PROJECT FINAL TECHNICAL REPORT

Project Title: Biological Air Emissions Control for an Energy Efficient Forest Products Industry of the Future

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Project Background

The U.S. wood products industry is a leader in the production of innovative wood materials. New products are taking shape within a growth industry for fiberboard, plywood, particle board, and other natural material-based energy efficient building materials. However, at the same time, standards for clean air are becoming ever stricter. Emissions of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) during production of wood products (including methanol, formaldehyde, acetaldehyde, and mercaptans) must be tightly controlled.

Conventional VOC and HAP emission control techniques such as regenerative thermal oxidation (RTO) and regenerative catalytic oxidation (RCO) require significant amounts of energy and generate secondary pollutants such as nitrogen oxides and spent carbon. Biological treatment of air emissions offers a cost-effective and sustainable control technology for industrial facilities facing increasingly stringent air emission standards. A novel biological treatment system that integrates two types of biofilter systems, promises significant energy and cost savings. This novel system uses microorganisms to degrade air toxins without the use of natural gas as fuel or the creation of secondary pollutants.

The replacement of conventional thermal oxidizers with biofilters will yield natural gas savings alone in the range of \$82,500 to \$231,000 per year per unit. Widespread use of biofilters across the entire forest products industry could yield fuel savings up to 5.6 trillion Btu (British thermal units) per year and electricity savings of 2.1 trillion Btu per year. Biological treatment systems can also eliminate the production of NO_x, SO₂, and CO, and greatly reduce CO₂ emissions, when compared to conventional thermal oxidizers. Use of biofilters for VOC and HAP emission control will provide not only the wood products industry but also the pulp and paper industry with a means to cost-effectively control air emissions.

The goal of this project was to demonstrate the effectiveness of a novel sequential treatment technology that integrates two types of biofilter systems – biotrickling filtration and biofiltration – for controlling forest product facility air emissions with a water-

recycling feature for water conservation. This coupled design maximizes the conditions for microbial degradation of VOCs and odor causing compounds at specific locations. Water entering the biotrickling filter is collected in a sump, treated, and recycled back to the biotrickling filter. The biofilter serves as a polishing step to remove more complex organic compounds (i.e., terpenes).

Specific Project Objectives

The gaseous emissions from the hardboard mill presses at lumber plants such as that of the Stimson Lumber Company contain both volatile and condensable organic compounds (VOC and COC, respectively), as well as fine wood and other very small particulate material. In applying bio-oxidation technology to these emissions Texas A&M University-Kingsville (TAMUK) and Bio•Reaction (BRI) evaluated the potential of this equipment to resolve two (2) control issues which are critical to the industry:

- First, the hazardous air pollutant (HAP) emissions (primarily methanol and formaldehyde) and
- Second, the fine particulate and COC from the press exhaust which contribute to visual emissions (opacity) from the stack.

In a field test in 2006, the biological treatment technology met the HAP and COC control project objectives and demonstrated significantly lower energy use (than regenerative thermal oxidizers (RTOs) or regenerative catalytic oxidizers (RCOs), lower water use (than conventional scrubbers) all the while being less costly than either for maintenance. The project was successfully continued into 2007-2008 to assist the commercial partner in reducing unit size and footprint and cost, through added optimization of water recycle and improved biofilm activity, and demonstration of opacity removal capabilities.

Field Scale Unit Performance Testing – VOC Removal

The evaluation of the field scale biological treatment test evaluation for VOC emissions control for the unit at Stimson Lumber Company at Forest Grove, Oregon was completed in April 2006. The unit collected and treated emissions from the pressboard steam vents on the top of the plant building and delivered the emissions into the biological control

unit consisting of a biotrickling unit and a biomatrix-filled biofilter module in series, with air flow capacity of up to 10,000 cfm. This unit successfully treated air flow emissions ranging from approximately 3,500 to 1,500 cfm during the testing phases, and provided an EBRT (empty bed residence time) of only 45 seconds. Figure 1 is a photo of the field scale unit. FID gas measurements from the unit indicated high removals of total VOCs coming from the press with a reduction down to less than 5 ppm at the outlet of the biological system. EPA Method 9 evaluations of opacity reductions also met project objectives with routine outlet measurements from 0-5% opacity readings, which were in compliance with regulatory guidelines. A scale up of the biological treatment technology to handle all of Stimson's press vent emissions output of almost 75,000 cfm was determined to be feasible.

Emissions samples were also collected at different points in the biological system with the use of silica lined canisters. Significant removal of alpha-pinene and other aldehyde based emissions were measured in the canister samples. Figure 2 and Appendix A show example VOC removal characteristics.

Figure 1. Field scale sequential biotrickling filter – biofiltration unit at Stimson Lumber Company, Gaston, OR. The trickling unit on the right has three stages/sections of media with side access; the biofiltration unit on the left has two stages. Both units operated in an upflow mode.

Figure 2. Example results for biofiltration VOC press vent emission removal testing at Stimson Lumber Field Test, December 2005, showing cyclic loading typical of press emissions and wood products operations. Blue curve is inlet loading, orange is outlet concentration, green is mass removal percentage.

While this test demonstrated the success of the technology to achieve the VOC target objectives, the project team determined that improvements in the application of the technology to reduce the field scale unit size and capital cost, could also improve the marketing attractiveness for BRI to use in the replacement of other thermal oxidizers throughout the industry, causing additional energy savings. A lab scale biofiltration system at TAMUK was also upgraded to use syringe pump injection to introduce synthetic pollutants into the system, in this case, formaldehyde and α -pinene to improve the process modeling. The target objective was to optimize total VOC removal for scale up to a smaller footprint unit. Opacity emissions at the Stimson location were also planned for evaluation for the most optimal biofiltration configuration and operating strategy. A refereed publication describing the field test was submitted and published in the *Biochemical Engineering Journal* attached here as Appendix A. At this point in time, the U.S. DOE also developed a fact sheet for dissemination for the Industrial Technologies Program e-bulletin, describing the advances in the biological control technology in this project.

Pilot Scale Unit Opacity Removal Evaluation Results

A second field test targeting opacity removal of the biofiltration technology at the Stimson Lumber Forest Products plant in Gaston, Oregon was completed in August of 2008. The unit deployed also included both a biotrickling unit and a biofiltration section. A Wager 6500 transmissive light sensing opacity meter was successfully installed for measurement of the emissions opacity from the hardboard press vents at the Stimson plant for a pilot test designed to treat approximately 1,000 acfm of emissions. Figure 3 is a photo of the opacity measuring device that was installed on the outlet stack. The opacity measurements were collected and compared to visual measurements based on EPA Method 9. Inlet opacity exhibited cyclic loading as expected based the operation of the press vent system. Biofiltration outlet opacity exhibited significant reductions which were further optimized with trickling water recycle rates modifications and air volume throughput variations which further improved opacity and VOC reduction in the outlet stream.

Figure 3. Opacity meter setup for inline opacity measurement and evaluation

The overall unit performance was successful enough to confirm a decision by Stimson Lumber to install a field scale Biological Treatment unit including a larger bioscrubbing

section and a biofiltration unit as a digester to further eliminate VOCs in the outlet gas and liquid phases.

The relationship between measured opacity and VOC emissions removal was evaluated using an RAE Systems organic analyzer and checked by GC-FID. Canister air samples were also measured for VOCs using GC-MS analysis. The removal rates, removal efficiencies and opacity reductions during these experiments were analyzed to confirm optimal conditions and developed into several refereed journal articles for additional peer review.

Outcomes and research results from this project allowed the commercial partner to improve unit efficiency, and optimize materials and costs. Dr. James Boswell and Dr. Kim Jones of the project team also developed and completed a presentation to chemical industry groups on the biofiltration technology at the Texas Chemical Council's annual meeting on June 12, 2008 in Galveston, Texas. The technology was presented at a session highlighting energy saving technologies for industry. The project partners presented and participated in DOE ITP Peer Review meetings in Washington, D.C. in both 2006 and 2008, and in DOE project site visits to the Oregon location in 2005 and 2008.

Private Partner (BRI) Commercialization Progress

The first commercial unit installed in the wood products industry by BRI was to control the press emissions from an oriented strand board (OSB) press (Huber Engineered Wood) in southeastern Oklahoma. That unit, installed in April or 2003, continues in operation after almost 6 years, causing no down time for the production operation at the mill. Recent testing showed average VOC removals in excess of 75%. In December of 2007 a 160,000acfm unit was completed in the wood products industry (OSB press emissions control). Start-up was conducted in March and the unit was in full operation controlling the VOC and HAP emissions from an oriented strand board (OSB) press.

Wood Products Installations Completed in 2008

Temple-Inland – Thomson, GA.	90,000 ACFM	HAPs
Norbord – Bemidji, Minnesota	120,000 ACFM	HAPs
Norbord – Guntown, Mississippi	120,000 ACFM	HAPs
Freres Lumber – Mill City, OR.	50,000 ACFM	HAPs
Weyerhaeuser – Elkin, NC.	110,000 ACFM	HAPs
Roseburg -- Dillard, OR	110,000 ACFM	HAPs
ATC Panels – Franklin, VA.	150,000 ACFM	HAPs
Collins -- Klamath Falls, OR.	90,000 ACFM	HAPs
Humboldt Flakeboard – Arcata, CA.	255,000 ACFM	HAPs

These nine (9) units noted above all start-up in 2008. Using bio-oxidation systems (instead of RTOs) in the 12 units in the wood products industry will annually save an estimated 7,500,000 therms (750,000 MMBTU) of natural gas; \$70,000,000+; and eliminate the emissions of greater than 80,000 tons of CO₂; and more than 500 tons of NO_x.

Bio•Reaction continues bio-oxidation evaluations with a major automobile manufacturer for paint emissions abatement (one unit is on-line in Canada). The pilot applications in the auto industry are being conducted to determine the use on specific paint emission streams that use predominately water soluble solvents. In addition, odor removal applications are being assessed for HVAC plant air systems. Also, BRI is working with a Chinese company on the design and installation of two bio-oxidation units for HAP and odor control in China; has an agreement with a Taiwanese firm for biofilter application in Taiwan; and is partnering with a European company for applications in Europe.

Patents: None

Publications/Presentations

Santos, S., Jones, K., and Boswell, J. (2005) Biological Treatment of Air Emissions for Forest Product Industry Applications, presented at the *NSF sponsored CREST-RESSACA Conference on Emerging Technologies for a Sustainable Environment*, October 20-21, South Padre Island, Texas.

Jones, K. (2006) Biological Emissions Control, Biological Treatment of Air Emissions Promises Significant Energy and Cost Savings, Fact Sheet published by the *U.S. DOE EERE Information Center*.

Santos, S., Jones, K., Baliwala, L., Abdul, R., Boswell, J. and Cochran, J. (2006) Treatment of Wet Process Hardboard Plant Emissions by a Pilot Scale Biological System, published in the Proceedings of the *2006 USC-TRG Conference on Biofiltration for Air Pollution Control*, Long Beach, California, October 18-20.

Jones, K., Santos, S., Baliwala, L., Boswell, J. and Paca, J. (2006) Biological air emissions control for α -pinene and formaldehyde for a forest product industry application with a coupled biotrickling filter and biofilter system, in Proceedings of 17th International Congress of Chemical and Process Engineering CHISA 2006, Prague, Czech Republic, 27–31 August 2006.

Jones, K., Khilnani, M., Karre, A., Santos, S., Paca, J. (2007) FT-IR Characterization of Biofilms formed on Engineered Biofiltration Media Treating Volatile Organic Emissions for the Forest Products Industry, in *Biotechniques for Air Pollution Control*, Kennes, C. and Veiga, M., eds. Universidade da Coruña, ISBN 978-84-9749-258-4.

Santos, S., Jones, K., Abdul, R., Boswell, J., Paca, J. (2007) Treatment of Wet Process Hardboard Plant VOC Emissions by a Pilot Scale Biological System, *Biochemical Engineering Journal*, v37, n3: 261-270.

Jones, K. (2007) Saving Energy, Saving Earth, *FDM Asia*, v19, n3, April 2007.

Ramirez, D., Chavan, V., Santos, S., Jones, K. (2008) Relative Humidity and Temperature Effect on Solid Phase Micro Extraction for the Monitoring of Volatile Organic Compounds, presented at the *101st Annual Meeting of the Air & Waste Management Association*, June 24-27, Portland, OR.

Milestone Status Table:

ID	Tasks/Milestones				
No.		Planned Completion	Actual Completion	Comments	
1.	Bench Scale and Field Scale Unit Design	12/31/04	12/31/04		
2.	Field Pilot Unit Construction	6/30/05	8/15/05		
3.	Field Pilot Unit Startup	7/31/05	8/15/05		
4.	Preliminary Pilot Scale Testing and Field Testing Plan Development	10/1/05	8/15/05		
5.	Optimization of Biotrickling Filter	12/31/05	3/15/06	Field unit 1	
6.	Optimization of Biofilter Section	12/31/05	3/15/06	Field unit 1	
7.	Develop process models	2/28/06	8/31/08		
8.	Optimize water reuse	2/28/06	8/31/08	Pilot unit 2	
9.	Characterize biofilms	2/28/06	8/31/08	Pilot unit 2	
10.	BF Tech Product marketing	8/31/08	2/28/09		
11.	Final Report Phase I Publication	9/1/06	11/1/07	Published BCEJ	
12.	Optimization of BTF	8/31/08	12/31/08	Pilot unit 2	
13.	Optimization of BF	8/31/08	12/31/08	Pilot unit 2	
14.	Final Report Phase II Publication	9/1/08	5/28/09		

Final Budget Data:

Texas A&M University – Kingsville Award DE-FC36-04GO14310 Project Spending and Estimate of Future Spending							
Quarter	From	To	Estimated Federal Share of Outlays*	Actual Federal Share of Outlays	Estimated Recipient Share of Outlays*	Actual Recipient Share of Outlays**	Cumulative
	Start		Note 1		Note 1		
3Q04	9/1/04	9/30/04	0	0	0	0	
4Q04	10/1/04	12/31/04	4,642	4,642	2,000	2,000	
1Q05	1/1/05	3/31/05	3,922	3,922	3,500	3,500	
2Q05	4/1/05	6/30/05	18,955	18,955	15,000	15,000	
3Q05	7/31/05	9/30/05	25,649	25,649	20,000	20,000	
4Q05	10/1/05	12/31/05	26,670	26,670	57,265	57,265	
1Q06	1/1/06	3/31/06	94,944	94,944	57,981	57,981	
2Q06	4/1/06	6/30/06	15,892	15,892			
3Q06	7/31/06	9/30/06	1,983	1,983			
4Q06	10/1/06	12/31/06	16,497	16,497			
1Q07	1/1/07	3/31/07	14,988	14,988			
2Q07	4/1/07	6/30/07	13,611	13,611			
3Q07	7/1/07	9/30/07	11,232	11,232			
4Q07	10/1/07	12/31/07	10,017	10,017			
1Q08	1/1/08	3/31/08	9,511	9,511	3,500	3,500	
2Q08	4/1/08	6/30/08	8,622	8,622	1,372	1,372	
3Q08	7/1/08	9/30/08	34,645	34,645	20,000	20,000	
4Q08	10/1/08	12/31/08	11,583	11,583			
1Q09	1/1/09	2/28/09	19,337	19,084			
Totals			342,700	342,447	180,618	180,618	

Federal Share = \$192,729 (9/1/04-8/31/06) + \$149,971(9/1/06-8/31/08)

* Update quarterly

**Estimated for 2006

General Note: DOE Laboratory partner spending should not be included in the above table. If a DOE Laboratory is a partner, report their spending and spend plan information in the table below (use separate tables if multiple DOE Laboratories are involved).

General Note: The information in this table should be consistent with the information provided in section 10 of the quarterly financial status reports (SF269 or SF269A).

Note 1: Leave blank. Only the actual DOE/Cost Share amounts spent through 6/30/04 are needed.

Note 2: Amount for this quarter and subsequent quarters should be updated as necessary on a quarterly basis. Estimates need to be provided for the entire project. If spending for a given quarter is different than estimated, then the remaining quarter's estimates should be updated to account for the difference. Total DOE and Cost Share amounts should be the same as the Award amount.

Appendix A. Publication in Biochemical Engineering Journal documenting VOC removal characteristics of the biotreatment system

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Treatment of wet process hardboard plant VOC emissions by a pilot scale biological system

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Abstract

A pilot scale biological treatment system for air emissions was installed and tested at a forest products plant in western Oregon, USA, which collected and treated gaseous emissions from the hardboard steam press vents on the top of the plant building. This system was installed mainly to demonstrate the effectiveness of biological treatment technologies in removing volatile organic compounds (VOC) and hazardous air pollutants (HAP) from the wet-process hardboard press emissions, and to test the efficiency of the system on fine particles and condensable organics with the presence of a pre-treatment wet dust collector. The bio-oxidation system was comprised of a particle pre-treatment unit Type W Rotoclone (wet hydrocyclone), a biotrickling filter and a biofilter with airflow capacity of up to 4.72 m³/s. This unit operated at approximately 0.71 m³/s, which is the optimal flow required for the Rotoclone's throughput, and provided an EBCT (empty bed contact time) of 45 s. Analysis of total VOC measurements from the system indicated removals down to less than 5 ppm in the effluent emissions. Evaluations of opacity reductions also met project objectives with routine outlet measurements of 0–5%, which are in compliance with state regulatory guidelines. Emissions air samples were collected at different locations in the biological system for GC–MS analysis and characterization to identify specific VOCs and their removals.

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Keywords: Biofiltration; VOC removal; Air pollution control; Forest products emissions

1. Introduction

1.1. Background

The forest products industry encompasses a vast number of wood processing companies, which can utilize large amounts of energy during product manufacturing and sometimes in emissions control applications. The forest products sector includes logging, sawmills and planing mills, softwood veneer and plywood mills, hardboard veneer and plywood mills, particleboard, oriented strand board (OSB), other reconstituted wood products mills and pulp and paper mills [1,2]. The production from these types of panel board production facilities includes a combination of dry and wet processes, which produce air emissions, including fugitive emissions, which may amount to several thousand tonnes of VOCs and HAPs per year potentially released into the atmosphere [3].

All facilities in this industry sector release mixtures of air pollutants consisting of VOCs, carbon monoxide (CO), nitrogen oxides (NO_x), HAPs and particulate matter (PM) to the atmosphere. Small quantities of air emission contaminants are emitted from the wood itself, with a large portion originating from the petroleum and biomass fuels powering the equipment. Higher emissions of these pollutants typically occur in the hot process equipment such as boilers, refiners, conveyers, driers, kilns and presses [4]. In most of the process equipment, the VOCs, HAPs and PM come directly from the moist wood and wood fibers when the temperature is raised, evaporating water and volatilizing these pollutants. The remainder of the pollution is emitted in the same process equipment, but due to the addition of resins, waxes, glues, and solvents from coatings and finishing operations [2–4].

Typically, the main contaminants from the wood product industries are α -pinene and β -pinene, formaldehyde, methanol, other aldehydes, ketones, hydroxyl groups, other terpenes and non-terpene acids such as formic, propionic and acetic acid and various other hydrocarbons [2,3,5]. According to the toxic

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release inventory (TRI) from EPA, the major chemical releases in the lumber and wood products industry include, acetone, ammonia, creosote, formaldehyde, methanol, methyl ethyl ketone, methyl isobutyl ketone, phenol, toluene and xylenes [6]. When condensed and blended with wood dust and PM, a number of these VOCs and hydrocarbons, produce aerosols, creating visible emissions commonly known as blue haze, which can be a major cause of opacity problems. The variability of VOCs and HAPs emissions can be large due to changes in raw material, its moisture content and temperature and alterations in the amount of resins, waxes, glues, and solvents added during the product fabricating process [3,4]. Many forest products facilities are being required to more tightly control the criteria pollutant emissions and apply MACT (maximum available control technology) to reduce HAPs. Thermal oxidizers can meet MACT standards as a control technology and have been implemented at several plants; however, these installations can come at a high operating cost, as significant amounts of natural gas must be used to efficiently combust even small amounts of VOC emissions. In contrast, biological treatment systems for air emissions control do not require natural gas fuel and yet can oxidize pollutants to carbon dioxide and water. The challenges for these systems include overcoming large footprints, with sufficient media and the associated capital costs that are necessary to adequately control the VOC and HAP emissions.

1.2. Biological air treatment systems

This large industry sector is required by EPA through BACT (best available control technology) and MACT standards to reduce VOC and HAP emissions from their plants, making these companies potential clients for the application of biological air treatment systems. Biofiltration systems represent low cost and operationally simple options for the treatment of VOCs in the wood products industry sector [7]. Effective pollutant reduction through the use of air emissions-controlling biological systems cannot only reduce operational costs, but provide a large benefit to the energy sector of the nation (by reducing natural gas consumption within this industry) through the market expansion of such an effective and energy efficient pollution abatement technology [8–10].

Since the first step to biofiltration is the transfer of pollutants (VOCs in this case) from air to water or biofilm, soluble compounds are more easily and rapidly removed in both biofilters and biotrickling filters than non-soluble compounds [11,12]. Alcohols (e.g., methanol), aldehydes (e.g., formaldehyde), weak acids and low C-chained hydrocarbons are examples of these hydrophilic compounds, which should degrade readily in biofiltration systems [13]. Other non-soluble compounds such as α -pinene and other terpenes and higher C-chained hydrocarbons, are hydrophobic and consequently harder to degrade in bioreactors [7,9,13,14]. Many lab scale biological systems have been successfully tested for treatment of contaminated streams with compounds such as toluene, xylenes, α -pinene, methanol and formaldehyde as well as with combinations of these pollutants, which can create interactions causing inhibition or competition [7,11–13,15,16]. However, these synthetic

combinations cannot totally resemble the complex contaminant mixtures emitted from actual wood products facilities.

1.3. Objectives

The primary objective of this study was to demonstrate the efficacy of an engineered biological treatment system for forest products VOC control, through the use of a pilot-scale bio-oxidation system with new media providing more air to biofilm contact area, and structured components, which eliminates the classic biofilter problems of compaction and bed collapse. A secondary objective of this project was the evaluation of the pilot scale biofiltration system to reduce the visual emissions known in the wood products industry as blue haze represented by opacity measurements.

2. Materials and methods

2.1. Stimson Lumber Company hardboard plant

Stimson Lumber Company, a private forest products and natural resource company located in the vicinity of the city of Gaston, Oregon, USA, emits low concentrations of VOCs and HAPs into the atmosphere from the plant's wet hardboard making process through the main ventilation system. Pulling in high volumes of air, the vent located directly above the steam press produces VOCs and HAPs emissions from the compressed, drying hardboard panels, which can be very dilute, especially when the variable press operations and press cycles are considered [17]. Press vent emissions from the hardboard plant do produce highly variable concentrations of VOCs and HAPs, which may create a visible plume commonly known as blue haze, the main cause of opacity issues at many facilities within this industrial sector. Low pollutant concentration emissions, especially when visible, are required by the United States EPA to be reduced by at least 90% [4].

2.2. Pilot scale biofiltration system

The pilot scale biofiltration system was a sequential treatment system, which collected and treated part of the emissions from the partially enclosed press as they exited the top of the plant building. The bio-oxidation system consisted of a wet particle removal pre-treatment unit type-W Rotoclone, a biotrickling filter and a biofilter with an air flow capacity of up to 4.72 m³/s. Fig. 1 is a schematic diagram of the pilot scale biofiltration system located at the Stimson Lumber Hardboard mill in 2005–2006.

The main purpose of the Rotoclone was to remove particles and reduce water volume in the inlet stream prior to entering the biotrickling unit. This unit operated as a wet scrubber similar to a hydrocyclone targeting large particle removal, usually >50 μ m. The biotrickling filter (BTF) was comprised of two beds of plastic CF-1900 cross-flow media from Brentwood Industries, Inc. with bed dimensions of 2.44 m $\times$ 3.05 m $\times$ 1.22 m. Two biotrickling filter beds were used for parallel treatment and then manifolded together to enter

Fig. 1. Schematic diagram of the pilot scale biofiltration system which treated press emissions at Stimson Lumber Co. at Gaston, OR.

the biofilter. The biofilter (BF) also had two media beds but with dimensions of $2.44 \text{ m} \times 3.05 \text{ m} \times 0.76 \text{ m}$. The BF media beds were comprised of engineered media of organic substrate formed around inorganic support material (manufactured by BioReaction Industries as BioAIRSpheres®) and connected in series. The uniform-shape engineered media were $2.54 \times 10^{-2} \text{ m}$ hollow polyethylene spherical structures packed with organic, nutrient-providing, compost-based media. Both units, the BTF and BF, shared a water sump with volume of nearly 5.66 m^3 . This biological system generally operated at approximately $0.71 \text{ m}^3/\text{s}$, which was the optimal flow required for the Rotocclone, and provided an EBCT (empty bed contact time) of 45 s for the bio-oxidation system. The water recirculation rate for the BTF was set to $6.562 \text{ lpm}/\text{m}^2$. The BF did not require additional humidification, since the air stream passing through the unit was saturated and maintained media moisture content of approximately 55% by weight.

2.3. Start-up and acclimation

The pilot scale biofiltration system installed at the Stimson Lumber Hardboard Plant was in operation from mid-August

2005 until early March of 2006. Since initially both media did not have developed bacterial growth, inoculation of the biological system was implemented. An innoculum of 38 l of water from the on-site, water treatment ponds of the timber section of the company was collected and added to the system's water sump. Since the inoculation of the system was completed with the indigenous water, the bacterial growth in the system resulted in a diverse microbial community. Primary acclimation of the BTF and the BF occurred during the first 60 days of the period of evaluation period.

2.4. Sample data collection

System air emission samples, daily water samples, and temperature data were collected to measure various parameters of the pilot scale biological system for air pollutants and water quality monitoring of the water sump. Total dissolved solids and (TDS) and pH were measured with an Orion Model 125 salinity and TDS measurement probe and an Orion Model 520-A pH meter. In addition, the water nutrient quality of the system's sump was periodically tested and analyzed for nitrates, sulfates and chemical oxygen demand (COD). These analyses

were completed using a HACH instrument using Test Numbers 355, 680 and 435 for nitrate, sulfate and COD, respectively. Permachem[®] powder pillows were used for nitrate and sulfate testing. Test'N[®] tube vials were used to measure COD content in the sump water samples. Other water quality parameters: TDS, TSS, VS, totals solids, fixed solids were obtained following procedures in standard methods for water and wastewater treatment [18].

2.5. Instrumentation

Other instruments used during the evaluation of the pilot scale biological system were a gas chromatograph equipped with a flame ionization detector (FID) and a gas chromatograph/mass spectrometer (GC–MS). Characterization of organic compounds with molecular weight larger than 28 was accomplished with the Agilent 6890 Series II GC–MS. The protocol utilized for this analysis was method TO-15 from EPA with the use of SUMMA[®] silica lined canisters. The GC-FID utilized for these experiments was a 20/2 Model FID from VIG Industries, Inc. and was connected in-line at the investigation site. The calibration gas used for the GC-FID testing was propane.

2.6. Sample analysis

Emission samples were collected at the system inlet (rotoclone inlet), rotoclone outlet (BF inlet), BF outlet (BTF inlet) and the BTF outlet (system outlet) of the biological system to determine specific performances of each system component using the GC-FID and GC–MS. GC-FID field testing provided a method for total volatile organic compounds analysis calibrated on a propane basis. From emission samples, each component of the biofiltration system was analyzed for individual unit removal efficiency as well as for the complete system. Initially, water impinger samples were also analyzed in the GC-FID, but due to the low VOC concentrations, results from these tests suggested that continued impinger sampling would be unsuccessful, and they were discontinued after collection and analysis of the initial sets. Method TO-15 from EPA was used for the determination of VOCs in the collected air samples. This EPA method verifies procedures for sampling and analysis for measurement of VOCs that are included in the HAPs list in Title III of the Clean Air Act Amendments of 1990 [19]. GC–MS analysis from the TO-15 method provided quantitative and qualitative analysis for some organic compounds. For other complex compounds not found in the TO-15 standards, qualitative analysis was performed based on peak areas of the individual compounds. This GC–MS characterization of the organic compounds in the emissions stream provided partial identification of VOCs, which could contribute to the opacity and provided insight into fluctuations in treatment of emissions associated with process variables and press operations.

2.7. Visual emissions measurements

Emissions from the biofiltration system outlet stack were visually inspected on a daily basis by certified opacity readers by

using EPA Method 9. Method 9 by EPA entails the determination of plume opacity by qualified observers [20]. This method includes training procedures for certification of observers as well as field procedures for determining plume opacity. These observations were recorded as ranges of readings, since variability of loadings from the press cycles, human error and daily ambient conditions such as luminescence and color contrast between plume and background can create some uncertainty in these observations.

3. Results and discussions

3.1. FID test results

During the period of operation of the pilot scale biofiltration system at the Stimson Lumber Hardboard Plant of August 2005–March 2006, four separate GC-FID total VOCs testing periods were implemented in the field providing total hydrocarbon concentration measurements and inlet and outlet concentrations. GC-FID testing periods were conducted on 8 September 2005, 1 December 2005, 19 December 2005 and 17 January 2006. GC-FID readings were recorded as 10-s averages over a period of at least 5 h during the test days. The amount of independent GC-FID data measurements collected ranged from 120 to 890 data points. Averages of these measurements are presented in Fig. 2 below including a standard deviation of the data based on a 95% confidence interval.

Accounting for the volumes of media for both the BTF and BF, the inlet VOC loadings to the complete pilot scale biofiltration system ranged from 0.725 to 1.81 g propane/h m³ media. This VOC inlet loading was lower than expected; however, the fluctuating VOC feed rate from the wet press was captured in the test data. This is an example of the actual dynamic loading experienced in field biofiltration applications, which can sometimes adversely affect overall removal efficiencies.

From Fig. 2, it can be observed that the inlet VOC loadings did fluctuate, varying from 6 to 15 ppm (as propane), with an approximate average value of 10 ppm. Over time, total VOC removals by the pilot scale biofiltration system slowly increased in efficiency during the testing period of the system. Over 4 months, the average removal efficiency (RE) increased from 42 to 83%. For this installation, the forest products plant had to consistently meet emission standards compliance for VOC discharge of less than 10 ppm for the wet press. The VOC emissions concentrations measured in the split stream from the stack-averaged 10 ppm with fluctuations ranging from low of 6 ppm to a high of 15 ppm. Thus, some control is going to be needed for some level of VOC removal as well as flexibility in operations and margin of safety. Expensive options such as regenerative thermal oxidizers (RTOs) and regenerative catalytic oxidizers (RCOs), which require excessive quantities of supplemental fuel for low VOC concentration control, are not cost effective options for many plants. Even though there were only four GC-FID tests, the testing results produced similar influent and effluent concentrations, which were changing gradually and demonstrated slow improvement on the removal efficiency over time. The overall level of influent VOCs, which were lower and more variable

Fig. 2. Inlet and outlet GC-FID tests results (as propane) for total VOC removals of the pilot scale biofiltration system at Stimson Lumber Co. in Gaston, OR.

than in some other biofiltration applications, may have inhibited the efficiency of the biofilm. While the RE during the acclimation period was lower than expected, the low VOC substrate concentration and the continuous addition of excess fresh water condensate from the wet press probably created less than optimal conditions for maintaining an adequate level of VOC degraders in both the trickling and biofilter units. The start-up efficiency might be improved with more concentrated VOC influents collected from refiners and dryers if possible, and/or improved fresh water knockout upfront of the biofilters to allow accumulation of a more concentrated level of suspended solids in the filter water sumps. Furthermore, due to the inorganic nature of the BTF media, nutrient addition to the trickling filter might also improve removal efficiency; this was not done during the field-testing.

3.2. Characterization of VOCs by GC–MS

GC–MS techniques were utilized to further characterize the compounds that comprised the input loading into the pilot scale biofiltration system. Simultaneous sampling and duplicate sampling were completed to validate the sampling method with vacuumed canisters. Sampling results showed average concentrations varying by less than 5% from replicate samples. The compound libraries of the GC–MS TO-15 method provided qualitative and quantitative information for many of the compounds found in the press emissions of the hardboard plant. The most commonly found GC–MS TO-15 compounds detected in the inlet stream of the biological system included ethane, propane, propylene, 1-butene, butane, *cis*-2-butene, *trans*-2-

butene, isobutene, *n*-pentane, 1-pentene, pentane and hexane. The GC–MS was also useful in characterizing other compounds not present in the TO-15 standard method. These compounds were analyzed on the basis of chromatograph peak areas. The major compounds identified with peak area analysis were acetaldehyde, acetone, ethanol, butanal, propanal, acetamide, α -pinene and pentanol. These compounds, along with the TO-15 compound standards appeared most frequently and significantly in the majority of the samples collected during the evaluation period of the pilot scale biofiltration system. In addition, extremely volatile VOCs such as methanol and formaldehyde were present in this pilot test. Impinger sampling was used to test for methanol and formaldehyde; however, the impingers probably were not very efficient in capturing these volatiles at such low concentrations and intermittent press cycles. From the analysis of a few impinger samples, it was estimated that the methanol and formaldehyde concentrations were sometimes less 1 than ppm_v for both compounds. These volatiles were not the target of the GC–MS analysis, but were measured in the liquid samples with the impingers. The GC–MS sampling detected other aldehydes and alcohols that were also significant. The difference between the total VOC measurements and the GC–MS detected compounds is expected to be representative of the highly volatile compounds, which are difficult to capture in liquid and gas samples.

3.2.1. Individual component efficiency of the system

Since GC–MS samples were taken at the inlet and outlet of each unit component of the biological system to evaluate individ-

Fig. 3. Individual unit performance of the pilot scale biofiltration system for the removals of GC–MS TO-15 compounds on 6 March 2006.

ual unit performances were estimated for the main compounds analyzed with this instrument. On 6 March 2006, the GC–MS TO-15 method compounds used to evaluate individual unit performance were butane, *n*-pentane, 1-butene, *trans*-2-butene, isobutene and 1-pentene. The pollutant inlet concentrations for compounds found by EPA TO-15 method with the GC–MS were found to be very small, in the range of ppb_v. The average inlet concentrations for butane, *n*-pentane, 1-butene, *trans*-2-butene, isobutene and 1-pentene were 140, 6, 25, 15, 40 and 5 ppb_v, respectively. Fig. 3 below illustrates the individual unit performance of the pilot scale system based on the particular unit's inlet and outlet concentrations and in accordance to detected TO-15 method compounds. In addition, unit and total cumulative removal efficiencies were calculated for each system component.

From Fig. 3, it is shown that the biofilter unit was the most effective section of the system for removal of butane, *n*-pentane, 1-butene, *trans*-2-butene and isobutene. The removal efficiency of this particular unit for these compounds ranged from approximately 70 to 80%. However, the effective or cumulative removals of the inlet loadings in the biofilter varied from 35 to 62%. The effective removals are based on the total input to the system and the removal efficiency of each section is based only on the inlet to that unit. The individual performance of the Rotocclone and the biotrickling filter for the same compounds ranged from 3 to 37% and 8 to 38%, respectively. The removals in the rotocclone constituted removals of 3–37% of the total input loading and in the biotrickling filter 8–25%. In the case of 1-pentene, the first two units, rotocclone and BTF, eliminated the majority of the compound. The concentration of 1-pentene was very low

causing some uncertainty in the measurement and most of this compound was apparently removed in the BTF. The complete pilot scale biofiltration system had overall removal efficiency for these six TO-15 compounds of 75–90%.

During the same GC–MS analysis for the sample collected on 6 March 2006, the other compounds detected with peak area analysis for individual unit performance were ethanol, acetaldehyde, acetone, butanal, and α -pinene. The pollutant inlet concentrations for compounds not quantified by EPA TO-15 method with the GC–MS were found to be more significant. The estimated inlet concentrations for ethanol, acetaldehyde, acetone and butanal were 50, 760, 140, and 4 ppb_v as propane, respectively. The estimated inlet concentration for α -pinene was the most significant being approximately 6.75 ppm_v as propane. Fig. 4 illustrates the individual unit performance of the pilot scale system based on the commonly found compounds analyzed with chromatograph peak areas.

From Fig. 4, it is evident that the biofilter unit was the most effective unit of the system for removal of α -pinene. The α -pinene removal efficiency of this unit was approximately 75%. The effective removals of total inlet loadings in the biofilter were 20% for ethanol (most of this compound was removed in the trickling unit) and 61% for α -pinene. The individual performance of the Rotocclone was roughly 10% for ethanol and α -pinene, in that same order. The removal efficiency of ethanol and α -pinene in the biotrickling unit was 66 and 6%, respectively. The removals in the Rotocclone for ethanol and α -pinene constituted roughly 10% of the total input loading in both cases. The BTF's efficiency represented removals of 60 and 5% for ethanol and α -pinene, respectively. In the case of acetalde-

Fig. 4. Individual unit performance of the pilot scale biofiltration system based on peak area analysis for the removals of other organic compounds in press vent emissions on 6 March 2006.

hyde and acetone, the biofilter had a smaller contribution to the removal of these compounds. The BF's removal efficiency of acetaldehyde was 23% and that for acetone was 0% (again most of this volatile compound had been removed prior to the BF). The BF's contribution to the removal of acetaldehyde was 15% of the input loading. The Rotoclone's and BTF's removal efficiency of acetaldehyde and acetone was more significant than that of the BF. The BTF removed 18% of the acetaldehyde and 9% of the acetone of the inlet stream; the BTF's removal efficiency was 24% for acetaldehyde and 81% for acetone. The Rotoclone's performance was 13% for these compounds. Butanal concentration in the inlet stream was also very low, and the measurements less reliable. This concentration may have been low enough to be captured in the Rotoclone by itself; consequently, the other components could not be removed in the following units. With the exception of butanal removals, the complete pilot scale biofiltration system had an overall removal efficiency ranging from 60 to 98%. Our analyses support the concept that the more soluble compounds are removed in the trickling filter and Rotoclone, while high chain hydrocarbons and other hydrophobic compounds were more amenable to treatment within the biofilter section [13].

3.3. Variability of emissions

The total production of hardboard at Stimson Lumber is variable depending on supply and demand. The manufacturing of different hardboard products can differ in press cycle duration, quantity and variability of raw materials and the addition of

binding agents such as resins and oil-based waxes. The wet press emissions can be directly affected by the product made and the time of the year in which they were manufactured. Thicker products take longer compressing times; therefore, press cycle periodicity for these goods was larger than that of thinner products [17]. Fig. 5 illustrates the variability of the Total VOC concentrations in the press emissions entering the pilot scale biofiltration system during a GC-FID test event on 19 January 2006. From this figure, it is clear that the inlet loadings into the biological system followed a cyclic pattern; however, the inlet loading concentrations represented by the cycles in this figure were dissimilar probably due to slight variations of raw material composition of the hardboard product in each cycle. The frequency and duration of the press cycles and the temperature at which they operated differed with the product thickness, which can create some variability in emissions. The emissions variability, according to plant personnel, is driven primarily the press cycle operation and by the wood product type, which is typically from one source. While visual emissions (opacity) may be affected by some conditions in ambient air causing more condensation near the outlet, but this is not proven. During the pilot testing no change in product feedstock supply occurred or is expected in the future.

In spite of the irregularity and fluctuation of the press vent emissions from the wet-process hardboard plant, the pilot scale biofiltration system successfully dampened the irregularities and kept the Total VOC emissions below 5 ppm (as propane). Additionally, the complete biological system was not affected by short or long duration temporary press shut downs during repairs and

Fig. 5. GC-FID propane based total VOC results for event 19 January 2006 describing inlet loading cyclic behavior of press vent emissions at the hardboard plant.

maintenance checks. Removal efficiency of the pilot scale system was not significantly influenced by a 12-day maintenance shutdown in December 2005, as indicated in the data collected during the 17 January 2006 sampling, although some additional acclimation periods could have been missed between sampling events.

For this installation, the plant is being tasked to consistently meet emission standards for VOC discharge of less than 10 ppm for the wet press. The VOC emissions concentrations measured in the split stream from the stack-averaged 10 ppm with fluctuations ranging from low of 6 ppm to a high of 15 ppm. Thus, some control is going to be needed for some level of VOC removal. Expensive options such as RTOs and RCOs which require excessive quantities of supplemental fuel for low VOC concentration control are not cost effective options for many plants.

3.4. Biofiltration system water quality

Water discharge and water quality were monitored during the study period of the pilot scale biofiltration system by monitoring parameters such as TS, TDS, TSS, VS, and fixed solids. Fig. 6 illustrates historical TS data as an indicator of these parameters linked to water discharge by the pilot scale biofiltration system. This graph displays high initial values for TS, which was similar to other solids measurement levels at the beginning of the tests, since inoculation of the media was implemented by the addition of water from the treatment ponds of the hardboard plant. Water sumps for all three units (Rotoclone, BF and BTF) were all connected. The Rotoclone discharge water was

sent back to the biofilter sump for reuse. Any VOCs removed by the Rotoclone discharge water were put back into the system, since one target was to minimize wastewater discharge if possible. The highest values were recorded at the beginning of September 2005 when a second inoculation event was administered and the TS, VS and fixed solids measured 1700 mg/l, 1140 mg/l, and 560 mg/l, respectively. At this time, the measured values for TSS and TDS were 170 mg/l and 1530 mg/l, respectively. VOC concentration in the water sump was not measured. COD concentration in the water sump was measured over time. COD concentrations in the water sump also followed the same trend as TS, TDS, TSS and fixed solids. At the beginning of the study, the COD concentration was approximately 2500 mg/l and by the end of this study it decreased to approximately 160 mg/l.

In this figure, the water quality of the sump water for the biological system can be seen to improve over time. Also, the amount of water discharged from this system increased over time. Since the hardboard manufacturing uses a wet press, emissions from the press were highly saturated. The improvement of the water quality occurred due to increased dilution of the sump water from the condensed inlet steam.

3.5. Visual emissions reduction

Visual emissions evaluations of the outlet stack of the pilot scale biofiltration system at Stimson Lumber Company were made almost daily during the period of study. Originally, the Rotoclone was brought in to improve particulate removal, potentially improve opacity and protect the biological treatment units

Fig. 6. TS measurements as water quality indicator and water discharge for the sump water of the pilot scale biofiltration system for the period of August 2005–February 2006.

from the formation of layers of particulate matter. However, it was undetermined which segment of the process treatment train was most effective in reducing opacity emissions. Previous to the installation of this biological system, the usual opacity measurement of the emissions air stream from the press vent of the hardboard plant was approximately 20%. After the installation of the complete biological system, the opacity of the system was reduced. Outlet stack visual emission levels from a certified opacity reader were always reported to be in the range of 0–5% during the testing periods.

4. Conclusions

In conclusion, the pilot scale biofiltration system operated at the Stimson Lumber wet-process hardboard mill demonstrated the successful removals of a variety of organic compounds that comprised the highly variable, but low concentration press vent emissions. The following specific conclusions were reached:

- The biological system, as a whole, was an effective pollution control technology for the removals of HAPs and VOCs. As demonstrated by the GC-FID and the GC-MS test results, the pilot scale biofiltration system was able to remove both hydrophobic and hydrophilic organic compounds to meet MACT standards for this application.
- The biological system was an effective air emissions control technology for the removal of a highly variable concentration

of HAPs and VOCs, as well as providing control for intermittent input loadings of these compounds. GC-FID and the GC-MS test results verified that the biological system, in fact, handled and treated with efficacy variable input loadings of numerous organic compounds resulting from differences in emissions from the press cycles.

- The complete biological system was not apparently affected by short or long temporary press shut downs during repairs and maintenance checks. Removal efficiency of the pilot scale system was not influenced by a 12-day temporary shutdown in December 2005, as measured a week after restart of the wet press. Some re-acclimation may have occurred during the week prior to measurement.
- The sump water of the pilot scale biofiltration system did not require the addition of freshwater to maintain a healthy water quality, due to the constant addition of water into the water sump from direct condensation of the water-saturated polluted stream, particularly in colder weather.

The efficiency of this biological system could be further improved by a longer investigation period of the pilot scale biofiltration system to fine-tune the BTF and BF, as well as to test different parameter settings such as water recycle rate, variable water quality and nutrients addition, nutrient concentrations, and EBCT. Also, a second phase of testing is planned with a smoke detector/opacity meter affixed to just the BTF and BF units without the Rotocloner to evaluate its effectiveness on opacity removal.

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References

- [1] Canadian Forest Sector Table National Climate Change Secretariat, Wood Products Energy Use and GHG Emission Reduction Opportunities, Final Draft Report, 1999.
- [2] U.S. EPA, The Pulp and Paper Industry, the Pulping Process, and Pollutant Releases to the Environment, (1997) Publication EPA-821-F-97-011.
- [3] T. Jiang, J.D. Gardner, M.G.D. Baumann, Volatile organic compound emissions arising from the hot-pressing of mixed-hardwood particleboard, *For. Prod. J.* 52 (2002) 66–77.
- [4] M.R. Milota, Emissions from wood drying: the science and the issues, *For. Prod. J.* 50 (6) (2000) 10–20.
- [5] V. Punsuvon, Identification of volatile materials emitted during drying of southern pine lumber, Ph.D. Thesis, Mississippi State University, MS, 1994, 128 pp.
- [6] Profile of the Lumber and Wood Products Industry, U.S. Environmental Protection Agency, Office of Compliance Sector, D.C., EPA/310-R-95/006, 1995.
- [7] Y. Jin, M.C. Veiga, C. Kennes, Performance optimization of the fungal biodegradation of α -pinene in gas-phase biofilter, *Process Biochem.* 41 (2006) 1722–1728.
- [8] Boswell, Jim, Understanding the capabilities of bio-oxidation, *Chem. Eng. Prog.* 98 (2002) 48–53.
- [9] J.S. Devinny, M.A. Deshusses, T.A. Webster, *Biofiltration for Air Pollution Control*, Lewis Publishers, Boca-Raton, FL, 1999.
- [10] M.A. Deshusses, Biological waste air treatment in biofilters, *Curr. Opin. Biotechnol.* 8 (1997) 335–339.
- [11] L. Malhautier, N. Khammar, S. Bayle, J. Fanlo, Biofiltration of volatile organic compounds, *Appl. Microbiol. Biotechnol.* 68 (2005) 16–22.
- [12] M.J. Miller, D.G. Allen, Modelling transport and degradation of hydrophobic pollutants in biofilter biofilms, *Chem. Eng. J.* 113 (2005) 197–204.
- [13] M. Mohseni, G.D. Allen, Biofiltration of mixtures of hydrophilic and hydrophobic volatile organic compounds, *Chem. Eng. Sci.* 55 (2000) 1545–1558.
- [14] V.J.W. Groenestijn, J.X. Liu, Removal of α -pinene from gases using biofilters containing fungi, *Atmos. Environ.* 36 (2002) 5501–5508.
- [15] M.R. Manninen, B.A. Niemi, G.T. Kleinheinz, Use of a coupled biological system to treat a chemically complex air stream, *Arch. Environ. Contam. Toxicol.* 45 (2003) 1–10.
- [16] M.C. Delhomenie, M. Heitz, Biofiltration of air: a review, *Chem. Eng. Sci.* 59 (2004) 3515–3525.
- [17] C.B. Dirk-Faitakis, D.G. Allen, Biofiltration of cyclic air emissions of α -pinene at low and high frequencies, *J. Air Waste Manage. Assoc.* 53 (2003) 1373–1383.
- [18] L.S. Clesceri, A.E. Greenberg, A.D. Eaton, *Standard Methods for Examination of Water and Wastewater*, American Public Health Association, Washington, D.C., 1999.
- [19] Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air: Method TO-15, 2nd ed., U.S. Environmental Protection Agency, Midwest Research Institute, OH, EPA/625/R-96/010b, 1999.
- [20] Visual Determination of the Opacity of Emissions from Stationary Sources: Method 9, U.S. Environmental Protection Agency, Emission Measurement Branch, EMTIC TM-009, 1990.

Appendix B. Project Final Financial Status Report

FINANCIAL STATUS REPORT

(Long Form)

(Follow instructions on the back)

1. Federal Agency and Organizational Element to Which Report is Submitted U.S. Department of Energy		2. Federal Grant or Other Identifying Number Assigned By Federal Agency DE-FC-36-04G014310		OMB Approval No. 0348-0039	Page of 1 1 pages
3. Recipient Organization (Name and complete address, including ZIP code) TEXAS A&M UNIVERSITY - KINGSVILLE, FISCAL AFFAIRS, CONTRACTS & GRANTS, CAMPUS BOX 104, KINGSVILLE, TX 78363					
4. Employer Identification Number 1-74-6001530		5. Recipient Account Number or Identifying Number 410314 & 410315		6. Final Report ☒ Yes ☐ No	7. Basis ☒ Cash ☐ Accrual
8. Funding/Grant Period (See instructions) From: (Month, Day, Year) 9/1/2004		To: (Month, Day, Year) 2/28/2009		9. Period Covered by this Report From: (Month, Day, Year) 9/1/2004 To: (Month, Day, Year) 2/28/2009	
10. Transactions:		I Previously Reported	II This Period	III Cumulative	
a. Total outlays		502,062.72	21,002.80	523,065.52	
b. Refunds, rebates, etc.				0.00	
c. Program income used in accordance with the deduction alternative				0.00	
d. Net outlays (Line a, less the sum of lines b and c)		502,062.72	21,002.80	523,065.52	
Recipient's share of net outlays, consisting of:					
e. Third party (in-kind) contributions		160,618.65	20,000.00	180,618.65	
f. Other Federal awards authorized to be used to match this award				0.00	
g. Program income used in accordance with the matching or cost sharing alternative				0.00	
h. All other recipient outlays not shown on lines e, f or g				0.00	
i. Total recipient share of net outlays (Sum of lines e, f, g and h)		160,618.65	20,000.00	180,618.65	
j. Federal share of net outlays (line d less line i)		341,444.07	1,002.80	342,446.87	
k. Total unliquidated obligations				0.00	
l. Recipient's share of unliquidated obligations				0.00	
m. Federal share of unliquidated obligations				0.00	
n. Total Federal share (sum of lines j and m)				342,446.87	
o. Total Federal funds authorized for this funding period				342,700.00	
p. Unobligated balance of Federal funds (Line o minus line n)				253.13	
Program Income, consisting of:					
q. Disbursed program income shown on lines c and/or g above				0.00	
r. Disbursed program income using the addition alternative				0.00	
s. Undisbursed program income				0.00	
t. Total program income realized (Sum of lines q, r and s)				0.00	
11. Indirect Expense		a. Type of Rate (Place "X" in appropriate box) ☐ Provisional ☒ Predetermined ☐ Final ☐ Fixed			
		b. Rate 50% S&W	c. Base 0.00	d. Total Amount 0.00	e. Federal Share 0.00
12. Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.					
13. Certification: I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.					
Typed or Printed Name and Title Claudia Conard, Assistant Director - Contracts & Grants				Telephone (Area code, number and extension) 361-593-3989	
Signature of Authorized Certifying Official				Date Report Submitted May 12, 2009	

FINANCIAL STATUS REPORT

(Long Form)

Public reporting burden for this collection of information is estimated to average 30 minutes per response, including time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding the burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Office of Management and Budget, Paperwork Reduction Project (0348-0039), Washington, DC 20503.

PLEASE DO NOT RETURN YOUR COMPLETED FORM TO THE OFFICE OF MANAGEMENT AND BUDGET.

Please type or print legibly. The following general instructions explain how to use the form itself. You may need additional information to complete certain items correctly, or to decide whether a specific item is applicable to this award. Usually, such information will be found in the Federal agency's grant regulations or in the terms and conditions of the award (e.g., how to calculate the Federal share, the permissible uses of program income, the value of in-kind contributions, etc.). You may also contact the Federal agency directly.

Item	Entry	Item	Entry
1, 2 and 3.	Self-explanatory.	10b.	Enter any receipts related to outlays reported on the form that are being treated as a reduction of expenditure rather than income, and were not already netted out of the amount shown as outlays on line 10a.
4.	Enter the Employer Identification Number (EIN) assigned by the U.S. Internal Revenue Service.	10c.	Enter the amount of program income that was used in accordance with the deduction alternative.
5.	Space reserved for an account number or other identifying number assigned by the recipient.	Note:	Program income used in accordance with other alternatives is entered on lines q, r, and s. Recipients reporting on a cash basis should enter the amount of cash income received; on an accrual basis, enter the program income earned. Program income may or may not have been included in an application budget and/or a budget on the award document. If actual income is from a different source or is significantly different in amount, attach an explanation or use the remarks section.
6.	Check <i>yes</i> only if this is the last report for the period shown in item 8.	10d.	e, f, g, h, i and j. Self-explanatory.
7.	Self-explanatory.	10k.	Enter the total amount of unliquidated obligations, including unliquidated obligations to subgrantees and contractors.
8.	Unless you have received other instructions from the awarding agency, enter the beginning and ending dates of the current funding period. If this is a multi-year program, the Federal agency might require cumulative reporting through consecutive funding periods. In that case, enter the beginning and ending dates of the grant period, and in the rest of these instructions, substitute the term "grant period" for "funding period."		Unliquidated obligations on a cash basis are obligations incurred, but not yet paid. On an accrual basis, they are obligations incurred, but for which an outlay has not yet been recorded.
9.	Self-explanatory.		Do not include any amounts on line 10k that have been included on lines 10a and 10j.
10.	The purpose of columns I, II, and III is to show the effect of this reporting period's transactions on cumulative financial status. The amounts entered in column I will normally be the same as those in column III of the previous report <i>in the same funding period</i> . If this is the first or only report of the funding period, leave columns I and II blank. If you need to adjust amounts entered on previous reports, footnote the column I entry on this report and attach an explanation.		On the final report, line 10k must be zero.
10a.	Enter total gross program outlays. Include disbursements of cash realized as program income if that income will also be shown on lines 10c or 10g. Do not include program income that will be shown on lines 10r or 10s.	10l.	Self-explanatory.
	For reports prepared on a cash basis, outlays are the sum of actual cash disbursements for direct costs for goods and services, the amount of indirect expense charged, the value of in-kind contributions applied, and the amount of cash advances and payments made to subrecipients. For reports prepared on an accrual basis, outlays are the sum of actual cash disbursements for direct charges for goods and services, the amount of indirect expense incurred, the value of in-kind contributions applied, and the net increase or decrease in the amounts owed by the recipient for goods and other property received, for services performed by employees, contractors, subgrantees and other payees, and other amounts becoming owed under programs for which no current services or performances are required, such as annuities, insurance claims, and other benefit payments.	10m.	On the final report, line 10m must also be zero.
		10n.	o, p, q, r, s and t. Self-explanatory.
		11a.	Self-explanatory.
		11b.	Enter the indirect cost rate in effect during the reporting period.
		11c.	Enter the amount of the base against which the rate was applied.
		11d.	Enter the total amount of indirect costs charged during the report period.
		11e.	Enter the Federal share of the amount in 11d.
		Note:	If more than one rate was in effect during the period shown in item 8, attach a schedule showing the bases against which the different rates were applied, the respective rates, the calendar periods they were in effect, amounts of indirect expense charged to the project, and the Federal share of indirect expense charged to the project to date.