though the maintenance on a conventional biofiltration unit is minimal compared to other APC technologies (Leson and Winer, 1991), a newly installed unit will require close expert attention during the early stages of operation and continued observation for the remainder of its useful life. Personnel already in the employ of the FRC would have to be trained to maintain the biofilter or additional personnel would need to be hired. General resistance among current employees about having to learn an additional skill and assume additional duties would have to be overcome. Strong leadership and support from the chain of command are essential components to the success of a project such as this. Fortunately, the results of this study showed that a biofiltration process could benefit FRC East and its surrounding community. This fact could ease the burden on the leadership to convince employees of the benefits associated with adopting a biofiltration system.

1.10 Significance

Despite possible limitations, the success of this study has potential DoD-wide effect. If, as predicted, biofiltration proves to be a cost-effective and appropriate air pollution control method for FRC East, significant cost savings may result. From an environmental standpoint, this technology reduces the amount of man-made material entering local landfills. Biofiltration facilitates the complete destruction of VOCs rather than their transfer from an air contaminant to a solid waste, requiring disposal. If this technology becomes a success at FRC East, biofiltration may become an option at other Naval and Marine facilities, as well as at sites within other military branches.

II. Literature Review

2.1 Background

Biofiltration is by no means a new technology. However, its lack of use and study in the United States until relatively recently easily deceive the layman into thinking it is a newly developed and fledgling air pollution control (APC) technology. This could not be further from the truth. Though the use of this technology for the purpose of APC started almost simultaneously in this country and in Europe, its study, development, and subsequent refinement established a stronger foothold overseas. Much of the pioneering work in biofiltration as an APC technology was accomplished by European countries such as Germany and the Netherlands with other nations such as Japan contributing scientific advances to the field along the way. Despite its late start in the development and prolific use of biofiltration for APC, the United States presently can certainly be compared to its European counterparts as “biofiltration savvy” and in many cases can be considered the new pioneer in this field.

2.2 History

Biofiltration can be traced to its earliest roots for odor control at sewage treatment plants. A German scientist named Bach alluded to the use of biological processes to treat the emission of odorous hydrogen sulfides at sewage treatment plants in Germany in 1923 (Leson and Winer, 1991). Soil beds were first used in the United States for the treatment of odorous sewer gases in 1953 when such a bed was installed in Long Beach, California (Wani et al, 1997). The first patent for a soil bed designed to treat odorous gases was issued by the United States in 1957 to Richard Pomeroy, the creator of the Long Beach soil bed (Leson and Winer, 1991; Delhomenie et al, 2002). The simplicity in its design can be noted in Figure 2.1, taken from the original

patent document issued by the United States Patent and Trademark Office (USPTO). In this design, malodorous air is led into a pump, through a pipe and then forced through another pipe to a distribution conduit out of which gases escape through cinders and into the permeable soil containing the microorganisms.

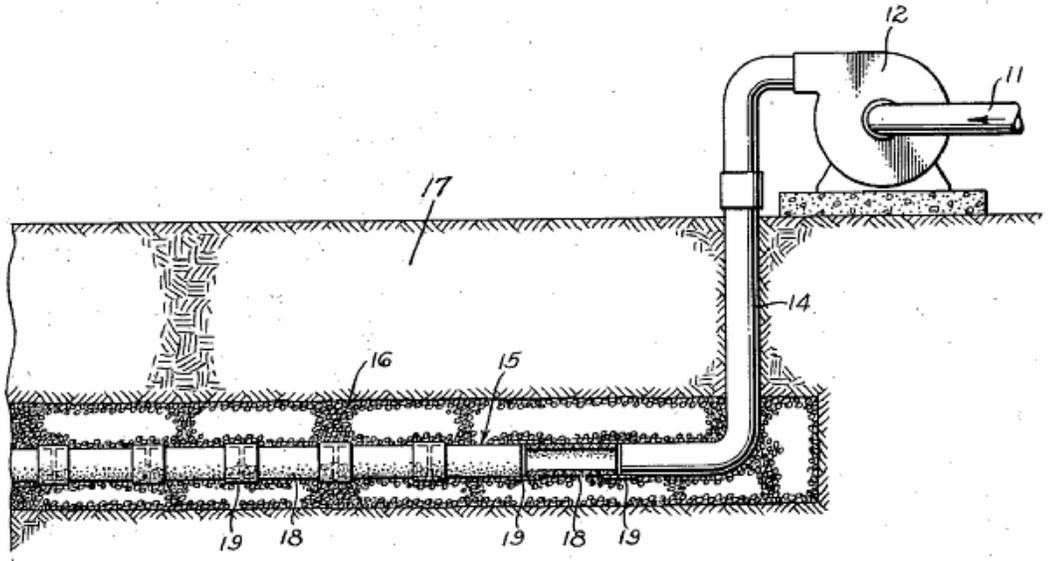


Figure 2.1. Drawing of soilbed filter. From original patent submitted by Richard Pomeroy to the United States Patent Office in 1953. Malodorous air is led into a pump (12) through a pipe (11) and then forced through another pipe (14) to a distributing conduit (15) out of which gases escape through cinders (16) and into the permeable soil (17) containing the microorganisms. (USPTO website, 2006).

Patents continued to be issued by the USPTO for methods of cleaning waste-gas streams using biofiltration technology for the next several decades, though sparingly and frequently from foreign pioneers in the field such as Simon Ottengraf of the Netherlands, Rainer Hoffman of Germany and Japan's Hisao Ishikawa (USPTO website, 2006). The preponderance of patent activity did not begin until the late 1980s and early 1990s, however; a testament to the general inactivity within the biofiltration field for the several decades following Pomeroy's invention.

Several reasons are attributable to the aforementioned “inactivity”. Since Carlson and Leiser’s systematic research on biofiltration for the treatment of hydrogen sulfide emissions from sewage in the early 1960s, not much literature has been published on the topic of biofiltration (Leson and Winer, 1991). In 1991, the number of biofilters estimated to have been installed and functioning in the United States and Canada collectively was less than 50 (Leson and Winer, 1991). At the same time, biofiltration had emerged in West Germany and the Netherlands as the preferred method of air pollution control to the point where the technology was considered a best available control technology (BACT) in both countries for odor control as well as volatile organic compound (VOC) control (Leson and Winer, 1991). By 2005, the number of biofilters in the United States had grown to over 300 for odor control capacities alone (Iranpour et al, 2005). Therefore, the assumption can be made that the biofiltration technology was almost completely ignored in the United States during the 1970s and 1980s while its European counterparts during these years raised it through its infancy and developed it into a competitive technology for APC.

Use of the biofiltration technology in the United States has been limited by the synergy of multiple factors. While soil beds have been recognized as effective odor control devices able to operate at low capital and maintenance costs, the relative low biodegradation capability of soil and the subsequent large volume of soil required for a bed have stymied the technology’s prolific use (Leson and Winer, 1991). Even after biofiltration was proven to be cheap and reliable due to the absence of additional waste-processing, additional resistance to the technology has occurred; a dismissive attitude of “if it’s cheaper, it can’t be any good” has developed among potential users negating serious research and development of biofiltration for nearly a two-decade period (Wani et al, 1997). Lack of governmental support for biofiltration in the United States, both in

regulatory programs and in research and development caused further neglect of the technology (Leson and Winer, 1991). West Germany and the Netherlands became pioneers in the biofiltration technology out of necessity. Strict regulatory requirements in both countries from the late 1970s forward spurred much research and development in biotechnology (Van Groenestijn and Hesselink, 1993). Though these two countries refined the fledgling technology during the 1970s and 1980s, they did so in their native languages. The resultant lack of technologic and scientific papers in English on the subject further hampered the technology's development in the United States (Leson and Winer, 1991).

2.3 Biofiltration Technologies

2.3.1 Biofilter

The simplest technology to be considered within the science of biological air purification is the biofilter. A biofilter consists of a stationary filter bed containing a porous media or packing material serving as a host to a microbial population. These microorganisms, which either live in a biofilm on the surface of the porous media or are suspended in a thin liquid phase surrounding the media, break down contaminants within a polluted air stream as the air stream passes through the filter bed. A wide range of materials can be used for the porous media, ranging from organic materials such as peat, soil, and bark to synthetic materials such as plastic rings or Styrofoam cubes. Though the concept behind biofiltration remains relatively simple—a filter that turns influent “dirty” air into a “clean” effluent air using microorganisms—there are many processes taking place within the filter bed (adsorption, absorption, degradation, and desorption) which are more complicated and require thoughtful and meticulous design prior to operation (Devanny, 1999).

Key factors in biofilter design play vital roles in the system's performance. It is generally desirable for the packing material within the filter bed to have a multitude of favorable qualities. Surface area is important because more surface area allows for more microorganisms to grow and contribute to the degradation process. The ability of microorganisms to grow depends on the ability of the media to retain moisture (Delhomenie and Heitz, 2005). Porosity and degree of compaction are also crucial; contaminated air needs to be able to move freely through the packing material without stagnating or clogging, both of which reduce biofilter performance. Moisture content of the influent air stream is critical; air that is too dry may dry the biofilm and the filter media. Additional parameters of concern within a filter bed are its pH and temperature (Devinny, 1999).

Two basic designs of biofilters have traditionally been used for treatment of waste-air streams. Early versions of biofilters were soil beds used for the elimination of odors from wastewater treatment operations (Carlson and Leiser, 1966). This design is called an "open" biofilter, that is, the filter bed is exposed to open air, and can be situated either above ground or below ground (Devinny, 1999). Biofilters eventually evolved into a "closed" model which does not have a filter bed exposed to the environment and provides for easier control of critical parameters such as water content and temperature (Kennes, 2001). Study and experimentation of these designs over several decades has led to today's use of efficient biofiltration methods.

2.3.2 Biotrickling Filters

Biotrickling filters are closely related to biofilters in that they operate similarly. Contaminants from a waste-gas stream are absorbed into a liquid phase. The liquid phase is then trickled over an inert, inorganic packing material such as plastic rings, open pore foam, or lava

rock (Cox and Deshusses, 2002). Microbes attached to the stationary and synthetic material along with suspended microbes in the trickling fluid work together to degrade the absorbed contaminants (Devinny, 1999). The trickling fluid is recirculated through the bioreactor either in co-current flow with the waste-air stream or counter-currently. No research to this point has indicated which direction of flow is better than the other (Kennes, 2001). The advantage of trickling fluid recirculation is the ability it affords the system operator to add nutrients, acids, or bases which in turn allows for adjustment of the fluid's environment for optimal pollutant removal (Devinny, 1999).

Biotrickling filters possess many advantages for use as an APC technology. Like biofilters, biotrickling filters are simple, inexpensive, and effective at removing target contaminants (Kennes, 2001). Biotrickling filters do not require humidification of the waste-air stream prior to entry to the bioreactor as do biofilters, negating the incorporation of an additional step in the treatment process (Kennes, 2001). Biotrickling filter systems can be constructed vertically, unlike most biofilters and therefore require less of a footprint which may be a consideration in urban or densely populated environments (Kennes, 2001).

Though there are many positive qualities to biotrickling filters, disadvantages of this technology also exist and frequently render biofiltration a more appropriate technology. A major problem with the use of this technology in the control of VOCs under field conditions is the tendency of biotrickling filters to clog as a result of excessive biomass growth (Choi et al, 2004). Numerous lab-scale studies have demonstrated this problem. For a biotrickling filter to be successful, its packing material must be able to host a thriving microbial population while simultaneously avoiding conditions that cause excessive growth and clogging situations

(Devinny, 1999). Another disadvantage of this technology, when compared to biofiltration, is the increased amount of complexity involved with its construction and operation (Kennes, 2001).

Incidentally, this technology has been successfully field-tested at a facility similar to FRC East. At San Diego's Naval Air Station North Island, a pilot-scale biotrickling filter was designed and installed at the facility's spray paint booth to treat methyl ethyl ketone (MEK) and *n*-butyl acetate, both of which are contaminants emitted by FRC East during its surface coating operations. The tests showed air pollutant removal rates consistently over 88%. Based on the success of these trials, a full-sized biotrickling filter was installed to treat air emissions from the North Island facility's industrial waste-water treatment plant (Frazer, 2000). This study at the North Island facility demonstrated the need for a biomass control strategy in order to prevent plugging within the packing material and showed the propensity these filters have towards clogging (Webster et al, 1998). For these reasons, a biofilter is frequently preferred over a biotrickling filter.

2.3.3 Bioscrubbers

From the biotrickling technology evolved the next generation of biological treatment systems known as bioscrubbing. To date, the majority of bioscrubbers in operation exist to eliminate odors from waste-gas streams. There are two types of bioscrubbers, fixed-film bioscrubbers and suspended-growth bioscrubbers (DeHollander et al, 1998 and Ockeloen et al, 1996). Fixed-film scrubbers are similar to conventional biofilters in that there is a porous packing material (filter media) present which exists to house the microbial community. The packing material, typically synthetic (Ockeloen et al, 1996), is configured in a tower. The waste air is pumped upwards through the packing material while a "scrubbing solution"—usually

nutrient-rich water—is forced downwards and continuously recirculated without additional treatment (Joyce and Sorensen, 1999 and Ockeloen et al, 1996) or with treatment and reuse (Van Groenestijn and Hesselink, 1993). Mass transfer of the odor within the waste-gas stream to the aqueous film on the packing material takes place, at which point the organics are biologically oxidized, thus removing the odor from the waste-gas stream (Joyce and Sorensen, 1999). Suspended-growth scrubbers are similar to fixed-growth scrubbers in that they each consist of a tower containing a packing material in which adsorption of the pollutant from the waste-gas stream to the aqueous “slurry” occurs. The aqueous “slurry” flows to a biological reactor where complete oxidation of the pollutant can take place and the recirculation of the slurry can continue (DeHollander et al, 1998).

Bioscrubbers exist with benefits and limitations. Reaction conditions can be controlled better in bioscrubbers because the liquid phase is mobile, as opposed to the stationary filter media in biofilters (van Groenestijn and Hesselink, 1993). The biologically active material within the aqueous solution can be controlled easily by adjusting pH, temperature, nutrient level, and buffer and titrant levels (van Groenestijn and Hesselink, 1993). Bioscrubbers, unlike biofilters, are appropriate only for compounds with low values of the Henry’s Law coefficient (DeHollander et al, 1998) or extremely low values if large water flows are present (van Groenestijn and Hesselink, 1993).

2.3.4 Rotating Drum Biofilter

A late addition to the family of biofilters is the rotating drum biofilter (RDB). Due to its relatively recent development, not many studies exist investigating this technology. Perhaps the most comprehensive document concerning the development and design of the RDB is the

doctoral dissertation presented by Dr. Chunping Yang at the University of Cincinnati in 2004. During the course of his research, Dr. Yang developed and constructed three types of RDBs for testing in the hopes of overcoming the common problems of conventional biofiltration methods while still retaining the biofiltration technology (Yang, 2004). Other studies of this technology concluded that variations of the RDB design result in better distribution of contaminants, nutrients, and biomass than conventional biofilters are capable of exhibiting (Yang et al, 2003; Yang et al, 2004).

Three varieties of RDB were developed for study; a single-layer model, a multi-layer model and a hybrid model. The bioreactor of both the single- and multi-layered models is a rotating drum on a horizontal axis housed within a larger chamber. The chamber of both models is filled with a nutrient solution sufficiently deep to completely submerge the lowest portion of each rotating drum and the single- or multi-layers of porous media attached to each. The contaminated waste-gas stream enters the biofilter through a distribution pipe at the drum's highest point where the pollutants are absorbed into and biodegraded by the biofilm within the drum (Yang, 2004). The hybrid RDB is a combination of a multi-layer RDB and an aerated activated sludge process. Bioreactor construction in the hybrid model is identical to the multi-layer model, however, the waste-gas stream inlet is submerged in the nutrient solution at the bottom of the chamber. As the contaminated gas enters the chamber through the inlet pipe in the liquid phase, absorption and degradation of the pollutants occurs within the nutrient solution. Pollutants in the waste-stream not degraded in this manner enter the RDB in the gas phase and travel through the multiple layers of filter media for further degradation before a purified gas-stream exits the bioreactor at the center of the drum (Yang et al, 2004).

All three RDB designs were shown to be efficient at contaminant removal. One study compared single- and multi-layer RDB models in their removal efficiency of diethyl ether as a representative VOC from a waste-gas stream (Yang et al, 2003). Both models performed efficiently at the conclusion of the study, however, the multi-layered RDB possessed a more even biomass distribution on the concentric surface than the single-layer model, which infers better performance (Yang et al, 2003). The hybrid RDB also showed favorable removal efficiency rates of a toluene-based model VOC (Yang et al, 2004). Removal efficiency in all three RDB models declined when concentration of the VOC feed increased causing an increase in organic loading rate within the biofilter (Yang, 2004).

2.3.5 Membrane Bioreactors

Also used for biological treatment of contaminated air, though less common than the above-mentioned technologies, is membrane biofiltration. A membrane bioreactor contains a series of membranes through which the contaminated air stream passes, surrounded by a circulating nutrient media. A biomass growth surrounds the membranes, which are fabricated of some type of diffusive material. As the contaminated air stream flows through the membranes, the soluble contaminants within it are transferred through the membrane material into the biofilm where they are degraded. The nutrient bath containing the degraded contaminant is then recirculated and treated or disposed of as waste (Kennes, 2001). The relative compact size of these reactors has encouraged their study amongst European and U. S. space agencies for potential use aboard space craft to treat contaminated air, especially during long-term missions (van Groenestijn and Kraakman, 2005). There are two types of membrane bioreactors available

for treatment processes; hollow fiber microporous membrane and dense phase membrane reactors (Roberts, 2005).

Hollow fiber microporous membrane reactors contain porous membranes through which waste-gas streams flow. Contaminants in the gas phase are transferred through the membrane pores to the surrounding biofilm. While this technology has some benefits over conventional methods of biofiltration such as low pressure drops, the absence of medium channeling, and the ease of nutrient addition and pH adjustment (Fitch et al, 2002), problems with membrane-pore clogging are frequent. This inhibiting factor and the high prices associated with hollow membrane reactors prevent the prolific use of the technology (Roberts, 2005).

Dense phase membrane bioreactors utilize non-porous membrane material that exhibits high oxygen permeability (Attaway et al, 2001). Membrane material such as silicone is hydrophobic and allows for the easy transfer of hydrophobic compounds to the surrounding biofilm. Studies of membrane systems utilizing non-porous membrane material have shown favorable results over micro-porous membrane systems (Attaway et al, 2002). The readily available nature of silicone products and thus their lower cost has established dense membrane bioreactors as preferable systems for treatment over hollow membrane reactors (Roberts, 2005).

2.4 Biofiltration Application

2.4.1 Appropriate Contaminants

Biological treatment has been found to be an ideal treatment process for large quantities of exhaust air containing low concentrations of contaminants (Wani et al, 1997; Leson and Winer, 1991). Additionally, biological treatment may only be applied successfully as an APC technology if the contaminants within the emissions of concern are biodegradable. For these

reasons, removal of VOCs from waste-gas streams is particularly suited for biofiltration.

Organic compounds that are easily degraded biologically are typically highly soluble, have a low molecular weight, and contain simple bond structures (Devinny, 1999). Examples of easily degraded organics include alcohols, aldehydes, and ketones. Simple aromatics such as benzene, toluene, styrene, and phenol are also easily degraded as repeated studies have shown (Ottengraf, 1986; Tonga et al, 1994; Zilli et al, 1993; Shareefdeen and Baltzis, 1994; Wani et al, 1997). Less biodegradable compounds include chlorinated, polyaromatic, and highly halogenated hydrocarbons. Complex bond structured-compounds and various anthropogenic compounds are not particularly biodegradable because the microorganisms within the packing media do not contain the necessary enzymes or energy to break down the contaminants (Devinny, 1999). Known biologically toxic compounds should be avoided altogether if using a biological process for APC to avoid killing the microorganisms.

Degradation of VOCs within a biofilter serves a dual purpose. First and foremost, if the filter is properly designed to eliminate the particular contaminant of interest in the waste-air stream, removal efficiency of the biofilter will be at its maximum level and the resulting clean air will contain little-to-no contamination. This is an environmental benefit as clean air is generally considered favorable over polluted air by society. The benefit to the biofilter is contained within the degradation process itself and less likely to be noticed by the casual observer.

Microorganisms within the biofilter are metabolizing and oxidizing the pollutants into mineral end products (Aizpuru et al, 2001). Portions of these end products are converted to new cell material which contributes to the biomass growth required to sustain the biofilter as a successful bioremediation technology. Cell growth increases biomass and prevents the addition of nutrients

for the same purpose (Van Groenestijn and Hesselink, 1993) but care must be taken by the system operator to prevent clogging due to excessive biomass growth.

2.4.2 Conventional Treatments and Economic Benefits

Biofiltration has been shown to be a cost effective method of treating contaminated waste-air streams. Conventional treatment methods (such as thermal oxidization, adsorption, or condensation) for VOC control vary, however, these systems often have higher energy requirements to operate effectively, processes that require additional chemicals and fuels, intricate and frequent maintenance requirements, and residual products requiring disposal or further treatment prior to environmental release (Wani et al, 1997). These operating costs are in addition to the capital costs—system equipment, labor to build and install system, and costs associated with interest (Deviny, 1999)—of the APC technology which they support. Biofiltration, an effectively simple yet low-maintenance technology, does not incur these additional operating costs which should be an appealing quality to those industries considering conventional technologies for their APC needs.

Thermal incineration requires large amounts of fuel to be an effective removal technology. More fuel is required if the waste-gas being treated contains low concentrations of contaminant, as is often the case with VOCs emitted from surface coating operations (Leson and Winer, 1991). Aside from the additional air pollution the burning of these fuels may create, the cost of these fuels over time to the operator may prove to be excessive (Wani et al, 1997). In fact, the investment cost of a typical incineration operation can reach up to \$450 per cubic meter of air per hour with operating costs reaching as much as \$150 per cubic meter of air per hour (Delhomenie and Heitz, 2005). Heat recovery processes and catalysis (decreasing the rate at

which the fuel burns) can reduce some of these costs, however, this reduction typically occurs at the expense of higher installation and maintenance costs (Bohn, 1992).

Carbon adsorption offers effective VOC removal rates from waste-air streams. However, the carbon filters used during this process will eventually become saturated and require removal. Once the filters are removed, they will either need to be regenerated (“cleaned”) and used again or disposed. Disposal of saturated carbon filters incurs an expense because the filters must often be treated as hazardous waste (Wani et al, 1997). Regeneration of the saturated carbon filters is possible, however, it is truly only cost-effective if on-site regeneration processes are available and a valuable raw material is recovered as a result (Leson and Winer, 1991). Investment costs of adsorption processes have been shown to range between \$15 and \$120 per cubic meter of air per hour and operational costs typically fall under \$35 per cubic meter of air per hour (Delhomenie and Heitz, 2005).

Chemical oxidation (sometimes called wet scrubbing) for treatment of contaminated air is another common method of APC. Contaminants in this process are changed from the gas phase to a liquid phase using chlorine, ozone, hypochlorite, or permanganate, among other chemicals. This technology has shown efficiencies as high as 95% (Bohn, 1992) but is typically not effective for hydrocarbons and other slow reacting compounds (Wani et al, 1997). Chemicals and scrubbing agents utilized for this process incur a consistent cost. Additionally, treatment of the resultant liquid phase to eliminate the contaminant raises the operating cost. Oxidation operations have been shown to incur investment costs of up to \$220 per cubic meter of air per hour with additional operational costs reaching as much as \$90 per cubic meter of air per hour (Delhomenie and Heitz, 2005).

Costs associated with biological treatment systems vary with each specific biological technology. Most of the literature discusses costs of these technologies collectively under the heading “biofiltration” rather than comparing the cost of each type of biological process (e. g., biotrickling, bioscrubbing, etc.). Capital (investment) costs for biofilters are typically measured by the cost per unit of air treated (Devinny, 1999; van Lith, 1997). Operating costs for biofilters are more variable depending on the system installed, contaminants being treated, energy and water consumption, and maintenance requirements (van Lith et al, 1997). Capital costs for a biofilter are reported to be between \$7 and \$70 per cubic meter of air per hour (Delhomenie and Heitz, 2005; van Lith et al, 1997; Bohn, 1992) while operating costs are shown to range between \$3 and \$10 per cubic meter of air per hour (Delhomenie and Heitz, 2005). Regardless of the biological process used, the cost savings over other conventional technologies for similar APC applications are evident.

2.5 Biofilter Design and Sizing

Choosing the right design and size biofilter is an important step in the process of controlling VOC emissions. The parameter of residence time is a function of the filter volume and the contaminated air flow rate into the filter. An increase in residence time yields improved biofilter performance. As the size of a biofilter increases, so does its gas residence time and together they increase the price of the biofiltration system. As the contaminated air flow rate is a fixed entity at many facilities due to production processes or designs, a careful balance must be reached between these phenomena in order to maximize the efficiency of the biofilter while simultaneously offering the most cost-effective solution (Devinny, 1999).

Design of a biofilter must incorporate a variety of crucial parameters in order to produce an efficient and effective system for air pollution control. Once the primary pollutant for remediation has been identified and is known to meet the criteria suitable for biodegradation, controlling factors in the biofilter design such as microorganisms, filter media, filter bed size, filter media water content, filter media pH, influent air contaminant loading, influent air flow, waste-gas temperature, and particulate control can begin to be considered. Filter media is the driving factor behind a successful biofilter and most of the above-listed parameters directly influence the behavior of the media. A discussion of each parameter follows in the sections below.

2.5.1 Filter Media

Perhaps of most vital importance to the design and function of any biofilter is the selection of the appropriate filter media, also referred to as packing material or porous media, and ensuring it will provide the biofilter system with optimum contaminant removal (Wani et al, 1997). Types, size, and origin of media vary greatly as do the costs associated with each. Organic materials are historically used as filter media, though in recent years synthetic materials have proven to be effective media as well when combined proportionately with organic material (Devinny, 1999; Wani et al, 1997). Regardless of the exact composition of the filter media, the filter bed must provide the microbial population with an optimum environment in which to survive and achieve maximum degradation rates, contain sufficient pore space to reduce the amount of pressure drop, contain a large amount of surface area for biomass growth, and not be susceptible to compaction (Leson and Winer, 1991). Selected types of media and some of their parameters relative to each other are presented in Table 2.1.

Soil

Soil is the original filter medium utilized in the earliest models of biofilters (Pomeroy, 1957). Advantages of soil use as a filter medium include its wide spread availability and easy access, its inexpensive cost and the ease with which it can be hydrated. Perhaps of most interest is the extremely large amount of microorganisms that are present in soil; a large population size can easily adapt to treating particular pollutants. When exposed to large volumes of water, soils tend not to aggregate like sand does, however, permeability levels in soil are typically lower (Devanny, 1999). As a result of this phenomenon, soil beds typically experience high pressure drops and can develop fissures and canals through which contaminated air will always pass, limiting the treatment potential of the entire filter. Soil beds typically require a large footprint due to the low specific activity (the soil's metabolic capability per unit volume) associated with most soils (Devanny, 1999). When these advantages and limiting factors are combined, soil beds are considered best for use in low-tech, open-bed biofilter operations with unlimited space.

Compost and Peat

Abundant nutrient content and large microbial populations make compost an attractive filter medium. Bacteria, fungi, algae, protozoa and viral organisms are all present in compost. The presence of these microorganisms precludes the need for their inoculation into the filter bed, greatly reducing biofilter start-up time or acclimation period (Leson and Winer, 1991). Water retention and consistently neutral pH levels are favorable in compost media. Compaction of a compost medium is more likely than compaction within a soil or peat bed and for this reason, it is often mixed with an inert or synthetic medium such as wood chips or plastic cubes to maintain the necessary porosity. Types of compost are only limited to the designer's imagination; sewer

sludge and yard wastes are common (Devinny, 1999) but some studies have shown the effectiveness of cow and pig manure, wheat bran, and bagasse (fibrous material extracted from the juice of crushed stalks of sugar cane) (Chou and Cheng, 1997).

Table 2.1. Comparative parameters of selected filter media, modeled after Devinny (1999).

	Compost	Peat	Soil	Activated carbon, Perlite, and other inert materials	Synthetic Material
Indigenous Microorganism Population Density	High	Medium-Low	High	None	None
Surface Area	Medium	High	Low-Medium	High	High
Air Permeability	Medium	High	Low	Medium-High	Very High
Assimilable Nutrient Content	High	Medium-High	High	None	None
Pollutant Sorption Capacity	Medium	Medium	Medium	Low-High	None-to-High, including Very High
Lifetime	2-4 Years	2-4 Years	Over 30 Years	Over 5 Years	Over 15 Years
Cost	Low	Low	Very Low	Medium-High	Very High
General Applicability	Easy, Cost Effective	Medium, Water Control Problems	Easy, Low Activity Biofilters	Needs Nutrients, Expensive	Prototype Studies Only

Peat has the advantage of being extremely porous compared to soil and compost. Peat has a large surface area-to-weight ratio (Kennes, 2001), allowing for increased microbial activity. Unfortunately, peat contains virtually no microbes and thus requires microbial inoculation prior to biofilter operation. Nor is there a sufficient nutrient presence to feed the

inoculated microbes, therefore necessitating a consistent supply through the addition of slow-release nutrients or a steady feed through a trickling process (Devinny, 1999). Compost-synthetic mixtures are generally preferred over peat as filter media, especially within the last decade as studies have indicated favorable compost performance (Devinny, 1999).

Wood Chips and Bark

Wood chips and tree bark are worth mentioning as possible filter media because there haven't been many studies made of either and their true behavior as packing material is not known in detail. However, wood chips are frequently used in conjunction with other organic materials as a filler to increase porosity and air flow and decrease the likelihood of medium compaction (Nicolai and Janni, 2001; Deshusses and Johnson, 2000; Deshusses et al, 1999). There is concern that due to the ability of wood to harbor antibiotic substances for self protection against disease and rot, these substances may have an effect on a biofiltration process (Kennes, 2001). Again, no conclusive studies have been made of this phenomenon and at this point the notion is purely speculative.

Perlite

Perlite is an inert material that has been utilized as a filler in other filter media and has also been successfully applied as a filter media by itself (Kennes, 2001; Cox et al, 1997). This material is volcanic in nature and has been exposed to extreme heating causing an increase in mineral particle volume, greatly increasing the surface area (Kennes, 2001). An inhibiting factor is perlite's complete lack of microorganisms or nutrients, requiring inoculation and addition of these materials separately.

Synthetic Materials

Synthetic materials have not yet gained widespread use as biofilter media. These materials contain no microorganisms nor do they contain any nutrients. Unlike organic filter media, no nutrient material is being released by synthetic materials to contribute to biomass growth, thereby necessitating the need for continuous addition of these nutrients. Variant absorptive properties of synthetic materials can lead to problems with leachate, wash out, and biomass growth (Devinny, 1999). There are some promising bench-scale experiments that have demonstrated the potential benefits of synthetic filter media. Cattlebone composite ceramics (CPB) and porous ceramics (Porcelite®) were shown to have effectively removed toluene from a waste-gas stream (Sakuma et al, 2005). Other materials tested but requiring further examination for potential use are horticultural perlite and open-pore polyurethane foam (Sakuma et al, 2005) and (Kennes and Veiga, 2004). Studies of biofilter performance containing mixed media such as compost and polystyrene spheres have been conducted with success (Deshusses et al, 1999). At this time, the high cost of synthetic material relative to organic products limits the use of synthetic media, however, examples of high performance synthetic media do exist (BIOREM Technologies Inc., 2007).

2.5.2 Design Parameters

Once an appropriate filter medium has been selected by the design engineer for the biofiltration system, other design considerations can begin to be examined. Many parameters must be included in the final design in order for the biofilter to perform as desired and treat the target pollutants. These parameters are discussed in the sections that follow below.

Microorganisms

Without microorganisms, there would be no biofiltration. There are countless types of microorganisms known to exist; those associated with biodegradation typically appear as either bacteria, fungi, or algae. For biodegradation purposes, microbes can be categorized into two distinct groups; autotrophic (microbes that feed from inorganic compounds) and heterotrophic (microbes that use organic compounds as a source of energy and carbon) (Wani et al, 1997). Microbes can survive and biodegrade in the psychrophilic, mesophilic and thermophilic temperature ranges, however, most biodegradation is executed by mesophiles and thermophiles (Leson and Winer, 1991). Of particular concern is the acclimation period or “start-up” time for a biofilter. Not all filter media, in particular synthetic types, will contain the necessary microbes required for degradation of the pollutant of interest. Common practice in this situation is to inoculate the filter media with the appropriate microorganism which will reduce the acclimation period. Another technique to assist in biofilter start-up is to introduce a small amount of the target pollutant to the filter media which will spur the growth of strains of microbes that metabolize the pollutant (Leson and Winer, 1991).

Industrial facilities do not typically run continuously, as is the case with FRC East. This phenomenon presents a concern to biofilter operators because long periods of shut-down may result in a severe decrease of biological activity. Microorganisms depend on the target pollutant for survival and denial of this pollutant can cause irreversible damage to the biofilter. Some studies have shown that biofilters can survive a two-week period of inactivity (Ottengraf, 1986) while other studies have suggested that a two-month period of inactivity is survivable by microbes if appropriate nutrients are provided by the filter material (Leson and Winer, 1991). Another phenomenon associated with microbial activity in a filter media is known as

stratification. As the influent waste-gas enters the biofilter, a higher density of microbes will develop in this area of the filter media because the most readily degraded pollutants will be degraded first. Smaller and less-dense patches of microbes that have adapted to degrading more complex pollutants will exist in different locations throughout the filter media, further from the entrance (Swanson et al, 1997). This characteristic should be monitored in order to prevent errant behavior and low-efficiency of the biofilter.

Moisture Content

Moisture content of a filter medium is critical to microorganism survival and is indicative of biofilter performance (van Lith et al, 1997; Swanson et al, 1997). Microbial activity cannot survive without water, however, too much water within the filter media will clog pore space—which reduces surface area for pollutant mass transfer—and possibly cause irreversible damage to the filter media through the wash-out of smaller particles (van Lith et al, 1997). Overwet filter media can also result in anaerobic zones creating odor problems and nutrient washing from the filter (Swanson et al, 1997). In addition to being one of the more important parameters of the filter media, moisture content also happens to be the most difficult to control (Devinny, 1999).

Optimal moisture content of a filter medium ranges between 30-60%, depending on the medium selected (Wani et al, 1997), though other studies indicate a range between 40% and 60% is preferable (Leson and Winer, 1991). Appropriate moisture content levels can be reached through a variety of methods. The two most common methods are to inject the inlet waste gas stream with water or steam prior to filter bed entry or to apply water directly to the filter bed via a sprinkler system (Wani et al, 1997; Bohn, 1992). The preferred degree of saturation for the influent gas-stream is approximately 95% (Wani et al, 1997; Leson and Winer, 1991). A

sprinkler system may be appropriate if the biofilter is an open design and located in an arid environment. Sprinkler systems in enclosed biofilters are also common. Adjusting the filter bed itself to facilitate moisture content control is an additionally possible; one method suggests that the bed have a shallow design, however, a shallow filter bed requires a tremendous increase in area in order to maintain the same efficiency (Wang et al, 1996). Biofilter designs should incorporate an allowance that prevents excess drainage from the filter bed; the discharged wastewater will often require further treatment prior to environmental release, causing additional costs (Leson and Winer, 1991).

Control of pH

Proper pH levels are essential to microbial survival within the filter media. Appropriate pH levels for most biological treatment systems are between the range of 6.5 and 8 (Wani et al, 1997), and the optimal level is closer to 7 and 8 (Swanson et al, 1997; Leson and Winer, 1991). Regardless of the exact value of pH within a filter media, it is generally desirable to maintain the pH level as constant as possible; changes in pH of 2 or more can adversely affect the rate of biodegradation (Kennes, 2001). Other challenges in the control of pH depend on the contaminant being degraded by the microbial population. Compounds such as chlorinated organics and those pollutants containing sulfur and nitrogen produce acidic by-products when oxidized. Microbes are typically incapable of surviving in low-pH (acidic) environments. To prevent this, a buffer material such as lime or crushed oyster shells is mixed in with the filter media to regulate pH drop. Buffering capacity is limited by time and when it is exhausted will require replacement of the filter material (Kennes, 2001). Control of pH is easier in biotrickling filters or bioscrubbers where the liquid phase can be directly adjusted. For this reason, these

methods of biofiltration are preferred for waste-gas streams containing high concentrations of compounds with acidic degradation products (Leson and Winer, 1991). Additional problems can arise from acidic degradation products, namely, their corrosive effect on the biofilter infrastructure (duct work, filter housing, and air distribution works) which is why careful monitoring of filter media pH levels is a critical factor.

Temperature

Microbial activity within filter media is readily affected by temperature conditions. Mesophilic conditions (25-40 °C) are ideal for biofiltration operations and most biofilters consequently operate in ambient temperatures. Some microbes are known to function effectively in thermophilic conditions (40-55 °C). For example, microbes were shown to have eliminated low concentrations of VOCs in compost and woodchip biofilters at ~50 °C and toluene was removed from a waste-stream in compost biofilter at almost 60°C (Kennes, 2001). Warmer temperatures increase metabolism rates, reaction rates and diffusion rates within a microbial population, however, in cases of extreme temperatures cell components can begin to decompose and proteins within enzymes can become denatured and ineffective (Deviny, 1999). Colder temperatures reduce metabolic rates and can cause microbes to enter a dormant phase which can eventually lead to their death if necessary functions cease to be carried out for prolonged periods. Treatment of the waste-gas stream during this period is greatly slowed and inefficient. Effects of temperature on a cell are demonstrated by a temperature-activity curve shown in Figure 2.2.

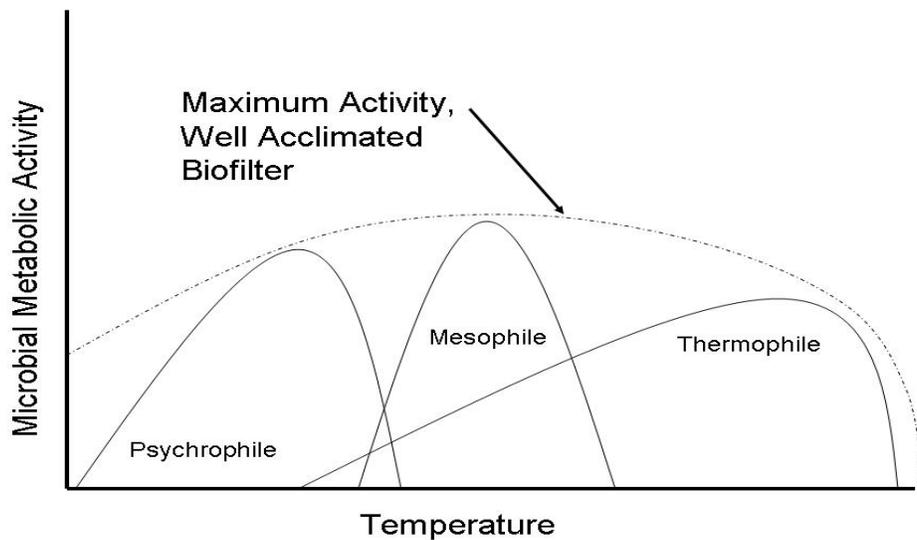


Figure 2.2. How temperature affects microbial metabolic activity; microbial activity rises as temperature increases, then drops off sharply when temperatures are too warm for microorganism survival (modeled after Devinny, 1999).

Activity within a cell will typically increase with temperature until a particular maximum value is reached at which point activity begins to decline rapidly (Devinny, 1999). Figure 2.2 shows that metabolic activity can occur at any temperature and thus biodegradation is possible, however, should the temperature within a biofilter suddenly change drastically—whether it is a sharp increase or a sharp decrease—it is the sudden change that will inflict the most damage to the microbes and cause biofilter failure. It is, therefore, of prime importance to maintain as constant a temperature as possible during biofilter operation. Temperature control of the biofilter is a direct result of waste gas stream temperature and is sometimes difficult. Heating of the stream or cooling the stream both require fuel and are usually too expensive to consider. Heat exchangers are capable of mixing air from different sources to create the desired temperature and do not incur any fuel costs (Devinny, 1999).

Nutrients

Microorganisms cannot survive on target contaminants alone. As most microbial cells in a biological treatment process are made up of carbon, nitrogen, oxygen, and hydrogen, these elements must be made available to them if they are not already present in the waste gas stream (Kennes, 2001). Other species of microbes may require further nutrient supplements in the form of minerals such as calcium, magnesium, potassium, sodium, and sulfur. Optimal biofilter operation depends upon the addition of the correct type and amount of nutrient to promote tenacious microbial activity. Compost is a desirable filter medium because it already contains the nutrients required by microbial populations, however, care must be taken while using this medium. Degradation rates may vary in compost and the rate at which nutrients are released from it may be too slow for the rate at which the microbes demand them (Devinny, 1999).

Synthetic and inert filter media contain no nutrients. Fertilizers must be added to these media as the biofilter is put into operation. Otherwise, slow-release fertilizers can be added directly to the media after biofilter construction. Careful monitoring of the biofilter is required to ensure that the proper amounts of nutrients are within at all times; biodegradation of the biomass combined with leachate sometimes produced by biofilters can cause a dramatic loss of nutrients. If adequate nutrients are not replaced, biomass growth within the biofilter can use up the remaining available nutrients and anaerobic activity will result in the filter medium causing biofilter failure (Devinny, 1999).

Contaminant Load in Waste-Stream

Contaminant load—the mass of contaminant entering the biofilter per unit time and per unit load—is also a critical design consideration. Biofiltration technologies are typically suited

for waste-gas streams containing low concentrations of pollutants, preferably within range value of 4 or 5 grams per cubic meter (Kennes, 2001), however, values up to 100 grams per cubic meter are also suitable (Leson and Winer, 1991). There are extreme cases where biofilters may treat industrial or soil vapor extraction (SVE) off-gases in quantities greater than 100 grams per cubic meter (Devinny, 1999). High loads such as this, however, can cause pH levels within the filter medium to drop resulting in its acidification. High-load streams will induce temperature increases within the medium as a result of increased metabolic activity. Biomass will also grow rapidly (if nutrients are available) under high-load conditions. Excessive biomass within the filter medium can cause clogging and large pressure drops across the filter. All of these negative effects of large contaminant loads decrease the removal efficiency of the biofilter and often lead to system failure. Therefore, waste-streams with low pollutant concentrations are appropriate; biofiltration operations treating waste-streams with pollutant concentrations in excess of the generally accepted value should include allowances for medium cleaning, replacement, and nutrient resupply in their design schemes (Devinny, 1999).

Contaminant load equalization is desirable during biofiltration operations. Variations of this parameter in industrial applications are common due to inconsistent operations, breaks, weekends, holidays, and similar situations causing the loading of a biofilter system to be non-steady. Some studies suggest that load equalization occurs “naturally” as a result of filter medium adsorptivity (Devinny, 1999). This may not always be the case, depending on the media utilized in the biofilter, thus requiring load equalization. This can be achieved by splitting the waste-stream and having it enter the biofilter at different locations or placing a granular activated carbon (GAC) absorber in the influent waste-stream prior to the biofilter. The GAC

will absorb the pollutant during peak concentration times and release them when the influent waste-stream is less polluted, for example, during an off-peak time (Devinny, 1999).

Particulates, Dust and Grease

Biofilters are intended to remove soluble and degradable pollutants from a waste-gas stream. They are not effective at removing particulate material in the waste-gas. While a biofilter may efficiently collect dust from a waste-stream—the filter medium being typically wet, allowing for particles to stick to it easily—a large collection of dust will cause clogging of the biofilter, loss of removal efficiency and require the filter medium eventually to be replaced. Some particulates may be degradable and a biofilter may be designed to accommodate large quantities (Devinny, 1999). Frequently, however, a pretreatment system cleans particulates from the waste-gas prior to its entry in the biofilter. This additional step of treatment incurs an additional cost and therefore requires close scrutiny by the design engineer for the expected waste-gas stream to be treated.

2.6 Laws and Regulations

Control of VOC emissions into the atmosphere was of minimal popular concern in the United States until the 1970s and 1980s. It wasn't until the passage of the 1990 Clean Air Act (CAA) amendments that VOC emissions became regulated, stirring further public interest and research into their control. As a result of the 1990 amendments establishing federal law regarding the emission of pollutants, individual states were charged with enforcing the new regulations and in many cases, tightening the regulations even further. The following sections

discuss the various federal and state laws in place governing the release of VOCs, executive orders affecting the environment and how all of them apply to FRC East.

2.6.1 Federal

President Nixon authorized the creation of the Environmental Protection Agency (EPA) in 1970 to establish and enforce environmental protection standards for the United States (EHSO, 2006). Federal environmental regulations set forth by the EPA establish a baseline for pollution control and emissions standards. Standards established by the EPA address public health issues (“primary” standards) and environmental impacts (“secondary” standards) associated with air pollution. The Environmental Protection Agency (EPA) sets the limit on the quantity and type of particular pollutants that can be in the air anywhere within the United States (EPA, 2006c). State, local and regional governments are free to create more stringent regulations than those established by the Federal government, should they see the need to do so but are not permitted to establish weaker controls. The ability of smaller governments to tailor environmental regulations to their local areas increases the efficiency of air pollution control in those particular areas and facilitates enforcement of national policies. Environmental policy enforcement at this low-level of government has forced industry-wide compliance from the smallest known emitters of air pollution to the largest.

The CAA requires the EPA to set pollution standards for pollutants considered to have adverse effects on public health and the environment. These are called the National Ambient Air Quality Standards (NAAQS) and the EPA has established six pollutants to be among the most common and called them “criteria pollutants”. These are ozone, particulate matter, carbon monoxide, nitrogen dioxide, sulfur dioxide and lead (EPA, 2006d). VOCs are not one of the six

criteria pollutants, however, they contribute directly to the formation of ozone. Ozone in Earth's lower atmosphere has been established as harmful to public health and the environment (EPA, 2006a). As a result, the 1990 amendments to the CAA address the emission of pollutants that are considered VOCs and the need for control of these emissions.

Title III of the 1990 amendments to the CAA lists 188 (originally 189) chemicals which are to be considered toxic air pollutants. By law, emissions of these 188 toxics must be reduced. Facilities that release into the environment over 10 tons annually of any one of these toxics or over 25 tons annually of any combination of two or more of these toxics must introduce control measures known as maximum achievable control technologies (MACT) to reduce emissions (EPA, 2006c). FRC East, due to its low emission of VOCs, does not fall into the EPA's MACT compliance criteria.

2.6.2 State

States are required by Federal law to develop and enforce state implementation plans (SIPs) for air pollution control. These plans detail to the Federal government how the state intends to execute the rules established by the CAA and how it will clean polluted areas within its borders. Creation of a SIP must involve the public through hearings and opportunities to provide comment and input. The EPA must approve each SIP prior to its implementation, however, should the EPA find a particular state's SIP insufficient the EPA reserves the right to enforce the CAA in that particular state. North Carolina's most recent SIP was published in January, 2007 (NCDENR, 2007a).

The NAAQS are standards promulgated by the EPA which establish pollutant concentration levels permitted in outdoor air. Areas of the United States which meet or have

better levels of concentration than the national standard are called attainment zones. Locations that do not meet the national standard and have poor quality air are called non-attainment zones (EPA, 2006e). With regards to ozone, the EPA has two standards; the more stringent 1-hour ozone standard which classifies an area as “non-attainment” if, over the course of one year, the average hourly levels of ozone exceed the NAAQS and the similar but less stringent 8-hour ozone standard. The North Carolina SIP has established no 1-hour ozone standard zones within the state and only limited 8-hour zones located in the central portions of the state around the more populated urban areas. FRC East is located in an attainment zone and is therefore not required to comply with these standards.

2.6.3 Executive Orders

Legislation regarding the treatment of the environment may come from sources in addition to the Federal government and individual states. An executive order (EO) is a directive issued by the President, free of interference from Congress or the courts, that requires or authorizes some action within the executive branch of government (Mayer, 1999). Reasons for issuing such an order have varied; to establish policy, to alter regulatory processes, and to affect how legislation is implemented have all been cited as justification for EOs (Mayer, 1999). Within the last fifteen years, a number of EOs have been issued regarding the Federal government’s relationship to the environment. A number of these apply to FRC East and are discussed below.

Executive Order 12088

EO 12088, “Federal Compliance with Pollution Control Standards” is of interest simply because it directs all Federal agencies to take any necessary action for the abatement of environmental pollution. The EO also requires the cooperation of all Federal agencies with the EPA, state, and local agencies to ensure these tasks are carried out (USP, 1978). While the FRC is well within all established environmental regulation, it is interesting to note that Federal compliance with environmental laws was an issue as early as 1978, when this EO was put into law.

Executive Order 12856

The “Federal Compliance with Right-to-Know Laws and Pollution Prevention Requirements” Executive Order 12856 directs Federal agencies to simply “store, treat, dispose of any waste in a manner that is protective of public health and the environment” (USP, 1993). The aim of the order is to obligate Federal agencies to follow and comply with all applicable environmental laws, which, as has already been discussed, the FRC is doing. However, should the environmental regulations become more stringent in the future and require the control of all VOC emissions, compliance with this executive order will once again become an issue and require the attention of FRC East.

Executive Order 13101

Executive Order 13101, titled “Greening the Government through Waste Prevention, Recycling, and Federal Acquisition”, was signed into law on September 14, 1998 by President Clinton. The order establishes a federal task force charged with implementing a plan in which,

among other things, Federal agencies will: Improve and enhance the environment; set an example for other governments, individuals, and the private sector; and create and strengthen markets for environmentally preferable products and services (OFEE, 2006). FRC East, as a government facility is thus obligated by executive order to ensure that its policies and actions are as environmentally “friendly” as possible.

Executive Order 13123

“Greening the Government Through Efficient Energy Management”, was signed into law in June of 1999. This order requires that Federal agencies do what they can to improve the energy efficiency of their buildings but of specific interest to FRC East is the requirement to reduce greenhouse gas emissions associated with energy use in their buildings (OFEE, 2006). VOCs, while not considered greenhouse gases by the EPA, are responsible for the creation of low-level ozone which has been shown to have negative effects on the environment.

Executive Order 13134

In August, 1999 “Developing and Promoting Biobased Products and Bioenergy” became law and establishes a council, an office and an advisory committee to investigate the use of biobased products as energy sources to the President. Additionally, this EO establishes as policy the development of a national strategy to stimulate the creation and early adoption of technologies needed to make biobased products cost-competitive in large national and international markets (USP, 1999). Though FRC East is not in the business of developing a new source of energy, the use of biofiltration—a “biobased” product—for an APC would be following the spirit and intent of the law to create a “greener” government.

Executive Order 13148

“Greening the Government Through Leadership in Environmental Management” is perhaps the most broad of executive orders released concerning the greening of the Federal government. Signed into law in April, 2000, the EO charges the head of each Federal agency with the responsibility of ensuring that all necessary actions are taken to integrate environmental accountability into agency day-to-day decision making and long-term planning processes (USP, 2000). Section 203 of the order refers to pollution prevention and how:

“Federal facilities shall be leaders and responsible members of their communities by informing the public and their workers of possible sources of pollution resulting from facility operations. Each agency shall strive to reduce or eliminate harm to human health and the environment from releases of pollutants to the environment. Each agency shall advance the national policy that, whenever feasible and cost-effective, pollution should be prevented or reduced at the source” (Section 203, EO 13148, April 2000).

FRC East is currently in compliance with all applicable environmental regulations. However, the facility could easily improve its environmental impact by implementing a biofiltration process to control its emission of VOCs. Not only could this be done in a cost-effective manner but it could improve the local opinion of the facility’s environmental goodwill and consequently, the goodwill of the Department of Defense.

2.6.4 Military Regulations and Orders

As a military facility, FRC East is additionally required to comply with various Department of Defense, Department of the Navy, and Marine Corps regulations. FRC East overlaps into many regulatory jurisdictions. As a Marine Corps facility aboard a Marine Corps installation, it must comply with Marine Corps regulations. However, as a Naval facility that receives its policies and funding from the Department of the Navy, it must also comply with Navy regulations. Governing military documents are not of a technical nature and do not

establish quantitative criteria by which the facility can be measured as a polluter. The documents are worthy of mention for purposes of policy clarification and are discussed briefly below.

Marine Corps Order P5090.2A

The Marine Corps' *Environmental Compliance and Protection Manual*, MCO P5090.2A, establishes Marine Corps policy regarding the environment. The document is clear in its intent to leave regulation-drafting to the appropriate authorities:

The Marine Corps will comply with environmental requirements in the following order: 1) statutory requirements, 2) regulatory requirements, 3) EO requirements, 4) DoD requirements, 5) DoN requirements, and 6) Marine Corps requirements. (MCO P5090.2A, para 1104)

Though the specific regulatory guidelines regarding emissions and pollutant concentrations released by FRC are not covered by the Marine Corps order (DoN, 1998), the FRC does comply with the various administrative policies set forth by the document which are inapplicable to this study.

OPNAV, NAVAIR and CNAF Instructions

Until the base realignment and closure (BRAC) laws of 2005 were enacted in October, 2006, FRC East was known as Naval Air Depot (NADEP), Cherry Point and fell within the controlling authority of Naval Air Systems Command (NAVAIR). NAVAIR in 1992 published NAVAIR instruction (NAVAIRINST) 5090.1, the *Naval Air Systems Command Environmental Program*. This document details NAVAIR's policy towards environmental protection and establishes procedures which its tenant commands must follow. Relatively speaking, this document is similar to MCO P5090.2A and covers much of the same issues in an identical manner, referencing many procedures of other Federal documents, such as executive order 12088

(DoN, 1992). NAVAIRINST 5090.2, is NAVAIR's *Ozone Depleting Substance Program*, issued in 1998. No mention of VOCs are made in this document, rather, the control of ozone depleting substances (OSDs) as outlined by the EPA is the focus of the instruction along with a brief discussion of the Montreal Protocol and the 1990 amendments to the CAA. NAVAIR documents, however, are soon to become obsolete. As a result of the 2005 BRAC laws, control of facilities like FRC East has shifted from NAVAIR to CNAF. At the time of this writing, the newly established Commander, Fleet Readiness Center (COMFRC) staff working in conjunction with CNAF, is in the process of reviewing previously established NAVAIR environmental policies for incorporation into new doctrine (Erwin, 2006). It can be expected that once the new COMFRC staff has been stood up and is operational, it will disseminate appropriate documents and instructions regarding environmental policies at the FRCs.

Overseeing the activity of NAVAIR and CNAF is the Department of the Navy (DoN). The DoN has also promulgated its own policies regarding environmental protocol in Chief of Naval Operations Instruction (OPNAVINST) 5090.1B, the *Environmental and Natural Resources Program Manual*, originally released in 1994 with several updates and changes since then (DoN, 1994). This instruction is the Navy's comprehensive environmental compliance guide, essentially serving the same purpose for the Navy as MCO P5090.2A does for the Marine Corps. The instruction follows closely the guidelines established by the EPA and the CAA regarding air pollution control. Specific control parameters are left to applicable local and state authorities.

2.7 Harmful Effects of VOCs

Why do VOCs need to be controlled? Considering the amount effort that has been placed in the research and study of technologies—in particular, the most recent developments and advancements of biotechnology for this purpose—to control the emission of VOCs, this question deserves a detailed answer. As mentioned previously, VOCs are not listed as one of the EPA’s six criteria pollutants. Ozone, on the other hand, is a criteria pollutant. The creation of ozone can be directly attributed to VOCs and nitrous oxides (NO_x) in the atmosphere (EPA, 2006a; Rabl and Eyre, 1998). Sunlight spurs photochemical reactions in the atmosphere between these compounds and oxygen, forming the O_3 compound commonly known as ozone. A simple and non-scientific equation showing this reaction is shown in equation 2.1:



It must be made clear that ozone demonstrates different tendencies depending on its location within the Earth’s atmosphere. In the stratosphere, ozone constitutes the Earth’s ozone layer; nature’s natural security blanket against harmful UV rays from the sun. Closer to the Earth’s surface in the troposphere, ozone is a health and environmental menace that does more harm than good.

Adverse health and environmental effects can result from ozone. Healthy individuals can begin to experience chest pain, coughing, throat irritation, and congestion as a result of breathing ozone. Individuals with existing cases of bronchitis, emphysema, and asthma can experience heightened conditions of these ailments as a result of breathing ozone. Lung function is adversely affected as are the mucus linings of the lungs and continued exposure may result in permanently scarred lung tissue (EPA, 2006a). Vegetation and agriculture is also affected by

ground-level ozone which causes sensitive plants to lose their ability to produce and store food. The EPA estimates that nearly \$500 million in reduced crop production is experienced annually (EPA, 2006a) by the United States. Finally, ozone is the prime contributor to smog (EPA, 2006a), the aesthetically displeasing haze seen hanging in the summer air over densely populated cities. VOCs, as precursors to ozone, must be reduced in the atmosphere and their release must be controlled. Biofiltration is the most effective method of doing so.

2.8 Economics

Great efforts have been made by researchers to demonstrate costs associated with air pollution. From the literature, the effect of air pollution on human health is clear. There is also an evident cost to the environment resulting from polluting Earth's atmosphere. The difficulty lies in applying a dollar value to these costs. This process spurs an intense philosophical and emotional debate among supporters of industry, champions of the environment, politicians, physicians, and the general public. The monetary value of a human life, a plant, or an animal varies greatly depending on the individual presenting the argument. However, for the sake of environmental protection, several researchers have been able to quantify various intangible entities in order to measure the effect air pollution has upon each.

Assigning dollar values to environmental quality is termed nonmarket valuation. Nonmarket valuation allows environmental benefits received by society to be compared monetarily to costs associated with programs, policies, or regulations intended for pollution control (Loomis, 2005). One established method of nonmarket valuation is determining society's willingness to pay (WTP) for a particular environmental benefit. A marketable good is valued based on the price consumers are willing to pay for one more unit of that good (Loomis,

2005). The same theory is applied to value environmental benefits. For example, a population can be surveyed to determine how much it is willing to pay for higher air quality or a reduction in the risk of premature mortality due to air pollution. This monetary value can be compared to the cost of an air pollution control system to establish the economic benefits the system will have on the population. If the population is willing to pay more for clean air than the air pollution control system will cost to install and operate for a specified period, the system can be regarded as a cost-saver. A second measure of environmental benefit to society is the cost of illness (COI) method. Actual dollar values are calculated from medical expenditures and lost wages accrued due to illness as a result of air pollution (Hall et al, 2006). All of the benefits of improved environmental quality are not captured by this method, however, as losses associated with the value of leisure time or general misery cannot be accounted for (Hall et al, 2006). An accurate measure of the benefits of air quality should therefore include both WTP and COI methods. Unfortunately, a study of residents near FRC East to determine their WTP for clean air and COI due to polluted air does not exist. Data for this region must be extrapolated from other similar studies.

A method of tying these values together and providing a present-day look at the future cost of air pollution is the net present value (NPV) method. This method equates the estimated value of money spent or gained in the future to today's dollar value over a predetermined period of time (Brigham and Ehrhardt, 2005). The benefits of biofiltration (both economic and environmental) can thus be determined. With the NPV method, monetary expenditures or gains associated with controlling air pollution over a period of time, can be shown in present-day dollars. Future costs of a biofiltration system in the same region over the same period of time can also be calculated in terms of present-day dollars. These two results—the cost of air

pollution to the environment and the cost of biofiltration—can be compared and analyzed.

Subsequent analysis shows that in the long run, the cost of biofiltration is much cheaper than the ultimate cost of air pollution to the environment and the human element it supports.

2.9 Summary

This literature review has presented biofiltration technology as a means of air pollution control. From its conception in the early half of the twentieth century, through its development and refinement both in the United States and abroad, to the acceptance of the technology as a valid and reliable method of controlling polluted air streams, the benefits and merits of biofiltration have been discussed. Various biological treatment processes have been noted that describe the versatility of the technology. Critical design parameters of conventional biofilters are detailed along with the importance of each to any design process. Filter medium, and the correct selection of one appropriate for the treatment process to be employed, was shown to be the “heart” of the biofilter through the discussion of multiple types of media. The environmental and human health impacts of VOCs in waste gas streams are shown. The cost of these impacts is proven to be significant. The relative cost of biofiltration to control the emission of VOCs is shown to be advantageous over other technologies available on the market and commonly used today. In short, this review has indicated that biofiltration is a cost-effective and efficient method of controlling the release of harmful VOCs to the Earth’s atmosphere.

III. Methodology

3.1 Introduction

Biofiltration may not be a new science but its use as an air pollution control (APC) technology is a relatively new concept in the United States. Its use by the Department of Defense (DoD) for the same purpose is not commensurate with the use of the technology by private and commercial industry. Using the case study method, consideration will be given to non-government industrial operations that have made successful use of biofiltration systems for air pollution control. An analysis of these case studies, combined with emissions data provided by Fleet Readiness Center (FRC) East and suggested parameters discussed in the literature review, will facilitate the design of a conventional biofilter for use as an APC at FRC East. The design will be tested mathematically for efficiency and its cost (both capital and operating) analyzed using a net present value method. A commercial biofiltration system manufacturer will be requested to design a system using the same parameters. Its design will be compared to this author's design and its recommendations for packing material, operating costs, and maintenance costs will be analyzed.

3.2 Procedures

3.2.1 Case Studies

In order to “sell” the concept of a biofiltration unit for use as an APC technology to control VOC emissions at a facility, an analysis was made of similar facilities already using the technology for the same purpose for comparison. Two such facilities were identified and brief case studies were conducted to present the advantages, benefits and limits of each. Questions asked of each facility manager during the case study are shown in Appendix A.

The case study method is suited for research involving the “how” and “why” of phenomena happening (Yin, 2003). This research effort meets these criteria as it intends to glean the successful aspects of various biofiltration applications and incorporate them into a viable design for FRC East. As there is no current VOC control in place at FRC East, biofiltration systems in use at other industrial operations need to be examined to determine the type of system best suited for this facility. Similarities and differences between biofiltration systems will be noted and the successful trends will be incorporated into the final biofilter design. For these reasons, an “exploratory” case study has been performed because the “how” and “why” of successful biofiltration applications are being examined to determine the most optimum design (Yin, 2003).

Commonly used sources of evidence for case studies come in six forms (Yin, 2003). The six forms are documentation, archival records, interviews, direct observations, participant-observation, and physical artifacts. Multiple sources of documentation were used including reports, articles and conference proceedings. Archival records were provided by FRC East from which data was drawn in order to design an appropriate biofilter. Questioning of subject matter experts was conducted with various representatives of biofilter manufacturing companies. Direct observations were made of biofilters in action as well as the tools and products associated with these systems. Of the six possible sources of evidence, the only source not used during the course of any of the case studies was participant-observation. At no time was the opportunity to participate in the construction and / or design of a biofiltration system examined in one of the case studies presented in Chapter IV. Though any one of the six sources of evidence can be used independently for a case study analysis, the use of as many sources of the six listed above is

recommended and will generally ensure a more well-rounded and credible case study (Yin, 2003).

The Plum Creek Timber Company, Inc. of Colombia Falls, Montana and Rothsay Recycles of Dundas, Ontario were chosen sites for study and analysis. Contact was made with a site supervisor or the company's environmental engineer in order to obtain first-hand information regarding each facility. Common questions were asked of each individual (Appendix A) and each operation is compared to the potential biofiltration operation at FRC East.

3.2.2 Design of the Biofilter

For a better understanding of the layout and size of FRC East, a personal visit was conducted in December, 2006. Information was also obtained during this visit regarding the paint booth selected to represent the facility for this study, paint booth D0129 in building 245. Data that had been previously requested from the Air Quality Department of FRC East was provided during the course of this visit. The data requested included the types and amounts of VOCs emitted by the facility's largest paint booth, specific airflow data related to that booth, the state-established emission levels which cannot be exceeded, and toxic inventory reports. Additional data requested from the same department was provided electronically after the visit and included purchase and disposal cost of particulate filters, and characteristics of paint used in aforementioned booth, specifically, the VOC concentrations of the vapor. Photographs of the paint booth and the three-stage particulate filters contained within were requested to be taken, however, for security reasons, the request was denied by FRC East.

Using design principles established in Deviny (1999), a biofilter was designed for use at FRC East. Parameters for the design were taken from paint booth D0129 in building 245; this

booth having been determined to be the most representative of the entire facility as the emitter of the largest amounts of VOCs at FRC East. Based on current literature and the case studies, a compost and wood chip mixture was chosen to be used as filter media in the biofilter design.

Equations to be used during the course of the design process are presented by Devinny (1999). The minimal design parameters required to be considered for a valid biofilter design were used; inlet contaminant concentration, air flow, filter bed volume, removal efficiency and elimination capacity (Devinny, 1999). Empty bed residence time (EBRT) represents the theoretical time contaminated air spends within a biofilter. EBRT relates the size of the biofilter to the flow rate of the contaminated air but is not a true representation of actual treatment time. Because the filter media (or packing material) within a biofilter takes up a large proportion of its space, air can only pass through the void space within the media. This parameter is known as the material's porosity and is defined as the ratio of the volume of void space to the volume of filter material (Devinny, 1999; Kennes, 2001). Equation 3.1 below represents EBRT and equation 3.2 represents *true* EBRT, taking into account filter media porosity.

$$EBRT = \frac{V_f}{Q} \quad (3.1)$$

$$\tau = \frac{V_f \times \theta}{Q} \quad (3.2)$$

where

EBRT = Empty bed residence time (seconds or minutes)

τ = true residence time (seconds or minutes),

V_f = filter bed volume (m³ or ft³),

Q = air flow rate (m³ h⁻¹, cfm, etc.)

θ = porosity

Performance of the biofilter design will be measured using a parameter called elimination capacity (EC). The EC represents the amount of pollutant the biofilter is able to remove per unit volume of filter material per unit time (Devinny, 1999; Kennes, 2001). The advantage to this parameter is that it is normalized and can therefore be used to compare biofilters of different sizes, which will be an important factor in this study. The mathematical representation of EC is:

$$EC = \frac{(C_{Gi} - C_{Go}) \times Q}{V_f} \quad (3.3)$$

where

$$C_{Gi} = \text{inlet concentration (ppmv or g m}^{-3}\text{)}$$

$$C_{Go} = \text{outlet concentration (ppmv or g m}^{-3}\text{)}$$

A second measure of biofilter performance is its removal efficiency (RE). The RE is a ratio expressing the amount of pollutant removed to the amount of pollutant fed into the biofilter (Kennes, 2001). RE is usually expressed as a percentage and is calculated as follows:

$$RE = \left(\frac{C_{Gi} - C_{Go}}{C_{Gi}} \right) \times 100 \quad (3.4)$$

It should be noted that RE can be misconstrued as a complete representation of biofilter performance; because RE varies with contaminant concentration, airflow, and filter size, it describes performance only under the conditions measured (Devinny, 1999). EC is better suited for comparison of separate biofilters due to its normalized results. Government compliance regulations frequently measure performance using EC, commonly referred to as “percent removed” (Devinny, 1999).

3.2.3 Contractor Design of the Biofilter

BIOREM Technologies, Inc., of Guelph, Ontario provided a biofilter design for VOC treatment of paint booth spray emissions at FRC East. As they use a patented filter medium developed internally by the company's scientists and engineers, the company's biofilter design processes and methods are proprietary in nature. However, the Industrial Sales Manager from BIOREM was able to share the fact that his company's work is based upon a mixture of work that has been completed in the past (over 400 biofilter installations since the company's formation in 1994), in-house laboratory work, pilot-scale work, and the collective efforts of the company's research and development group, process engineers, and applications engineers (Mullin, 2007). BIOREM also uses a safety factor during its biofilter design process to ensure any performance guarantee is met, though this value is proprietary and kept within the company. Due to the patented nature of the filter medium, filter bed sizing and residence time design process are confidential, though BIOREM provided appropriate parameters and costs for evaluation.

3.3 Net Present Value Calculations

Several methods exist for demonstrating the ultimate cost over time in present-day dollar-value of installing and operating a particular system or project. The principal reason for such methods is to provide the buyer of the system with an idea of how quickly they will receive "payback" on their investment, that is, to determine at what point in the future the system or product purchased will earn enough money to balance the cost of its initial purchase and installation. This information can be critical to the buyer and often is the deciding factor when a decision must be made regarding the purchase of a particular system or project.

The net present value (NPV) method of project evaluation is an effective technique. The concept is easily demonstrated visually by the use of a cash flow diagram. Over the course of a system's or project's predicted life span, expenditures and incomes (outflows and inflows, respectively) are represented by arrows pointed downward to show outflows and upwards to show inflows at the end of each period (Fabrycky, 1991). Figure 3.1 is an example of a cash flow diagram.

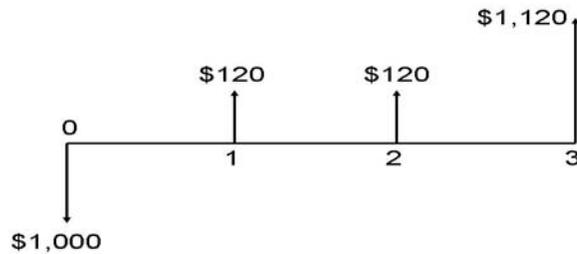


Figure 3.1. Example cash flow diagram representing \$1,000 loan from a bank and subsequent repayment of loan. The bank starts with a \$1,000 expenditure or “outflow” at time zero. Interest payments and repayment of loan over next three periods of time are represented as “inflows” (Fabrycky, 1991).

Investors typically are interested in determining how long it will take to recover the original amount of money invested in a project or system. To do so, an NPV calculation can be made by first determining the present value of each cash inflow and outflow subtracted from the project or system's capital cost. The sum of these discounted cash flows is defined as the NPV. A positive NPV is favorable and should be accepted by the investor (Brigham and Ehrhardt, 2005).

Equation 3.5 is a mathematical representation of this process and will be used during the course of this study as a basis for all NPV calculations.

$$NPV = \sum_{t=0}^n \left[\frac{CF_t}{(1+r)^t} \right] \quad (3.5)$$

where

$CF_t = \text{expected net cash flow at Period } t$

$r = \text{project's cost of capital}$

$n = \text{project's life}$

The cost of the conventionally designed biofilter for this study was compared to the conventional particulate filter unit currently in use. Operating and maintenance costs of the particulate filter unit currently in operation will take into account energy costs related to filter fans. Additionally, the cost of a similar biofiltration system proposed for installation by an independent manufacturer will be obtained for comparison to this author's cost analysis.

As FRC East currently does not control its VOC emissions because there is no regulation requiring the facility to do so, the natural question "why bother?" is raised. Answers to this question vary and are explored in this study. An economic solution to this question will be provided utilizing NPV techniques. The first NPV calculation will show the cost of a biofiltration system to FRC East using only tangible parameters. The second NPV calculation will show the potential monetary savings to the community as a result of controlling VOC emissions. For the purpose of this study, tangible assets will include cost of system, system installation, system start-up, and system maintenance over a specified period (5 years). Intangible assets to be included in the second NPV calculation will represent the value of VOC control to the environment and residents of the local community, and the environmental goodwill of FRC East. NPV calculations are shown in Appendix B.

The difficulty in executing NPV calculations that incorporate intangible assets is in assigning those assets tangible values. One study indicates that poor environmental performance has a significant negative effect on the intangible-asset value of publicly traded firms (Konar and

Cohen, 2001). Another study offers support to the theory that being a good environmental steward helps create a reputational advantage that leads to enhanced marketing and financial performance (Miles and Covin, 2000). FRC East is certainly not a publicly traded firm, however, this fact does not change the public's perception of the facility as an industrial polluter. Such a parameter is therefore appropriate for inclusion in an NPV calculation.

The presence of VOCs in the troposphere and their contribution to the creation of ozone is known to cause negative effects on human health. Human health is a phenomenon upon which it is difficult to place a monetary value. Human morbidity is a measure often used to gauge the impact of a pollutant on its surroundings. The measure of morbidity is easily transferred to a variety of dollar values—medical expenses incurred as a result of pollution prior to death, work lost as a result of illness, value of human life, etc.—and for this reason will be included in the final NPV calculations.

3.4 Assumptions

FRC East is a large-scale industrial operation. Due to there being a variety of types of aircraft accommodated at this facility as well as a multitude of different and diverse production operations, surface coating operations at FRC are not limited to one area or one building. There are five surface coating facilities within FRC which require constant observation, monitoring, and data collection for submission to the North Carolina Department of Environment and Natural Resources (NCDENR). Sizes of these facilities have considerable range; the smallest is a ventilated hood used for painting small components and the largest is an aircraft hangar with a down-draft system and eight large exhaust stacks.

Designing and installing five separate biofiltration systems for each of the surface coating facilities is not practical. Nor is the notion of collecting the exhaust air from each of these facilities and directing it via an extensive duct system to one biofilter; the physical layout of the FRC and the location of each individual surface coating facility within it render this concept implausible. Therefore, for the purpose of this study, one of the five surface coating operations in use has been chosen as a “representative” facility. Booth D0129 in building 245, due to its size and amount of VOC emissions, best represents the daily pollutant output of FRC East. The biofilter designed in this study will use the parameters of booth D0129 as provided by the FRC’s Air Quality Department.

Contaminated air from paint booth D0129 in building 245 is currently being drawn down through the hangar floor and into the particulate filters. This system is referred to as a “draw-down” filtration system and is the only system of this type at FRC East. For the purpose of this study, the assumption will be that the same fans will be used to force the contaminated air through a potential biofiltration system. It should be noted that the particular filter media contained within a biofilter will determine the required influent flow rate. For example, a severe pressure drop may be incurred if the chosen filter media for a proposed biofiltration system is closely packed. Accounting for such a pressure drop and re-designing the fans currently operating in booth D0129 to accommodate various biofiltration systems containing different media is beyond the scope of this study. Therefore, the current fan system will be used in the final cost analysis and NPV calculations, based upon the rate of \$0.65/kWh paid for electricity by FRC East (Jackson, 2007).

IV. Results and Discussion

4.1 Overview

This chapter discusses the results and predicted performance of the biofilter designed for FRC East. The predicted performance of a similar design offered by a commercial contractor is also discussed. The behaviors of both designs and the respective costs to install, operate and maintain each system are compared and analyzed. Two case studies concerning biofilters currently in operation are also presented for comparison to the offered designs. The material in this chapter will be presented in the following order:

4.2: Study design

4.3: Design presented by commercial biofilter vendor

4.4: Cost Comparison: Study vs. Vendor

4.5: Case Study, biofilter 1

4.6: Case Study, biofilter 2

4.7: Discussion

4.8: Summary

4.2 Study Design

The data for the biofilter design was provided by FRC East. These data were provided to the commercial vendor as parameters for their biofilter design. The data contains amounts and types of VOC release, air flow quantity, contaminant concentrations within influent air flow, particulate filter cost, particulate filter maintenance costs, paint parameters, hangar D0129 dimensions, and current energy requirements for fan operation within hangar D0129.

4.2.1 FRC VOC Emissions

The North Carolina Department of Environment and Natural Resources (NCDENR) has stipulated via Title V Air Quality Permit number 5506T35 that VOC emission levels from hangar D0129 shall not exceed the values presented in Table 4.1. Values were modeled by NCDENR and represent maximum potential-to-emit (PTE) amount of contaminant. Actual amounts of VOCs released (CY 2005) by hangar D0129 are presented in the third column of the table.

Table 4.1. PTE values and actual emissions (CY, 2005) of VOCs at hangar D0129, building 245, FRC East (Game, 2007; NCDENR, 2006a).

	PTE (lbpd / tpy)	Emissions, CY 2005 (tpy)
Benzene	0.48 / 0.0624	0.000779
Butoxyl Ethanol	a*	0.506
Diethanolamine	a*	0.0
Ethyl Acetate	65 / 8.45	0.0245
Ethyl Benzene	a*	0.0346
Ethylene Dichloride	a*	0.0
Methyl Ethyl Ketone	452 / 58.8	1.8
Methyl Isobutyl Ketone	255 / 33.2	0.291
Toluene	433 / 56.3	1.73
Xylene	431 / 56.0	0.223

a*: These compounds are included in one category labeled “other” with PTE of 409 lb d⁻¹ / 53.2 tpy.

For calculation purposes, FRC East utilizes a 260 production-day year. One production day is considered to consist of 16 hours of production.

4.2.2 Paint

During industrial paint operations, VOCs from the paint are emitted into the air via two methods; during application and during the curing process. According to FRC data, approximately 40% of VOCs are released at the time of application as overspray. As the paint cures on the surface to which it was applied, the remaining 60% of VOCs continue to be released, the preponderance of which are released during the earliest stages of curing (Game, 2007). For the purpose of this study (as discussed in Chapter 3), all VOCs are assumed to be released at the time of spraying.

Paints and surface coatings used in paint booth D0129 include an aerospace standard primer and coating as prescribed by the Naval Air Systems Command (NAVAIR) *Corrosion Control Manual* (DoN, 2005b). Primer coatings generally contain 2.9 lbs of VOCs per gallon and topcoats contain 3.5 lbs of VOCs per gallon (DoN, 2005b). Specifications indicate that primer coatings should not exceed 0.0009 inches in thickness and topcoats should not exceed 0.002 inches (DoN, 2005b). These thickness values can be compared by a ratio of 2:1 and the following calculation can be made to determine the VOC content per painting evolution:

$$(0.67 \times 3.5 \frac{lb}{gal}) + (0.33 \times 2.9 \frac{lb}{gal}) = 3.3 \frac{lbVOC}{gal} \quad (4.1)$$

This equation shows the VOC content of single layer of primer covered with a single topcoat, the standard configuration for aircraft painting (DoN, 2005b). Given the maximum paint usage in hangar D0129 of 16 gallons per hour and 16,000 gallons per year (Game, 2007), the following calculation can be made:

$$3.3 \frac{lbVOC}{gallon} \times 16,000 \frac{gallons}{year} = 52,800 \frac{lbVOC}{year} \quad (4.2)$$

$$52,800 \frac{lbVOC}{year} \times \frac{1ton}{2000lbs} = 26.4 \frac{tons}{year}$$

Thus, the maximum value of VOCs released during the surface coating process at FRC East can be considered to be 26.4 tons of VOC per year.

4.2.3 Hangar D0129 Airflow and Contaminant Concentration

Minimum flow of air within an operating paint booth is prescribed by Occupational Safety and Health Administration (OSHA) standards. OSHA requires air velocity with a paint booth such as D0129 must be at least 100 feet per minute. The cross-sectional area of the hangar through which this air passes is 2944 square feet (92 feet x 32 feet). Using the minimum air velocity standard and the cross sectional area, airflow (Q) can be calculated:

$$2944 \text{ ft}^2 \times 100 \frac{\text{ft}}{\text{min}} = 294,400 \frac{\text{ft}^3}{\text{min}} \quad (4.3)$$

A rounded value of 300,000 cubic meters per minute is appropriate in the biofilter design.

Fluctuations in airflow and hangar use can be accounted for in this manner. This value will be used as the airflow “Q” for the biofilter design.

No measurements have been made of contaminant concentration levels within the D0129 paint booth during operation (Game, 2007). As a result, a calculated value must be determined using the airflow and VOC values above. Conversion to metric units is necessary:

$$300,000 \frac{\text{ft}^3}{\text{min}} \times \frac{60 \text{ min}}{1 \text{ hr}} \times .0283 \frac{\text{m}^3}{\text{ft}^3} = 509,400 \frac{\text{m}^3}{\text{hr}} \quad (4.4)$$

The annual VOC release rate must be re-calculated as an hourly rate, as shown in equation (4.5), in order to calculate the air stream contaminant concentration. Given the maximum paint usage rate of 16 gallons per hour (Game, 2007), the following is determined:

$$3.3 \frac{lb}{gal} \times 16 \frac{gal}{hr} = 52.8 \frac{lbVOC}{hr} \quad (4.5)$$

$$\frac{52.8 \frac{lbVOC}{hr} \times \frac{453.6 \text{ grams}}{1lb}}{509,400 \frac{m^3}{hr}} = 0.047 \frac{g}{m^3} \quad (4.6)$$

Thus, the C_{Gi} used for the design of the biofilter will be the result of equation (4.6).

4.2.4 Design Results

Using equations presented by Devinny (1999) to calculate biofilter parameters as well as knowledge gained from the literature, a biofilter was designed. Packing material for this design was selected to be compost with a mixture of wood chips, which as indicated in the literature, is preferred for its organic and nutrient content, its large surface areas, air permeability, its inexpensive cost and the low maintenance required for its upkeep (Delhomenie and Heitz, 2005; Delhomenie et al, 2002; Wani et al, 1997; Leson and Winer, 1991). The ratio of compost to wood chips is between the range of 20% to 80%, a value which has been repeatedly proven in studies (Nicolai and Janni, 2001; Deshusses and Johnson, 2000). Optimal empty bed residence time (EBRT) from the literature (Mann et al, 2002) for a compost-wood chip filter medium is between 30s and 60s. Using these parameters, a filter bed size can be determined:

$$\begin{aligned}
V_f &= EBRT \times Q \\
V_f &= 45s \times 509,400 \frac{m^3}{hr} \\
V_f &= 6367.5m^3 \approx 6370m^3
\end{aligned}
\tag{4.7}$$

Filter bed volume is used to determine the measurements of the filter bed. To accommodate the recommended height-to-width ratio of the filter bed necessary to avoid compaction of the filter medium (Deviny, 1999), the ultimate dimensions of the filter bed will be 30m x 30m x 7.1m.

At this point in the design process, a removal efficiency (RE) must be determined. Typically there is an outside force driving the RE, for example, newly implemented regulations which are more strict than current laws. As FRC East is in an ozone attainment zone and there are no regulations for VOC control in this area, other regions of North Carolina were considered. According to the NCDENR, Guilford County, NC is reported to have released 2,746.7 tons of VOCs in 2005 and 6,513.6 tons in 1993 (NCDENR, 2007b). Guilford County is an ozone non-attainment zone and its air quality is regulated by a state implementation plan (SIP); the *Greensboro/Winston-Salem/High Point, North Carolina Ozone Attainment and Maintenance Plan* (EPA, 1993). This plan mandated a 6.58% reduction of VOC release by 2004, however, emissions data reported to the date shows an actual reduction rate of 57.8%. Using these figures as a basis, the author has chosen to reduce FRC East CY 2005 VOC emissions of 26.4 tons by 60%. A design RE of 75% ensures this goal is met.

In order to determine the elimination capacity at the 75% RE rate, the volumetric mass loading rate must first be calculated. The volumetric mass loading rate was determined in the following manner:

$$VML = \frac{Q \times C_{Gi}}{V_f} = \frac{509,400 \frac{m^3}{hr} \times 0.046 \frac{g}{m^3}}{6370 m^3} \quad (4.8)$$

$$VML = 3.68 \frac{g}{m^3 \cdot hr}$$

This value is then utilized to determine the EC for the biofilter:

$$EC = VML \times RE$$

$$EC = 3.7 \frac{g}{m^3 \cdot hr} \times 0.75 \quad (4.9)$$

$$EC = 2.8 \frac{g}{m^3 \cdot hr}$$

If the load and EC are represented graphically (with load on the x-axis), there is a point when the mass loading rate exceeds the EC and removal efficiency of the system begins to decline. This point is called the critical load or critical elimination capacity (Devinny, 1999). Loading rates which exceed this critical load point become less efficient and experience lower removal efficiencies. Therefore, the contaminant waste-gas stream must not load the filter bed at a larger rate than the EC, which for this filter will be $2.8 \text{ g m}^{-3} \text{ hr}^{-1}$.

A schematic of the final design is presented in Appendix C. A concrete “shell” houses the filter bed and humidifier. Contaminated influent air flow first enters the humidifier where it mixes with water droplets to achieve 98% saturation. Saturated air then passes through ports in the wall of the humidifier into a chamber beneath the filter bed. This chamber is one meter high, covers the same area as the filter bed, and is intended to evenly distribute the moist air prior to its entry to the filter media. As the uncontaminated air is released from the top of the filter bed, an exhaust fan external to the biofilter draws the clean air out of the biofilter for release to the atmosphere. The footprint of the entire biofilter system is 32 meters by 30 meters and is located directly adjacent to the Hangar 245 where booth D0129 is located. Appendices D and E contain

plan drawings of the FRC facility, building 245, and the proposed locations of the biofilters. The external height of the biofilter is 9.1 meters, however, 1 meter of the concrete “shell” is below ground-level to allow for ground-level access to the filter media. Access doors to the filter bed are large enough to allow a Bobcat™ or similar vehicle entry to change the filter media. Table 4.2 is a summary of this biofilter’s design parameters.

Table 4.2. Summary of biofilter design parameters.

Air flow (Q)	509,400 m ³ hr ⁻¹ ; 300,000 acfm
Influent Contaminant Concentration	0.047 g m ⁻³
Filter Bed Volume (V _f)	6370 m ³ ; 224,925 ft ³
Media	Compost / Wood chip mixture
Empty Bed Residence Time (EBRT)	45 seconds
Volumetric Loading Rate (VML)	3.68 g m ⁻³ h ⁻¹
Elimination Capacity (EC) at 75% Removal Efficiency (RE)	2.8 g m ⁻³ h ⁻¹

4.2.5 Biofilter Cost

Using the Devinny (1999) cost estimate as a model, calculations follow below which estimate the cost of the study’s compost biofilter. The estimated cost of concrete construction was obtained through a web-based estimating program sponsored by McGraw Hill Construction (MHC, 2007). Filter medium cost, humidifier cost, equipment rental, labor costs, overhead costs, construction crew mobilization cost, and miscellaneous costs are Devinny (1999) values increased by an inflation rate of 20.69% to account for today’s dollar values (InflationData.com, 2007). The 20% safety factor is used based on Devinny’s (1999) design model.

Capital costs

A. Site preparation costs

1. Filter bed volume = 6370 m^3
2. Assume 20% safety factor:

$$V_f \times 1.2 = 6370 \text{ m}^3 \times 1.2 = 7644 \text{ m}^3$$

(L x W x H of 32 m x 30 m x 9.1 m, to accommodate humidifier and open space above and below filter bed)

3. Concrete structure, enclosed, (includes equipment, labor, overhead / profit, excavation and off site disposal of non-hazardous materials on a 10-mile roundtrip): \$272,164

B. Medium costs

1. Assuming $\$45 \text{ m}^{-3}$ for compost: $\$45 \text{ m}^{-3} \times 7644 \text{ m}^3 = \$343,980$

2. Installation of medium:

$$\text{Equipment} = \$0.85 \text{ m}^{-3}$$

$$\text{Labor} = \$1.3 \text{ m}^{-3}$$

$$\text{Profit / overhead} = \$0.85 \text{ m}^{-3}$$

$$\text{Total} = \$3 \text{ m}^{-3}$$

$$\text{Total installation cost of medium} = \$3 \text{ m}^{-3} \times 7644 \text{ m}^3 = \$22,932$$

3. Total medium cost: $\$343,980 + \$22,932 = \$366,912$

C. Equipment

1. One humidifier: \$2500

D. Piping (10% of capital costs)

E. Equipment installation (4% of capital costs)

F. Engineering design (4% of capital costs)

G. Mobilization and demobilization of construction and installation crew (\$6,050 lump sum)

H. Miscellaneous (\$6,050 lump sum for permitting, spare parts, etc.)

The total capital cost equals the sum of the costs listed above. Set value of capital cost to “x” and place in equation:

$$\$272,164 + \$366,912 + \$2500 + 0.10 (x) + 0.04 (x) + 0.04 (x) + \$6,050 + \$6,050 = x$$

$$\text{Total Capital Cost: } = x = \mathbf{\$3,631,533}$$

Annual Operating Cost

Blower size was provided by Cliff Game (2007) of FRC East. Electricity rates and water rates were provided by Brian Jackson (2007) of FRC East. Predicted water consumption rate is based on a 250,000 acfm biofilter currently in operation which uses 500 gallons per minute ($2725 \text{ m}^3 \text{ day}^{-1}$) to saturate its air stream to 98% humidity (Aulkh, 2007). Labor cost is Devinny (1999) value with 20.69% inflation added.

A. Electricity (eight blowers)

1. Annual blower electrical consumption:

$$\text{Consumption}_{\text{blower}} = 60 \text{ Hp} \times 0.75 \text{ kW Hp}^{-1} \times 260 \text{ days yr}^{-1} \times 16 \text{ h day}^{-1} = 187,200 \text{ kW}$$

2. Total electrical consumption = $187,000 \text{ kW} \times 8 = 1,497,600 \text{ kW}$
3. Total electrical cost = $1,497,600 \text{ kW} \times \$0.065 \text{ kW hr}^{-1} = \$97,344 \text{ yr}^{-1}$

B. Water consumption

1. Estimate $2725 \text{ m}^3 \text{ day}^{-1}$ used to humidify air stream. Water cost is $\$0.60 \text{ m}^{-3}$.
2. Water consumption = $2725 \text{ m}^3 \text{ day}^{-1} \times 260 \text{ day yr}^{-1} \times \$0.60 \text{ m}^{-3} = \$425,100 \text{ yr}^{-1}$

C. Labor

1. Assuming an hour of labor per working day for one year:
 $1 \text{ hr day}^{-1} \times \$25 \text{ hr}^{-1} \times 260 \text{ day yr}^{-1} = \$6,500 \text{ yr}^{-1}$

D. Overhead

1. Annual cost of overhead at 25% labor cost = $\$6,500 \times 0.25 = \$1,625 \text{ yr}^{-1}$

Total Annual Operating Cost:

$$\$97,344 + \$425,100 + \$6,500 + \$1,625 = \mathbf{\$530,569 \text{ yr}^{-1}}$$

Medium Replacement Cost (Every 5 Years)

A. Medium removal cost

1. Excavation, transportation (10-mile roundtrip), and disposal = $\$8.6 \text{ m}^{-3}$
2. Volume to be excavated: 7644 m^3
3. Total cost for removal = $7644 \text{ m}^3 \times \$8.6 \text{ m}^{-3} = \$65,739$

B. Medium replacement cost

1. Assume same cost as original batch: $\$45 \text{ m}^{-3}$
Medium cost = $7644 \text{ m}^3 \times \$45 \text{ m}^{-3} = \$343,980$
2. Assume installation cost (including labor, equipment, and overhead): $\$3 \text{ m}^{-3}$
3. Total installation cost = $7644 \text{ m}^3 \times \$3 \text{ m}^{-3} = \$22,932$

Total 5-Year Medium Replacement Cost: $\$65,739 + \$343,980 + \$22,932 = \$432,651$

Net Present Value (NPV) Cost

The total cost of the treatment system designed by this author in terms of NPV is \$6.4 million. The formula used to arrive at this value is shown in equation 4.9. NPV calculations are

$$NPV = \sum_{t=0}^5 \left[\frac{CF_t}{(1+r)^t} \right] \tag{4.9}$$
$$NPV = \sum_{t=1}^5 \left[\frac{\$530,569}{(1+.049)^1} \right] + \dots + \sum_{t=5}^5 \left[\frac{\$963,220}{(1+.049)^5} \right] = \$6,382,384$$

shown in the spreadsheet in Appendix B. For these calculations, a 5-year project was assumed based on an NPV study made of a biofilter at Tyndall Air Force Base in 2001 (Webster, 2001) and the need to replace organic media between every three-to-seven years (Devinny, 1999). A 4.9% discount rate was used as this is the applicable rate established by the Federal government for the purpose of cost analysis (OMB, 2007). This NPV total amount does not include air stream sampling, monitoring, testing, or analysis, each of which could potentially increase treatment cost. These costs can vary greatly depending on the facility and whether it wants to employ and train an individual for full-time sampling or out-source its sampling needs to a third party.

As discussed in the literature, the most effective valuation of environmental benefits should consist of both willingness to pay (WTP) and cost of illness (COI) measurements. Conducting extensive surveys among the local population surrounding Marine Corps Air Station

(MCAS) Cherry Point would have been too costly in time and money and were therefore beyond the scope of this study. Existing studies of similar nature were obtained and monetary values presented by them were used for calculations in this study.

Multiple studies exist which value the benefits of improving air quality. A 2006 study valued the effects of air pollution on residents of the San Joaquin Valley, California (Hall et al, 2006). In this study, the authors used WTP and COI methods to arrive at an annual benefit of roughly \$1,000 per person should ozone national ambient air quality standards (NAAQS) be attained through an air pollution control technology. WTP and COI methods considered the value of respiratory hospital admissions, asthma attacks, emergency room visits, school absences (ages 5-17), and minor restricted activity days (ages 18-64) to calculate the above dollar figure. This figure, when applied to the Craven County (where MCAS Cherry Point is located) 2000 census population of 91,436 (NCSDC, 2007), yields a \$91.4 million annual benefit. An earlier study examined the benefits of a 35% reduction of VOC emissions across a population sample of 129 million people (Krupnick and Portney, 1991). This study estimated the value of improved health benefits associated with air pollution controls achieving a 35% reduction in VOCs to be \$800 million annually. Over the population sample of 129 million, this value equates to \$6.2 per person, in 1991 dollars. Today, taking into account an inflation growth of 47.33% since 1991 (InflationData.com, 2007), that value is \$9.13 per person. A savings to the residents of Craven County of \$834,810 is thus possible. Yet a third study showed the economic value of fewer school absences among children aged 5-18 resulting from respiratory illnesses in southern California to be approximately \$245 million annually, or, \$75 per child (Hall et al, 2003). From these studies and others like them, an economic value can be applied to air pollution control techniques for the purpose of demonstrating their benefit.

For the purpose of this study, the effect of not controlling VOC release from FRC East will be measured using the recent Hall (2006) study and the \$1,000 annual savings it shows per person when ozone standards are met. This value is applied to the residents near MCAS Cherry Point by comparing the per capita income values of the study population (the San Joaquin Valley, California) and the population of the town nearest FRC East (Havelock, North Carolina). Though it is likely that residents in the predominantly urban San Joaquin Valley (SJV) would be willing to pay more for cleaner air than the residents of the predominantly rural area of Havelock, there are no studies available that support this claim. Therefore, the most favorable method of applying the SJV results to Havelock is by comparing the respective per capita income of each region. The most recent figures available state per capita income in the San Joaquin Valley (SJV) in 2001 was \$21,317 (J. K. Inc., 2004) compared to the per capita income of Havelock residents in 2000, which was \$15,586 (NCSDC, 2007). The Havelock per capita income is 73.1% of that in the SJV, so the assumption was made that Havelock residents can each potentially save 73.1% of the \$1,000 shown to be saved by the SJV residents when ozone standards are met (Hall et al, 2006). If each of the 22,442 residents of Havelock, NC (NCSDC, 2007) were to save \$731 per year as a result of stricter air pollution control, the potential annual savings of the residents equals \$16,405,102.

The potential savings to society of controlling ozone-producing VOCs in terms of NPV is presented in Appendix B. Over a 5-year span, the present value of savings in environmental and human health costs is \$71,222,272 as shown below (Equation 4.10). This figure was calculated using the 4.9% government discount rate (OMB, 2007).

$$NPV = \sum_{t=0}^5 \left[\frac{CF_t}{(1+r)^t} \right] \tag{4.10}$$

$$NPV = \sum_{t=1}^5 \left[\frac{\$16,405,102}{(1+.049)^1} \right] + \dots + \sum_{t=5}^5 \left[\frac{\$16,405,102}{(1+.049)^5} \right] = \$71,222,272$$

It is evident that the amount of savings to the community surrounding FRC East greatly exceeds the predicted cost of installing a biofilter. Therefore, there is economical benefit of having such a system installed. After the cost of installing the biofilter and the costs associated with its operation and maintenance for five years are subtracted from the potential savings to the local community, Havelock residents can value their economic benefit of a biofiltration system at FRC East for the first five years of its operation at \$64,839,888.

4.3 Design Presented by Commercial Biofilter Vendor

Bohn Biofilter Ltd., owned and operated by Karl Bohn, was the first biofilter manufacturer to be approached about designing a biofilter for FRC East. Bohn Biofilter primarily builds and installs soil biofilters and is thus more commonly requested to provide VOC control for smaller operations with significantly less airflow (Q) than FRC East. Based on the parameters provided, Mr. Bohn estimated a soil bed approximately “the size of a runway” would need to be constructed in order to treat emissions from this paint booth (Bohn, 2007). Given the available space at the FRC and the location of the paint booth within the compound, a large soil bed such as that is not practical.

BIOREM Technologies, Inc., of Ontario, Canada, is the largest manufacturer of biofilters in North America. When presented with the parameters from FRC East, the company’s Industrial Sales department quickly provided a design option for a biological treatment process complete with potential investment and operating costs. Design results of treatment processes

for hangar D0129 are presented in Table 4.3. Two design estimates are presented; the BIOFILTAIR™ system, and the SYNERGY™ system.

The BIOFILTAIR™ system is a conventional biofilter designed to the customer's specifications and built of corrosion resistant concrete. Designs can be either up-flow or down-flow (this design is an up-flow, see Figure 4.1) and the floor is a patented concrete slotted design strong enough to support the weight of the media and bobcat-type vehicles used to replace the media. Standard features of the system include a 10-year warranty against acid corrosion, a gate entrance allowing for media replacement, and a pneumatic humidification manifold to ensure a minimum of 98% air flow saturation at all times. The SYNERGY™ system is a combination of biofilter technologies. At its core is a conventional biofilter with a pre-humidifier, however, added to the process is a downstream adsorber. This system is particularly suited for operations such as those at FRC East which are not continuous and show fluctuating and irregular operating conditions. The design of this system is centered about the degradation efficiency of the microbial population in the filter media rather than the conventional design method of empty bed residence time. This design factor allows for a slightly smaller filter bed size. VOC inlet concentrations are adjusted to enter the filter bed at a higher rate, forcing the microbes to degrade the contaminants faster than normal. Since the smaller residence time in the smaller filter bed does not allow for complete treatment of the contaminants, residual contamination is collected in the downstream adsorber and recycled back to the biofilter for further degradation. The filter bed in the SYNERGY™ system is smaller than the BIOFILTAIR™ system and the footprints of each reflect this. The SYNERGY™ system is also slightly larger because of the adsorption and recirculation steps added to its process (BIOREM Technologies, Inc., 2007).

Filter beds of each system are filled with a unique filter medium designed and patented by BIOREM Technologies, Inc. BIOSORBENS™ is an inert, homogenous, mineral-based, engineered medium, the granules of which are uniform in shape. During production of the medium, an inert mineral is exposed to an 1800°F treatment process which expands each granule

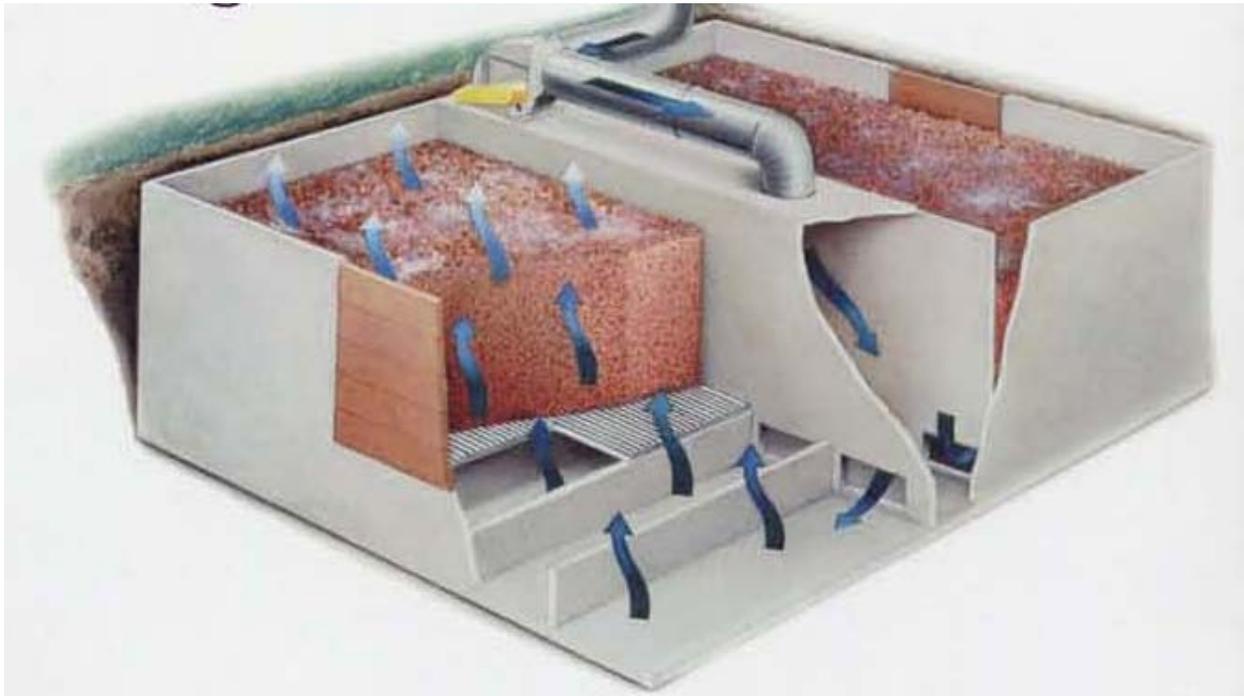


Figure 4.1. BIOREM™ up-flow biofilter design, reproduced with permission from BIOREM Technologies, Inc. company brochure (2007)

to produce a strong and porous substrate. A coating is then added and sealed to the substrate containing nutrients, pH buffers, adsorbents, and other ingredients essential to ideal microbial activity and which facilitate the collection of contaminants from the air. This medium is resistant to decomposition and its strength prevents any compaction from occurring. These factors combined with its high porosity allow for minimal pressure drop across the filter bed. BIOREM Technologies, Inc., consider this the first permanent filter medium on the market and guarantee its efficiency for 10 years (BIOREM Technologies, Inc., 2007).

BIOREM made the following assumptions with respect to each design presented: 1) A 2008 installation; 2) pricing includes turn-key installation of biofilter structure, supply and installation of media, and installation of mechanical and electrical controls; 3) there is sufficient area near hangar D0129 to install the biofilter and the subsurface is suitable; and 4) pricing does not include any ducting, removal of contaminated material, or engineered fill for subsurface improvement if conditions warrant. Additionally, BIOREM offers a service with each installation in which it monitors the system's performance for the first year of operations. Every three months a sample of the filter medium and facility records of system operation need to be sent to the laboratories at BIOREM for analysis. The results of the analysis are shared with the facility and if necessary, corrective actions are either made by BIOREM or the facility where the biofilter is installed. For an additional charge to the customer (not included in the prices listed in the table) there is also a web-based monitoring service available for each biofiltration system through which representatives at the BIOREM facility can observe the behavior and operation of an installed system, ensuring continuous optimal performance of the biofilter.

The "footprint" presented under each design is the volumetric size of the entire biofilter system. Each biofilter will be approximately 16 feet in height, with 4 feet of this height below ground level. Plan area for the BIOFILTAIR™ is approximately 17 m by 17 m (55 feet by 55 feet) for an area of 289 m² (3025 ft²) while the SYNERGY™ system will occupy a space slightly larger; approximately 18 m by 18 m (58 feet by 58 feet) for an area of 324 m² (3300 ft²).

Table 4.3. Biofilter design results presented by BIOREM Technologies, Inc. (Mullin, 2007).

	BIOFILTAIR™	SYNERGY™
Airflow (Q)	509,400 m ³ hr ⁻¹ ; 300,000 acfm	509,400 m ³ hr ⁻¹ ; 300,000 acfm
Removal Eff. (RE)	65% - 75%	85% - 95%
Fan Hp	600	700
Natural Gas Required	None	Small quantities may be required to regenerate carbon
NOx Emissions	None	About 1% - 5% of the amount generated by a thermal oxidizer
CO Emissions	None	About 1% - 5% of the amount generated by a thermal oxidizer
Greenhouse gases from combustion of fossil fuels	None	About 1% - 5% of the amount generated by a thermal oxidizer
Footprint	1325 m ³ ; 46,800 ft ³	1495 m ³ ; 52,800 ft ³
BUDGET PRICE	\$9,204,000	\$12,036,000

The SYNERGY™ system clearly shows a superior RE when compared to the BIOFILTAIR™ system. However, the increased cost may render the system prohibitive, especially considering the target RE for the study design is 75% which is easily achieved by the BIOFILTAIR™ design. Additionally, the trace amounts of air pollution produced by the SYNERGY™ system are worth consideration. Removing VOC emissions from the atmosphere at the expense of adding additional—though miniscule—amounts of different pollutants to the air is counterproductive. Trading one contaminant for another is not helping to clean the air around FRC East. Installation of the BIOFILTAIR™ system is therefore recommended over SYNERGY™.

4.4 Cost Comparison: Study vs. Vendor

Estimated NPV costs of potential biofilter treatment systems indicated by this study and provided by a commercial vendor are commensurate. Initial purchase of the system and installation comprise the majority of the costs in both projects and at first glance, appear to be excessively expensive. However, the savings introduced over time by a biofilter treatment system and the savings afforded to the environment and human health (as seen in Table 4.4), far outweigh the investment cost of any biofiltration system.

Table 4.4. Study and vendor biofilter design results.

System	Study Design	BIOFILTAIR™ by BIOREM	SYNERGY™ by BIOREM
VOC Reduction	75%	65%-75%	85%-95%
Footprint	960 m ² (30 m x 32 m)	289 m ² (17 m x 17 m)	324 m ² (18 m x 18 m)
Five-Year NPV cost	\$6.4 million	\$9.2 million	\$12 million
Potential Environmental Benefits to Havelock residents in Monetary Savings over 5 yrs.	\$64.8 million	\$62 million	\$59.2 million

4.5 Case Study One

4.5.1 Background and Design

Rothsay Recycles of Ontario, Canada, is a division of Maple Leaf Foods and is one of its country's largest rendering plants. The rendering process recycles animal and poultry by-products that are ultimately used in the production of such items as pet and livestock feed, fertilizer, soaps, candles, pharmaceuticals, and a host of other consumer products (Rothsay Recycles, 2007; CRS, 2004). Recently at its plant in Dundas, Ontario, Rothsay installed a large biofilter for odor control. The biofilter was designed and installed by BIOREM Technologies,

Table 4.5. Characteristics of Rothsay Recycles, Dundas, Ontario, biofilter.

Owner and location	Rothsay Recycles, Dundas, ON
Builder	BIOREM Technologies, Inc.; Guelf, ON
Type of air stream	Exhaust air from rendering process
Year of installation	2003
Volume and type of medium	4671 m ³ (164,934 ft ³); BIOSORBENS™ medium
Layers and medium height	One layer per cell; 1.68 m (5.5 ft)
Biofilter construction type	Two concrete banks, three biofilter cells each, down-flow
Humidification	Three-chamber pre-conditioning unit achieving 98% air stream saturation
Air flow rate	424,808 m ³ h ⁻¹ (250,000 acfm)
Empty bed residence time	35 seconds
Pressure drop	5.08 cm (2 inches)
Average bed temperature	16°C (60.8°F)
Pollutants treated	Odors; ~2600 to 10,220 odor units m ⁻³
Biofilter controls	Computer controlled humidifier and temperature
Biofilter design and acceptance criterion	>90% removal efficiency
Approximate investment cost	Confidential
Approximate operating cost	Approximately USD 300,000
Performance	~94%, highs at 97%

Inc., in 2000 and treats a contaminated air flow of approximately 250,000 acfm. Table 4.5 above lists the important characteristics of the Rothsay biofilter.

The Dundas plant has been in operation for approximately 40 years. Over recent years, urban development has grown closer to the plant. To prevent potential complaints from nearby residents over the rendering odors and to comply with Canada's Ministry of Environment (MOE)

5 odor units (OU) m^{-3} odor limit, Rothsay decided to replace its chemical scrubbing process (two scrubbers) being used for odor control. Odor RE of the scrubbers was a combined 54% and the odor limit set by the MOE could not be met with the scrubbers operating at anything less than 98% RE. A thermal oxidation system was examined and was capable of removing 100% of the odorous air stream. However, the excessive operating cost of approximately \$1 million per year (2002 U. S. dollars) encouraged further study of more cost-effective solutions. Pilot testing of a scrubbing process with new chemicals yielded less-than-desirable results. A second pilot test of



Figure 4.2. Construction phase of Rothsay Recycles, Dundas, ON biofilter by BIOREM Technologies, Inc. in 2003 (Mullin, 2007).

a biofiltration system using BIOREM Technologies' BIOSORBENS™ filter medium showed removal rates in excess of 90% over a three-month period. After a competitive bid process involving three other biofilter providers, BIOREM was selected to begin construction of a new, full-scale system at the Dundas site in 2002 (Geisberger, 2005).

Benefits of the biofiltration system design are numerous. The filter bed has been split into six individual cells (see Figure 4.2). Any one of the six cells can be isolated and shut down while the remaining cells continue to operate. Compartmentalized construction such as this facilitates maintenance and upkeep of the system. Each cell is supplied air via its single 150 horsepower variable frequency drive (VFD) fan controlled by a centralized automated control process. The VFD fans are particularly suited for intermittent plant operations. For example, during a reduced production winter weekend, the automated control process can reduce the fan power to 25% capacity to save costs. There is one central humidification cell from which each of the six filter beds draws an air stream. Water for the humidification cell is recycled through a nearby pool to reduce water costs. A secondary water tank is available for media irrigation purposes, should the media require nutrient treatment or other additives. In addition to these design advantages, the system continues to operate almost four years after installation at consistent levels of removal efficiency over 92% (Geisberger, 2005).

4.5.2 Relevance

The biofilter installed and operating at the Dundas facility is of interest to this study for a number of reasons. Though the biofilter was installed at Dundas to control and reduce odor emissions, many of the odors are caused by VOCs at this plant (Seth, 2005) and BIOREM Technologies utilizes identical technology to control odors and VOCs (Mullin, 2007). Second,

the size air flow being treated by the Dundas biofilter is comparable to the air flow requiring treatment at FRC East. Contaminant concentration levels in the air flows at each facility are relatively small as well as intermittent. The Dundas facility compensates for this with its VFD fans and the ability of each of the six biofilter cells to operate independently. Third, the annual operational cost of the biofilter is lower than the annual operational cost of any of the technologies that were examined for possible installation at Dundas. This fact should be of particular interest given the removal efficiency of the Dundas system of over 92%. Lastly, the Dundas biofilter is almost completely self sufficient. Water for humidification and irrigation purposes comes from a storage pond on the facility. Zero waste is generated by its day-to-day operation. The only outside support required is electricity, which is utilized at efficient rates by the VFD fans. The proposed biofilter at FRC East will operate under similar parameters by not generating additional waste, not increasing the power requirements through the use of in-place fans, and operating at low annual costs.

4.6 Case Study Two

4.6.1 Background and Design

Plum Creek Timber Company, Inc. is one of the largest private landowners in the United States with over 8 million acres of timber-producing land in its possession (Plum Creek, 2007). Lumber production is the company's principle source of income, supported by ten wood product manufacturing facilities located throughout the Northwest. At a facility in Columbia Falls, Montana, Plum Creek manufactures medium density fiberboard (MDF) for distribution throughout North America and the Pacific Rim. MDF is a homogenous-cored, wood panel created from the residual material of lumber and plywood production. MDF is used for a variety

of applications including furniture, cabinetry, and moldings. During the production process, wood fibers are exposed to extreme pressures and “glued” together using an urea formaldehyde (UF) compound. After the pressing process, the wood product requires drying prior to the final finishing processes. During the drying process VOCs are released from the



Figure 4.3. The Plum Creek Timber Company, Inc., medium density fiberboard facility biofilter in Columbia Falls, Montana (Leu, 2007).

fiber board, the emissions of which require control by Plum Creek. During the construction planning process for the MDF facility, Plum Creek decided to simultaneously construct the APC technology required for the purpose of controlling VOC emissions.

In order to prevent the release of methanol and formaldehyde vapors from its new manufacturing facility, Plum Creek decided to install a biofilter. The biofilter was constructed

simultaneously with the manufacturing facility in 2001; there was no conventional APC technology in place prior to the biofilter. An aerial photograph of the biofilter in operation is shown in Figure 4.3. Biofiltration was selected as an APC technology by Plum Creek for its ease of operation and its low cost. The only available alternative APC for an operation of this size was a regenerative thermal oxidizer which would have been too costly of a technology given the size of the effluent airflow (600,000 acfm; 1,018,800 m³ h⁻¹) and the contaminant concentration contained within.

The biofilter consists of three individual filter beds. Each bed is a “box” constructed entirely of concrete (ceiling, walls, and roof) to protect against the cold winter months of Montana. The ceiling is insulated with three inches of foam and a rubber membrane to prevent heat escaping from the filter medium and to protect the medium against rain. Further insulation in the walls and floor is not required due to a majority of the filter “box” being below ground level (see Figure 4.3) and due to the extreme amount of thermal mass contained within each filter

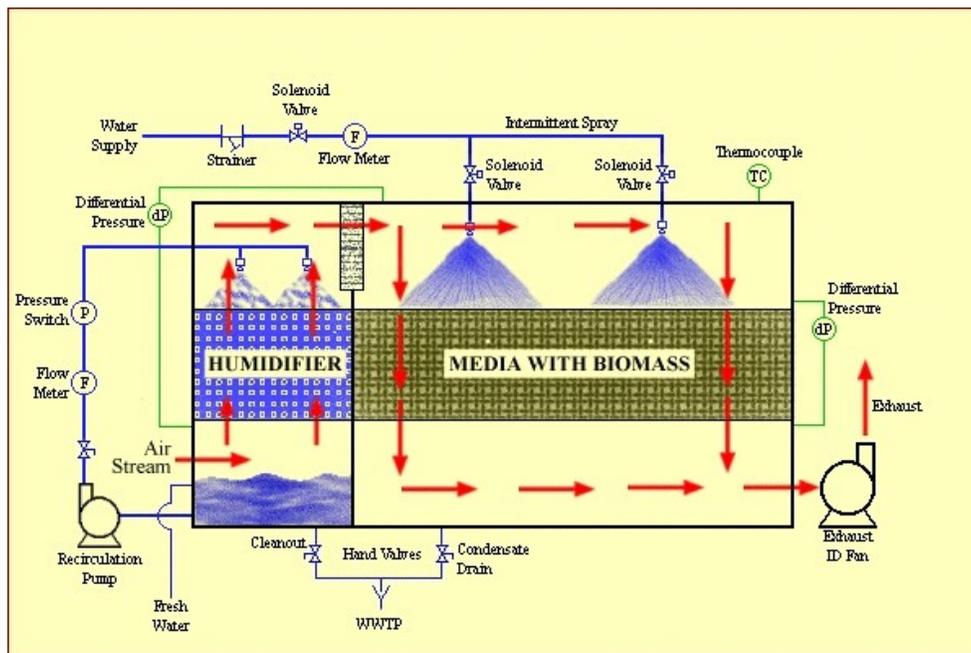


Figure 4.4. Schematic drawing of Columbia Falls biofiltration system (Leu, 2007)

bed. For example, a four-day shutdown of the entire system in February, 2006 in -10°F weather did not affect the filter medium significantly. The medium remained at temperatures well above freezing for the entire period. During operation, a constant temperature of 102°F is maintained by an automated system which controls each of the three VFD fans. Filter media in each bed is composed of round river rock with rocks varying in size from .75" (1.91 cm) to 1.5" (3.81 cm). Moisture content of the filter media is controlled via humidification of the airflow in a single wet chamber from which all three filter beds draw air. The water humidifying the air stream contains bacteria which assist in maintaining a constant microorganism population within the filter bed biomass. Figure 4.4 is a schematic drawing of the biofiltration system at the Columbia Falls facility.

Performance of the biofilter is consistently reported at over 97% removal efficiency. Contaminant concentration is reduced from 40 ppm (0.050 g m^{-3}) in the influent air stream to less than 1 ppm ($1.25 \times 10^{-3} \text{ g m}^{-3}$) in the effluent air stream. These rates are achieved at an annual operating cost of \$600,000, most of which can be attributed to the cost of the electricity required to power the three 700 Hp fans. Table 4.6 lists a majority of the parameters associated with the Columbia Falls biofilter, which according to the Columbia Falls environmental engineer, is the largest of its type in the United States. Despite this noteworthy fact, Plum Creek will begin construction in May, 2007 of a new biofilter directly adjacent to this one which will treat an air flow of 900,000 acfm ($1,528,200 \text{ m}^3 \text{ h}^{-1}$) (Leu, 2007).

4.6.2 Relevance

At first glance, the biofilter at the Columbia Falls MDF plant may appear to have nothing in common with a proposed biofilter system at FRC East. The amount of property available in

Montana to accommodate a biofilter that can treat the given amount of air flow at an extremely small residence time with such removal efficiencies as this far exceeds the property available at FRC East. However, the treated contaminants, while not identical to the compounds requiring treatment at FRC East, are VOCs and are concentrated in the waste air stream at almost exactly the same amount as the FRC emissions (0.047 g m^{-3} at FRC versus 0.050 g m^{-3} at Columbia Falls). The small contaminant concentration in the large air stream successfully being treated at

Table 4.6. Characteristics of Plum Tree Timber Company, Inc., biofilter.

Owner and location	Plum Tree Timber Company, Inc.; Columbia Falls, MT
Builder	PPC Biofilter; Longview, TX
Type of air stream	Exhaust air from a wood fiber dryer
Year of installation	2001
Volume and type of medium	Three beds at 1783 m^3 ($21,000 \text{ ft}^3$) each; round river rock
Layers and medium height	One layer per bed; 1.07 m (3.5 ft)
Biofilter construction type	Concrete box, three each, down-flow mode
Humidification	One wet section with water sprays and air mixer used by each filter bed
Air flow rate	$1,018,800 \text{ m}^3 \text{ h}^{-1}$ (600,000 acfm)
Empty bed residence time	6 seconds
Pressure drop	7.6 cm (3 inches)
Average bed temperature	38.9°C (102°F)
Pollutants treated	Methanol (50%), Formaldehyde (50%); average total inlet concentration is 0.050 g m^{-3} (40ppm)
Biofilter controls	Computer controlled temperature, moisture
Biofilter design and acceptance criterion	>90% removal efficiency
Approximate investment cost	Confidential
Approximate operating cost	\$600,000 annually
Performance	>97% removal efficiency; average outlet concentration is $<1.25 \times 10^{-3} \text{ g m}^{-3}$ (1ppm)

Columbia Falls indicates that a similar treatment system with slight design adjustments at FRC can experience the same success. Annual operating cost at the Columbia Falls plant appears expensive because of the increased biofilter size and the large air flow requiring treatment. A similar system at FRC East will operate at a less costly price because the fans currently in operation there were incorporated into the biofilter study design. Excellent removal efficiencies at large-scale operations such as the Columbia Falls MDF plant should be encouraging to smaller yet similar operations requiring VOC emission control.

4.7 Discussion

Three different biofilter designs were presented as possible air pollution control systems for FRC East. Though all three were designed for the same purpose—the reduction of VOC emissions—each design is different in size and cost. These phenomena deserve closer explanation.

The study design is the least costly and largest sized of the three biofilters presented. Standard design equations as developed and presented by Devinny (1999) were used, so the natural question that follows is “why are the vendor designs so much smaller and more expensive?” The most efficient and inexpensive filter medium as discussed in the literature review was selected for use in the study’s design. An appropriate residence time allowing for optimal filter bed performance was also selected from the literature. Together, these two parameters created the large filter bed seen in the final design. The vendor’s designs are each approximately one third the size of the study design. This extreme difference in size can be accounted for by the filter medium used by the vendor. The vendor utilizes a filter medium which was developed through research and experiments conducted at its in-house laboratories by

its own engineers and scientists. The resulting synthetic product has since been patented and used consistently in all of the vendor's biofiltration products. While the manufacturing process of this filter medium is known to the public and discussed in an earlier section of this chapter, the design process used by the vendor to calculate filter bed sizes is directly correlated to the performance characteristics of the medium and therefore confidential. This factor helps to explain the increase in cost for the vendor's biofilter, that is, the vendor is offering a product and a performance that no other biofilter vendor currently on the market is offering. Another factor for the increased cost of the vendor's biofilter is the performance guarantee that comes with each design. The vendor guarantees target removal efficiencies of its biofilters and its media for a 10-year period after installation. Should removal efficiencies drop below the customer's target rate, the vendor will replace the filter medium. Costs of the SYNERGY™ system from the vendor are more expensive than the conventional BIOFILTAIR™ system because of the additional technologies attached to the design, namely, the adsorber downstream of the biofilter designed to catch and recirculate contamination not degraded by the biofilter. Removal efficiencies of the SYNERGY™ system are also superior to the other two biofilter designs which contributes to further increase of cost.

There is no doubt that the addition of any one of these three biofilters to the grounds at FRC East would be a significant increase in infrastructure. Building 245, within which hangar D0129 and D0106 are located, is approximately 210 ft by 160 ft (64 m by 49 m) in size, is located near the east property boundary of FRC on one side and is surrounded on two other sides by buildings. The only feasible location to construct any of the three biofilters is directly adjacent to building 245 on its east side (see Appendices D and E). In order to place a biofilter there, however, an agreement will have to be reached between FRC East and MCAS Cherry

Point. The property immediately to the east of the boundary line belongs to the MCAS and is currently used for aircraft parking. No structures exist in the area that would effect construction. Both the north and south sides of building 245 contain hangar doors. Blocking any doors on building 245 with a permanent structure would have a degrading effect on painting operations as they are the primary ingress / egress points for each paint booth and for the aircraft paint preparation area. Painting operations will be able to continue during construction because no hangar doors will be blocked. During construction of any of the biofilters at this location, space will be limited, however, there will be an adequate amount of useable space around the biofilter and existing buildings post construction.

At first glance, the cost and size of any of these biofilters appears prohibitive. However, the ultimate objective of an APC technology—VOC emissions reduction—must remain the central focus of any decision process regarding an installation at this location. Conventional technologies for the same purpose, though smaller in size than any biofilter, were shown to be much more expensive and less efficient than biofiltration. Construction of a biofilter at this facility may temporarily interrupt operations, however, once complete the biofilter will operate with little-to-no impact on the surrounding infrastructure. Biofiltration can thus be considered a viable APC technology for the reduction of VOCs at this facility.

4.8 Summary

Two biofilter designs and two case studies showing the successful application of industrial-sized biofilters have been presented in this chapter. The designs presented and the subsequent cost analysis of each show that while biofilter treatment process have an expensive up-front investment cost, the savings they offer in long-term environmental and human health

impacts are justification for the implementation of similar treatment systems at like-facilities.

The case studies each show that large-scale biofiltration is not only possible but also a benefit to the natural environment in terms of pollutant reduction in the Earth's atmosphere. These findings will be discussed in further detail in Chapter V.

V. Conclusion and Recommendations

5.1 Conclusion

The purpose of this research was to determine if a DoD facility, like the FRC East paint facility, and its surrounding area can benefit both economically and environmentally from a biofiltration system for air pollution control rather than a conventional treatment process. The questions answered by this research were:

1. What is the anticipated reduction in VOC emissions from the paint facilities if a biofiltration unit is installed?
2. Will conventional biofiltration be a satisfactory air pollution control method for use at FRC, East given their low levels of VOC emissions, intermittent operations, and varied aircraft / aircraft component throughput?
3. What is the best packing media for the appropriate size of a conventional biofilter for the FRC facility?
4. Will biofiltration be a cost effective method for reducing FRC East VOC release to the atmosphere, i.e., will a net present value calculation show conventional biofiltration is cost effective for this facility?

Each question was answered during the course of this research. This section presents a summary of those answers, limitations encountered during the research, suggested follow-on research and recommendations for improvement of this and any follow-on research.

5.2 Research Questions Answered

As the release of VOCs in the region of North Carolina where FRC East is located are currently not controlled by any legislation, minor reductions in the amount of contaminants

emitted can still be considered improvements to air quality. However, this research has shown through the design of a biofilter and through the analysis of a biofilter design presented by a commercial biofilter manufacturer, that between 75% and 90% of the VOC vapors currently being released by this facility can potentially be eliminated. The amount of VOCs eliminated is a function of the biofilter design itself; a larger filter bed with a longer gas residence time improves performance but will also increase the capital cost of the biofilter.

Conventional biofiltration will be a satisfactory air pollution control method for use at FRC East. Despite the intermittent use of the paint facility and the variance in VOC load emitted while applying surface coatings to different sized aircraft and aircraft parts, the research shows that biofiltration technology is appropriate for these types of conditions. From the literature, it is known microorganisms within the filter medium responsible for contaminant degradation are capable of surviving for as long as two weeks without a contaminated air stream, provided the conditions within the filter medium are optimal. It is therefore essential that the filter medium within the biofilter is closely monitored during the course of its operation to ensure optimal conditions exist not only for maximum degradation of target contaminants but also for maximum survivability of microbes during off-peak hours of operation and shut-down periods.

The best packing material for the size of biofilter required at FRC East is a composite mixture of compost and wood chips. Compost is a porous material containing an abundance of organic material in which microorganisms can thrive. Wood chips will provide the compost with the additional porosity required for an effective treatment regimen of the contaminated air stream. An effective filter medium mixture should contain between 70% and 80% compost and the remainder wood chips. Both materials are inexpensive and do not require treatment when removed from the biofilter. Removal and replacement of the media is recommended every five

years, which, as the research shows, is an advantage over conventional treatment methods requiring filter media replacement much more frequently.

Biofiltration is shown to be a cost effective method for reducing VOCs at FRC East. The capital and operating costs of a biofiltration system were shown using a net present value calculation. While these systems incur expensive capital costs, the literature and case studies have shown their operation costs less than any conventional system for the same purpose. Additionally, through a net present value calculation, the cost savings associated with environmental damage and human health degradation as a result of VOC pollution in the atmosphere was shown to be far greater than the cost of a biofiltration system to prevent the same pollution over the same period of time. This research shows that while the investment cost of a biofilter appears to be excessive, the cost savings versus a conventional APC technology and the cost savings versus potential damage to human health and the environment are significant.

5.3 Research Limitations

Research during the course of this study was limited by varied factors. Lack of funding was a critical limiting factor. This study was not requested by a particular facility or a command within the DoD or DoN. Instead, this author approached FRC East and offered his services to conduct the research in an effort to encourage pro-active interest in the field of biofiltration. Repeated requests for funding assistance from Headquarters, Marine Corps, NAVAIR, and FRC East were each denied. The inability to conduct lab- or pilot-scale experiments using the desired filter media at the FRC location is limiting because results are strictly theoretical as opposed to empirical. The study of only one location within the DoD is also limiting. Though there are many similar surface coating facilities within the DoD and the U. S. Navy, usage, facility size

and layout, air quality regulations, and treatment needs are different at each location. Another limiting factor is the fact only one commercial biofilter manufacturer was requested to provide a cost estimate for the installation and start-up of a biofilter capable of meeting the needs of FRC East. Through the course of this research several biofilter manufacturers were discovered and contacted, though only one was willing to respond with useful data. It is likely that pricing for a similar system from each would have varied. However, for the purpose of this study, the analysis provided by one vendor meets was adequate.

5.4 Suggested Improvements

If the control of VOCs released from FRC East were to be studied again, research should focus on a system that captures and treats all combined VOCs being emitted by the facility. As there are five separate paint booths operating and emitting VOCs at this facility at varied locations, the need to treat the emissions of each will become necessary should air quality regulations in this region of North Carolina become more stringent in the future. The concept of using one biofilter for the treatment of waste gas streams from five separate locations across a facility the size of FRC East may not be impossible but nevertheless presents numerous challenges worthy of examination.

Future study of VOC treatment at FRC East would benefit from a pilot-scale study. Empirical results from an experiment using the same filter media and treating the same contaminants intended for a full-scale biofilter would provide irrefutable evidence for FRC East and other similar DoD facilities demonstrating the capabilities and benefits of a biological process for the treatment of VOCs. Should regulation of VOC emissions such as those released by FRC East become compulsory, an effective, safe, and economic solution to control those

VOCs will be sought. A study which provides data showing the advantages of a pilot-scale biofilter for VOC control would serve as compelling evidence for the argument to install a full-scale biofilter operation. Funding for this type of research as well as the cooperation of a commercial industrial biofilter vendor would be critical to the study's success and should be considered thoroughly for future projects of this type.

5.5 Recommendations for Follow-on Studies

Future research in the biological treatment of VOCs at DoD surface coating facilities should focus on a method by which waste gas streams from multiple, small-scale booths can be collected and treated simultaneously. A pilot-scale study of this phenomenon already exists (Webster et al, 2001) but further research is necessary to provide more evidence of the concept's success. As most DoD surface coating facilities already exist and are operating at full-scale production levels, future research will have to examine methods of treating multiple sources of VOC emissions at one facility. Due to production processes, industry standards, and the chances of increasing construction costs, the likelihood of the DoD building future depot-level aircraft maintenance facilities with centrally located surface coating operations is low, however, a study of this concept is perhaps warranted. The notion of moving paint booths at current facilities to one location for ease of emissions treatment deserves study, especially if regional regulations require control of these emissions. Research and solutions to VOC emissions control over a large facility with multiple sources is thus paramount.

Close examination of filter media in order to reduce the footprint of a biological treatment process is necessary. Space is often an inhibitor at facilities considering biofiltration for APC purposes. Increased gas residence time equates to an increased filter bed size and thus a

large biofilter “footprint”. However, if a filter medium can be developed capable of treating the same amount and type of contaminants in an identical-sized air stream as a conventional biofilter and do so in much less space, DoD facilities could benefit.

An additional study of value would involve the Havelock residents and MCAS employees directly. A survey of a representative sample of each population to determine the WTP for clean air and the COI for polluted air amongst each group would provide valuable data that can be used to estimate the cost benefit of a biofiltration system at FRC East. Also, this survey could determine if, in fact, there are any trends in adverse health affects amongst the population as a result of polluted air. The results of this type of survey, if the data indicate that air pollution is a problem in Havelock, could weigh heavily in favor of the argument to install a biofiltration system for air pollution control at FRC East.

5.6 Significance

This study was the first of its type conducted at FRC East. Though there are no regulatory changes underway regarding the treatment of VOC emissions to prompt this study of VOC control at FRC East, it is possible that such changes could take place in the future. Legislation regulating air pollution control has undergone significant changes multiple occasions since the inception of the CAA in 1963. By that calculation, more changes could be in store within the next five years. If stricter controls of VOCs are mandated at that time in the coastal region of North Carolina, quick and effective solutions will be in demand. This study has opened the door to finding solutions for such an eventuality and offered a proactive look at an inexpensive and effective method of meeting the types of emissions standards already in place in other parts of the U. S. This study is significant also in that it may encourage similar DoD

facilities in similar, non-regulated regions of the U. S. to study possible solutions to stricter air emissions requirements.

Appendix A: Case Study Questions

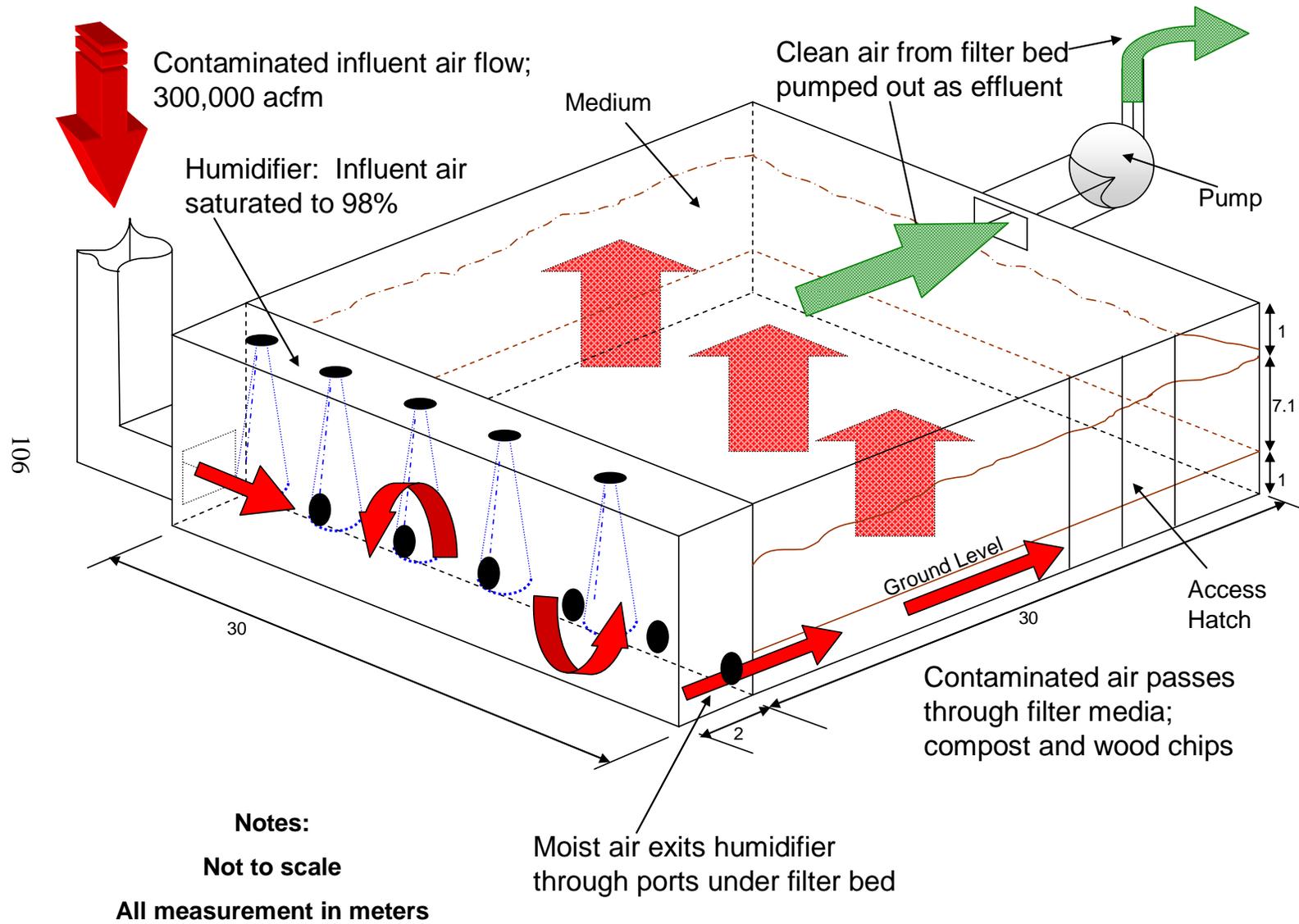
1. What is the type of operation for which your facility has selected a biofiltration system?
2. What are the target contaminants for the biofiltration system?
3. How big is the filter bed (L x H x W)?
- 4a. What is the filter medium?
- 4b. If the filter medium is a composite mixture, what is the ratio of each ingredient to the whole?
- 4c. If the medium needs replacement after a particular time period, how often does this occur and when is the next replacement scheduled?
- 4d. What will the cost be of the removal and disposal of the old medium?
- 4e. What will the cost be of installing the new medium?
- 4f. Are there nutrients and / or buffering material added to the filter medium?
- 4g. If so, are they added via a one-time process during start-up or are they introduced via a consistent trickling method?
- 4h. Is there a pH control of the filter medium in place?
- 5a. What is the facility's target removal efficiency?
- 5b. What is the biofilter's contaminant removal efficiency?
- 6a. What pre-treatment processes are there in this system for the contaminated influent airflow?
- 6b. What is the airflow into the biofilter?
- 6c. What is the concentration of contaminant within the airflow into the biofilter?
- 6d. What is the contaminant contact time with the filter medium?
7. What was the acclimation (start-up time) for the biofilter?
8. How long did construction of the biofilter take?
- 9a. What was the cost of construction for the biofilter?
- 9b. What was the cost of installation for the biofilter (including labor)?

- 9c. What is the annual operating / maintenance cost associated with the biofilter?
- 10. From which company was the biofilter purchased?
- 11. When was the biofilter installed?
- 12. When did the biofilter begin operation?
- 13a. Was there a conventional APC technology in place prior to the biofilter?
- 13b. If so, what are the monetary savings noticed over the conventional system from the biofilter?
- 13c. Did the conventional system treat the same contaminants as the biofilter does?
- 14a. Did the installation of the biofilter facilitate a reduction in manpower at your facility?
- 14b. Was there a requirement to hire extra manpower to operate / maintain the biofilter?
- 15. What prompted / caused your facility to choose biofiltration as an APC technology?

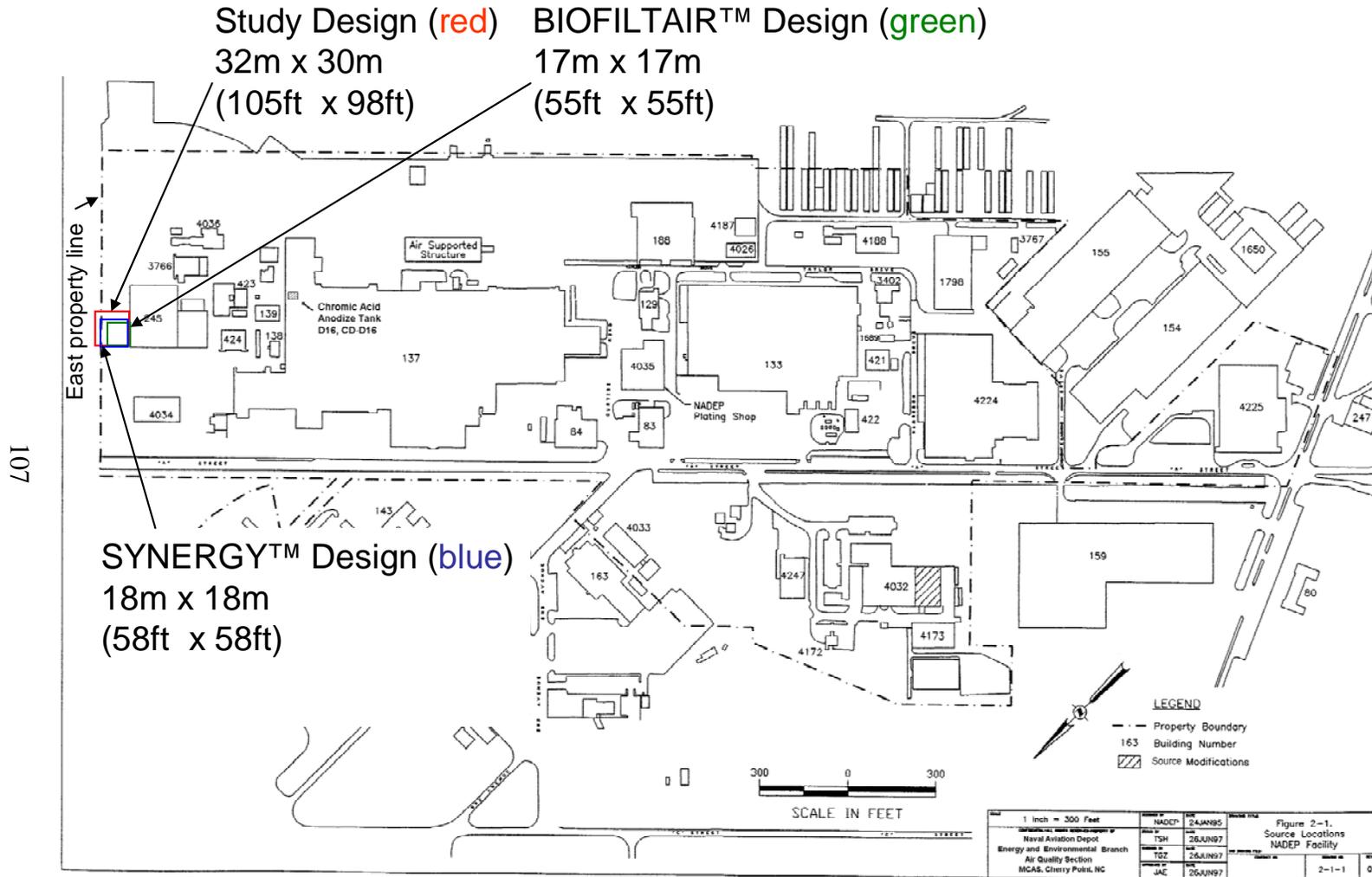
Appendix B: Net Present Value Calculations

Study Biofilter; Net Present Value over 5-Year Period						
discount rate	0.049					
Year	0	1	2	3	4	5
Capital Cost	\$3,738,322.00					
Ops and Maint		\$530,569.00	\$530,569.00	\$530,569.00	\$530,569.00	\$963,220.00
NPV per Year	\$3,738,322.00	\$505,785.51	\$482,159.69	\$459,637.45	\$438,167.25	\$758,312.21
Total NPV	\$6,382,384.11					
Environmental Benefits (monetary savings resulting from pollution control in Havelock, NC.)						
discount rate	0.049					
Year	0	1	2	3	4	5
Annual Savings, Havelock, NC.		\$16,405,102.00	\$16,405,102.00	\$16,405,102.00	\$16,405,102.00	\$16,405,102.00
NPV per Year		\$15,638,800.76	\$14,908,294.34	\$14,211,910.71	\$13,548,055.97	\$12,915,210.65
Total NPV	\$71,222,272.44					
Difference	\$64,839,888.33					

Appendix C: Study Schematic

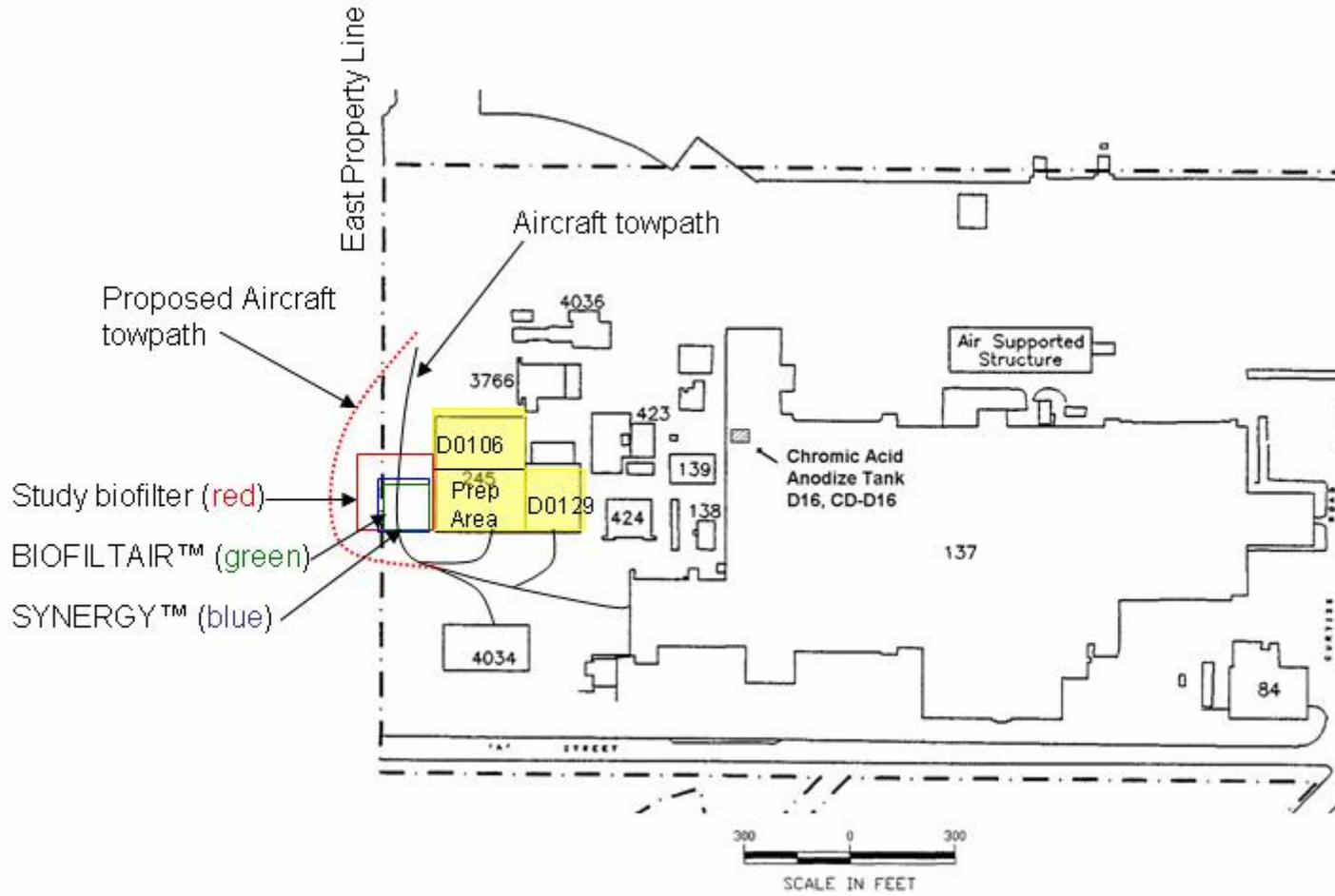


Appendix D: FRC Plan with Proposed Biofilters



Appendix E: Enlarged FRC Plan with Proposed Biofilters

108



Appendix F: Conversion Factors

To Convert from:	To:	Multiply by:
Meter (m)	Foot (ft)	3.28
Meter (m)	Inch (in)	39.37
Square Meter (m ²)	Square Foot (ft ²)	10.76
Cubic Meter (m ³)	Cubic Foot (ft ³)	35.31
Cubic Meter per Hour (m ³ h ⁻¹)	Actual Cubic Foot per Minute (acfm)	0.5885
Gram per Cubic Meter (g m ⁻³)	Part per Million (ppm _v)	At 25 °C, (g m ⁻³ x 24,766 / molecular weight of contaminant in g mol ⁻¹)
°C	°F	(°C x 9/5) + 32

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Vita

Captain David M. Hudock is a graduate of Broadneck Senior High School in Annapolis, Maryland. He matriculated to the Virginia Military Institute where he graduated in May of 1997 with a Bachelor of Science degree in Civil and Environmental Engineering. Following graduation, Captain Hudock worked for the Virginia Department of Transportation in Colonial Heights, Virginia, as a Road Design Engineer before entering the Marine Corps in January, 1998.

Upon completion of Officer Candidate's School, Captain Hudock was commissioned a 2ndLt and reported to The Basic School for infantry training. Following The Basic School, Captain Hudock attended Aircraft Maintenance School in Pensacola, Florida where he earned his Aircraft Maintenance Officer military occupational specialty.

His first fleet assignment was as the Support Equipment Officer at Marine Aviation Logistics Squadron (MALS) 36 aboard Marine Corps Air Station (MCAS) Futenma, Okinawa, Japan. In September of the same year, he reported to Marine Medium Helicopter Squadron (HMM) 262 where he eventually spent three years. In June of 2002, Captain Hudock departed Okinawa and reported to Commander, Fleet Air Mediterranean, Naples, Italy, where he served as staff Marine Aviation Maintenance Liaison Officer. While on the COMFAIRMED staff, he also served three months in 2005 as the Officer-in-Charge, Naval Air Mediterranean Repair Activity, Detachment Al Asad, in support of 2nd Marine Aircraft Wing and OIF operations.

Captain Hudock entered the Graduate School of Engineering and Management, Air Force Institute of Technology in August, 2005. Upon graduation, he will be assigned to Commanding General, Marine Corps Base Kaneohe Bay, Hawaii.

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14. ABSTRACT Surface coating operations at aircraft depot facilities are common throughout the Department of Defense (DoD). During paint application processes at Navy and Marine Corps Fleet Readiness Centers (FRCs), spray paints emit volatile organic compounds (VOCs) known to have harmful effects on human health and the environment. FRC East at Marine Corps Air Station Cherry Point, does not control the emissions of VOCs from any of its paint booths. The purpose of this research is to determine if FRC East and its surrounding area can benefit both economically and environmentally from a biofiltration system for air pollution control (APC) rather than the current conventional method of dry filtration. Dry filtration reduces only particulate matter in waste air streams and though there was no regulatory requirement to control VOC emissions at FRC East, the possibility exists that such legislation may be enacted in the future, affecting this facility and other similar DoD facilities. Three biofilters were designed for this study. The cost of each was analyzed using a net present value calculation and compared to potential monetary savings amongst the local population should VOC emissions from FRC East be controlled. Results show that FRC East and similar DoD facilities can benefit environmentally and economically from VOC control using biofiltration technologies.					
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