WEF/A&WMA ODORS AND AIR POLLUTANTS CONFERENCE
MARCH, 2010

Removal Effectiveness of Reduced Sulfur Compounds In Multi-Stage Biotrickling Filter For Biosolids Handling Processes

Neil A. Webster, P.E.
Webster Environmental Associates, Inc.
13121 Eastpoint Park Blvd., Suite E
Louisville, KY 40223
Sharon Worley, P.E., Louisville & Jefferson County Metropolitan Sewer District (MSD)
Brian Herner, Biorem Technologies, Inc.

ABSTRACT

The application of biotrickling filters (BTF) has become commonplace for the removal of hydrogen sulfide and for the reduction of odors from air emissions in wastewater treatment facilities. Operation at a low pH of 1.5-2.0 provides an environment for rapid reproduction of thiooxidans bacteria and metabolism of hydrogen sulfide (H_2S). An elimination capacity in excess of 90 gm of H_2S per cubic meter of media per hour can be achieved. However, a family of organic sulfur compounds (OSCs) that contributes significantly to nuisance odors often co-exist in air emissions. Some of these OSCs are highly resistant to removal in a biotrickling filter due to their low water solubility as expressed by the Henry's Law Coefficient. Solubility is further depressed in a low pH environment. Low removal efficiencies impact the odor removal performance of a biotrickling filter.

To address this problem, a dual train biotrickling filter operating at MSD's 120 MGD Morris Forman Water Quality Treatment Center (MFWQTC) was modified from a three stage neutral pH process to a multi functional three stage BTF. The modifications provided the flexibility to operate one or two of the three stages at neutral pH to improve OSC removal with the first stage or stages always recirculated to maintain a low pH. Each stage has a different type of media designed for a specific function and duty, and includes polyurethane cubes and a combination of advanced, inorganic granular media with high surface area. This study traces the removal path of some common OSCs at three stages of operation in the 9,200 cfm multi-stage biotrickling filter system at both acidic and neutral pH levels. Significant data on H_2S and OSC compound removal efficiencies has been collected and will be presented.

A performance test conducted on August 14, 2008, showed a 99.2% removal efficiency for H_2S with inlet H_2S ranging between 50 and 100 ppm and an 83% reduction of total RSCs with the bottom two stages at low pH and the top stage at neutral pH. A test was also conducted in the summer of 2009 to compare an Alpha mode (recirculate bottom two stages for low pH and third stage as neutral pH with surface irrigation) on one vessel to a Beta mode on the other vessel (recirculate one bottom stage only). The objective is to increase OSC removal and not sacrifice H_2S removal efficiencies. Odalog data has been collected continuously since the spring of 2008 on the inlet and outlet (each vessel) for H_2S performance monitoring.

KEYWORDS

Biotrickling Filters, organic sulfur compounds, Biorem media, recirculation of low pH water

INTRODUCTION

MSD's Morris Forman Water Quality Treatment Center is designed to treat 120 MGD of raw wastewater. In addition, all of the biosolids from Louisville's other treatment plants are processed at the Morris Forman plant. Up until several years ago, air from much of the solids handling processes were treated by fume incineration. MSD was spending over $670,000 per year for natural gas for operation of the fume incineration process. In 2004, the decision was made to convert to biological treatment for control of odors from these sources.

A Biotrickling Filter (BTF) system was designed to treat 9,200 cfm of air with H_2S concentrations up to 200 ppm. Approximately 2,900 cfm comes from the Solids Receiving Tank (which holds sludge trucked and/or pumped from other Louisville plants), and approximately 6,300 cfm comes from the Centrifuge conveyors, Wet Bins, Dewatering Wet Well and Thickened Sludge Holding Tanks. An odor control system was required which would provide 99.9% Hydrogen Sulfide (H_2S) removal, 95% removal of all organic sulfur compounds (OSCs) and an outlet odor level of no more than 800 dilutions to threshold. A neutral pH system was selected because pilot testing indicated that this technology would effectively treat not only the H_2S but also the OSCs. But because this was a rather new technology, the BTF bid documents included strong performance guarantee language to ensure that the unit would treat the odorous air to the same level of odor removal efficiency as the fume incinerators. If the units did not meet the performance requirements, MSD would require the Contractor to install a 10-foot diameter dual bed carbon vessel as polishing to the BTF. In the initial construction, space for the carbon vessel was provided on the same concrete as the BTF and the exhaust fan was sized with capacity to push air through the BTF and the possible future carbon adsorber.

As part of the neutral pH system, nutrients were required and caustic water had to be supplied for spraying onto the media layers to maintain a neutral pH to promote OSC removal.

Numerous problems with the neutral pH system occurred including, faulty caustic pumping and pH control, a malfunctioning H_2S analyzer, pump cavitation and ultimately the BTF media disintegrated to a mushy mess. MSD shut down the system and the existing fume incinerator was placed back into operation on a temporary basis until a permanent BTF could be retrofitted.

Throughout the construction and startup phases of the project, comprehensive H_2S data had been gathered with Odalogs, as shown in **Figure 1** for a typical week. Review of the Odalog charts showed that there were wide variations in H_2S concentrations. Therefore, in addition to the replacement of the BTF, MSD also pursued options for controlling the peak H_2S spikes, with chemical addition at key locations.

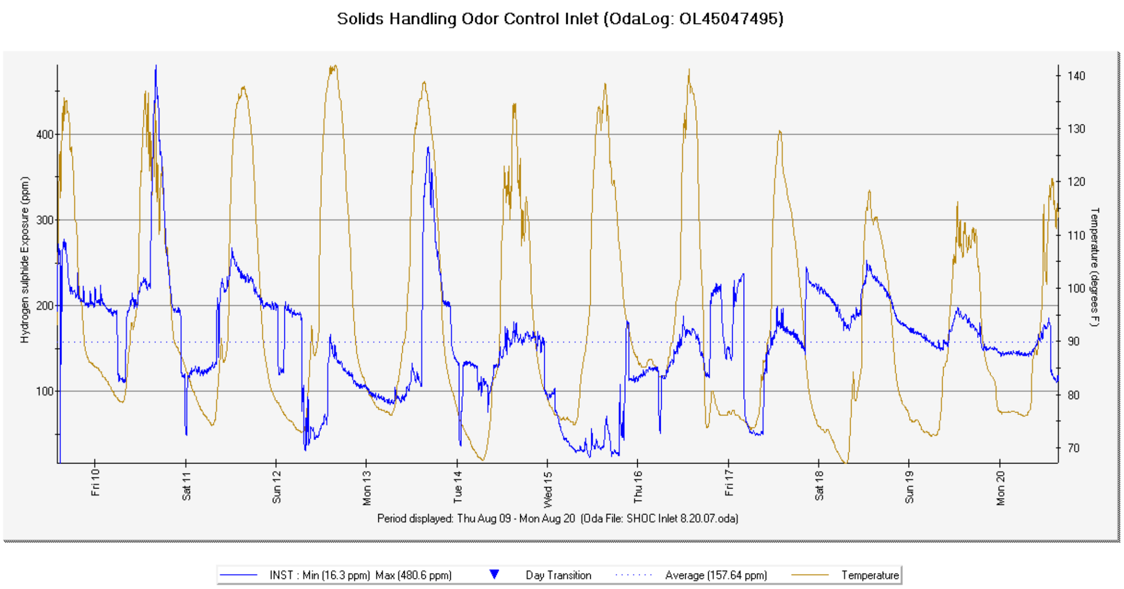

Figure 1

MSD considered permanently returning to the use of the fume incinerator, but one of the two incinerator units had been completely decommissioned, so there would be no backup unit for the one remaining incinerator. Also, MSD recognizes that biological systems are better than incineration from an environmental perspective. The incineration process emits 1,185 tons of carbon from the use of 77,000,000 cubic feet of natural gas annually. After a thorough evaluation of the system requirements and available treatment technologies, MSD requested proposals from other media manufacturers to find one who would provide a media suitable for the retrofit application.

MSD had several requirements for the new design:

- Reuse the existing vessels.
- Recirculation. Benefits from recirculation included water savings, better H_2S removal at lower pH, not flushing away the biomass, and systems with water recycled tend to be more stable (with respect to pH and biology).
- Two or more stages of removal. The goal of the re-design was to provide multiple layers, such that we could operate the lower bed or beds at a low pH with recirculation. The upper bed(s) could be allowed to operate at neutral pH..

Seven BTF manufacturers were considered. Two were eliminated because they could not physically make their media work with the existing vessels. Two declined to bid. Three submitted proposals in February, 2008.

After much evaluation, MSD selected the proposal from Biorem for several reasons. They could meet the required schedule, they were willing to do a retrofit project, Biorem had a plan to maximize flexibility in which the middle layer could operate as either a Biotrickling Filter or as a polishing biofilter, and they would make a performance guarantee. A description of the Biorem stages follows:

- First Stage Biotrickling Roughing Filter: A 4.5 ft bed of roughing media consisting of polyurethane foam (PUF) provides 9 seconds of Empty Bed Residence Time (EBRT). The system is designed to be operated at a pH of approximately 1.5 to 2.0. Water will be recirculated from the sump and the pH will be controlled simply by adjusting the bleed rate of the sump water. Final effluent is used as makeup water. No additional nutrients are required.
- Second Stage Biotrickling Polishing Filter: A 5 ft bed of BIOREM LWE is used to remove the residual H_2S from the first stage and it can be operated at the same pH as the first stage. LWE is an ultra low density, porous mineral material in a free flowing granular form. It has a very high surface area that provides high H_2S elimination capacity.
- Third Stage Biofilter: A 5 ft bed of combined LWE / XLD low density and high performance biofilter media is used to polish all residual H_2S and to achieve removal of combined OSC through the total system. The XLD media is also low density and is coated with materials to enhance the capture and biological degradation of low level OSC. This system will be irrigated with plant effluent or potable water twice per day for 5-10 minutes, as required to keep the media moist

Originally, Biorem was going to provide a higher density Biosorbens media for the top layer, but a structural analysis indicated that the load on the existing vessel would be too high. Therefore, BIOREM developed a layered approach of LWE and XLD for the third media layer.

The first 2 layers of media were placed into service in June, 2008. The third layer was placed into service in July 2008. Contract performance testing was conducted in August, 2008. The design specifications required H_2S removal to exceed 99% and total OSC removal to exceed 80%.

THEORY OF BIOLOGICAL TREATMENT OF REDUCED SULFUR COMPOUNDS

The application of biotrickling filters (BTF) has become commonplace for the removal of hydrogen sulfide and for the reduction of odors from air emissions in wastewater treatment facilities. The removal and destruction of offensive compounds from air streams is a two-step process consisting of phase transfer and biodegradation. The phase transfer is an aqueous solubilization of the chemical compounds and the sorption of the dissolved compounds into the biofilm on the surface of the BTF media. The biofilm hosts the bacteria population which oxidizes the sorbed chemical compounds and breaks them down into inorganic salts through a complex chemical pathway. The efficiency of removal is dependent on solubility and biodegradability of the chemical compounds.

Hydrogen sulfide is water soluble and easily biodegradable by a family of autotrophic bacteria designated as *thiobacillus*. A most common and highly effective species is *thiooxidans* which oxidizes hydrogen sulfide to sulfate ion. This creates a solution of sulfuric acid in the recirculation water in the biotower. *Thiooxidans* is acidophilic and operation at a low pH of 1.5-2.0 provides an environment for rapid reproduction of *thiooxidans* and metabolism of hydrogen sulfide at an elimination capacity in excess of 100 g/cu m of filter media/hr. The most common process design for the removal of H_2S in a biotrickling filter is, therefore, the recirculation of water at a pH of 1.5-2.

In addition to H_2S, OSC that contribute significantly to nuisance odors often co-exist in air emissions. The major odor causing OSC components are methyl mercaptan (MM), dimethyl sulfide (DMS) and dimethyl disulfide (DMDS). While methyl mercaptan is oxidized in the biotrickling filter partially in the presence of autotrophic bacteria, the latter two are highly resistant due to their low water solubility, and the fact that heterotrophic bacteria required for oxidation do not survive under the highly acidic conditions present in the biotrickling filter, Low OSC removal efficiencies significantly impact the odor removal performance of a BTF.

While *thiooxidans* can survive at neutral pH, another sulfur oxidizing bacteria, designated *thioparens,* can also metabolize H_2S. *Thioparens* is different than *thiooxidans* in that it is not acidophilic and it can reduce OSC compounds more effectively at neutral pH. Since OSC compounds have better phase transfer at neutral pH, this is a more favorable condition for the destruction of odors due to OSC. Another by-product of biological oxidation of OSC is elemental sulfur. *Thioparens* can also oxidize elemental sulfur into sulfate ion. Other metabolic pathways include the conversion of readily oxidizable MM to DMDS. Thus in the early stages of a biological treatment process, a temporary increase in DMDS may occur, depending on the vessel configuration and the sample points.

The key objective of the design and selection of the biofilter media and the operating modes of the biotrickling filter was to optimize the removal of high odors caused by both high H_2S and high OSC. This required careful selection of the media and design of the operating process.

The selection of an appropriate filter media for use in a BTF must take several factors into consideration. First, the media must be chemically inert and resistant to acidic and alkaline conditions so that it can function at low pH for the support of *thiobacillus* that operate best in the range of 1.5-2.0 and support an alkaline environment in the event of addition of caustic to the filter for neutral pH operation or chemical cleaning of the filter bed. The media should also be free flowing so that it can take the form of the vessel to minimize dead spaces and support good air flow distribution. It must also have structural integrity to prevent compression and compaction during operation. Compaction will cause increased resistance to airflow and result in higher head loss and can distort the air flow patterns which will impact the efficiency of operation.

Once the physical requirements are met, media selection is based on void volume and surface area. Void volume will influence air flow patterns and pressure loss through the system, while surface area will determine the amount of exposed biofilm and is a critical parameter in determining the chemical elimination capacity of the biofilter media, normally measured in g/m3/hr. There is a trade-off in high void volume for low pressure drop and surface area for maximum elimination capacity.

During normal operation of a BTF, elemental sulfur and dead biomass will form on the surface of the media. The amount of deposit will depend on the concentration of contaminants (H_2S) in the air stream, the water recirculating rate and the physical structure of the media.

For the retrofit at the Morris Forman plant, it was decided to use a specific selection of different biofilter media to achieve optimum operation. The three tray vessel design and the ability to control the recirculation rate at each level provided significant flexibility in the mode of operation. The design enabled a selection of three different media, each with specific operating characteristics that would address high level H_2S as well as a high level of MM, DMS and DMDS that all contributed significantly to the odor.

Since it was anticipated that the inlet air could have very high H_2S levels on occasion that could cause rapid buildup of deposits, the media selected for the first inlet tray was a polyurethane foam (PUF) with a high void volume and high surface area. This would provide excellent H_2S removal with minimal pressure drop and is a material that can be easily removed and cleaned, in the event of excessive buildup.

The second stage was provided with BIOREM LWE, a granular, low density media with extremely high surface area. This media has excellent H_2S removal characteristics down to very low residual levels, providing both a working and polishing effect. The combination of the PUF at the first stage and LWE at the second stage with a total of 19 seconds Empty Bed Residence Time (EBRT) provides comprehensive H_2S removal under all operating conditions.

The final stage was provided with a combination of BIOREM LWE and XLD a coated media which is designed to provide exceptional removal of OSC at neutral pH.

MODIFICATIONS TO EXISTING SYSTEM AND START UP

The two (2) existing fourteen (14) foot diameter vessels each underwent extensive modifications and upgrades. All the previously installed media was removed, and the recirculation pumps and caustic system were abandoned. New media and media support screens were installed. Also installed were a new irrigation system make-up water valves and flow meters, 100 gpm acid resistant recirculation pumps (Wilfrey models), recirculation flow meters, spray nozzles, hydrogen sulfide analyzers (inlet and outlet), and an access man-way to the sump were all added. The existing fan was sized properly for the new conditions and was not replaced. The system was started up in the Alpha mode, with the bottom media stages 1 and 2 recirculated as a biotrickling filter (BTF) and stage 3 as a biofilter. The top layer is designed for intermittent irrigation water. Make-up water for the lower two layers is added using a mechanical float ball valve in the vessel sump, and a solenoid valve is activated if the system pH drops below 1.5. Water is continuously blown down at a fixed rate.

The supply of components and the installation went smoothly, except that the 3rd layer of Biosorbens had too high a density and weight for the vessel structure and therefore a blend of XLD (23 lbs/ft^3) and LWE (13 lbs/ft^3) were used. A summary of the media configuration and BTF design is shown in **Figure 2**. The BTF provides about 29 seconds of total detention time.The vessels are operated in parallel, each receiving 4,600 cfm of air flow and the system is called the Solids Handling Odor Control (SHOC) system.

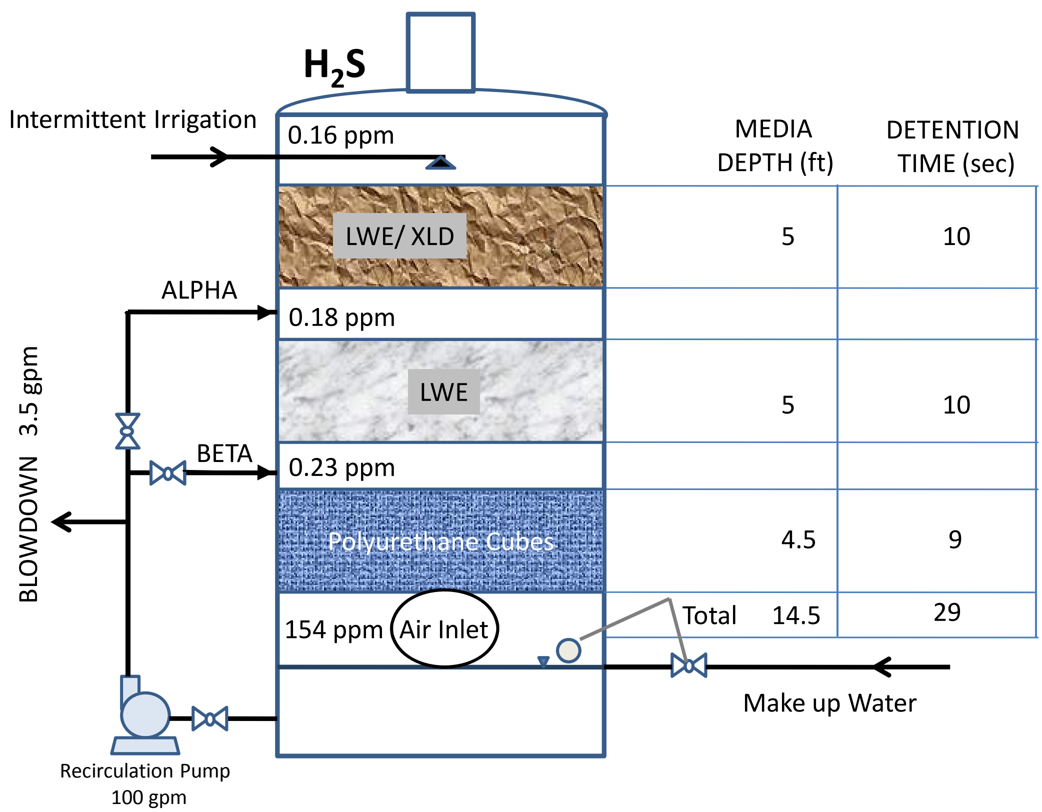

Figure 2

Diagram of the Biotrickling Filter Installation at the MFWQTC in Louisville, KY

<u>Start-up</u>

The biofilter start-up began on June 2, 2008 with the lower two media layers in the recirculation mode (Alpha). The concept was to attain reasonable H_2S removal prior to installing the top layer to preserve the Biosorbens. The average H_2S during the first few weeks of operation were as follows:

	Inlet H_2S		Outlet H_2S	
Week	**Daily Avg (ppm)**	**Peak (ppm)**	**Avg (ppm)**	**Peak (ppm)**
1	14.1	77	No Data	
2	42.7	88	2.44	30.7
3	40.4	140	1.89	19.2
4	29.2	68	1.08	2
5	24.2	271	0.52	54.9
6	14.4	78	0.08	0.6
7	30.7	104	0.09	0.6

Within six (6) weeks the H_2S removal was greater than 99.7%. The top layer of media was installed after the sixth week of operation.

There was no blowdown of water until the pH of the recirculated water stabilized at around 2.0 and then the blowdown was adjusted depending on the inlet H_2S. The pH decreased rapidly during start-up, as shown in **Figure 3**. The desired range of pH is 1.5 – 2.0 in the lower stages. An initial performance test was conducted to check the guarantee on August 14, 2008, and the results are shown below in **Table 1**. The guarantee was 99% H_2S removal and a minimum of 80% OSC removal. The guarantee on media life is 10 years for LWE and XLD and 5 years on the PUF media.

The system passed the performance test but MSD decided to continue testing in the Alpha and Beta modes and allow further biological acclimation to check on improved removal efficiencies of DMS and DMDS. Another round of testing was conducted on September 22, 2008 and significant improvements were seen as shown in **Table 2**.

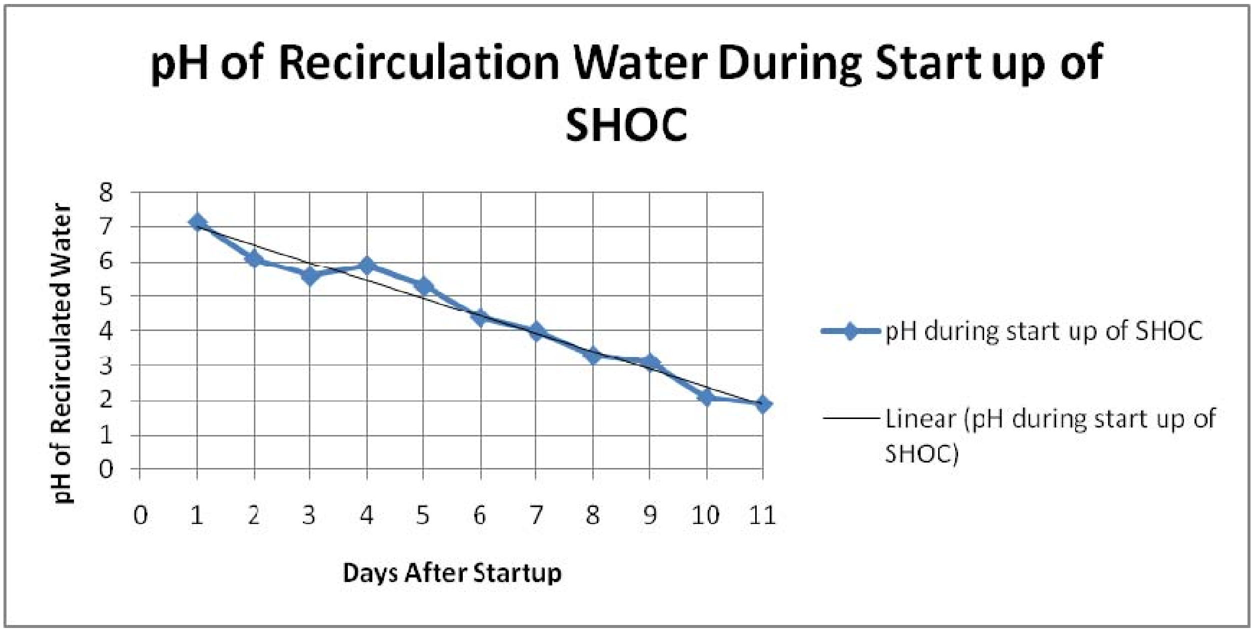

Figure 3

Table 1 SHOC Performance Test on August 14, 2008 Average of Three Rounds (6 weeks after start up)			
SHOC #1			
	Removal Efficiency (%)	**Inlet (ppm)**	**Outlet (ppm)**
H_2S (ppm)	99.5	79.8	0.41
MM (ppm)	88.8	3.67	0.41
DMS (ppm)	12.3	0.106	0.093
DMDS (ppm)	67.6	0.034	0.011
Total OSCs	86.5	3.81	0.514
SHOC #2			
H_2S (ppm)	99.4	79.8	0.48
MM (ppm)	85.7	3.671	0.524
DMS (ppm)	5.7	0.106	0.100
DMDS (ppm)	67.6	0.034	0.011
Total OSCs	83.3	3.81	0.635

Table 2 SHOC Performance Test on September 22, 2008 Average of Three Rounds (11 weeks after start up)			
SHOC #1			
	Removal Efficiency (%)	**Inlet (ppm)**	**Outlet (ppm)**
H_2S (ppm)	99.9	152.6	0.12
MM (ppm)	99	27.15	0.266
DMS (ppm)	52.8	4.09	1.932
DMDS (ppm)	96.1	0.94	0.037
Total OSCs	93.0	32.18	2.235
SHOC #2			
H_2S (ppm)	99.9	152.6	0.12
MM (ppm)	98.6	27.15	0.376
DMS (ppm)	57.4	4.09	1.742
DMDS (ppm)	84.7	0.94	0.144
Total OSCs	93.0	32.18	2.262

DISCUSSION AND RESULTS

Odalog H_2S monitors were maintained on the inlet and outlets of the two vessels continuously. During the year 2009 (Jan. 1 – Nov. 4, 2009), the daily average inlet H_2S was 38 ppm, with a range of 1 to 187 ppm (winter and summer) as shown on **Figure 4**. The H_2S removal efficiency averaged 99.4 and 99.1% for vessels #1 and #2, respectively during this time frame. Usually, outlet H_2S was around 0.01 ppm but there were some excursions on the units in early June, 2009. It is difficult to say if these were instrument issues or actual H_2S concentrations in the 5 – 10 ppm range on the outlet. The pH of the recirculation water ranged from 1.5 to 2.5, with normal pH value of 1.8 – 1.9 during this year.

Several tests were conducted on the SHOC to document OSCremoval efficiencies, both over-all and on a stage by stage basis. These tests were also conducted to determine if a polishing stage of treatment would be required, or if a change to the BETA mode of operation would be better for odor control and OSC removals. Tests were run in November, 2008 (air temperature 30 – 60^{o}F) and again in July, 2009 (air temperature 90^{o}F). Both units were operating in the Alpha mode (2 lower stages recirculated) in November, 2008 and one vessel (SHOC #1) was converted to Beta mode shortly thereafter. There were four separate sampling days in November, 2008.

In November, 2008 and July, 2009 Methyl Mercaptan (MM) removal efficiencies were 90% and essentially100%, respectively, as shown in **Table 3**. **Figure 5**, is a graph of this data showing stage wise removal of MM in the Vessel No. 1, similar removals were experienced for Vessel No. 2. Removal efficiencies for MM improved during the nine months of operation, particularly for the recirculated media beds. More than 96% of MM is removed in the first layer with 9 seconds detention time and a pH of about 2.0.

Dimethyl Sulfide (DMS) and Dimethyl Disulfide (DMDS) removal efficiency were not very good in November, 2008 but improved significantly by July, 2009. **Table 4** is a summary of the DMS data and **Table 5** is a summary of DMDS data for these two test periods. In July, 2009,

H_2S removal efficiency in Stage 1 for Vessel 1 (BETA) and Vessel 2 (ALPHA) was 99.39% with an inlet H_2S concentration of 142 ppm and 167 ppm, respectively. H_2S removals are shown in **Table 6**. Hydrogen sulfide elimination capacity is about 92 g/m^3/hr.

There did not appear to be significant differences in the Alpha vs. Beta modes of operation for OSC removals as shown in **Figure 6, 7 and 8**, which compares MM, DMS and DMDS removals, respectively, for the November, 2008 and July, 2009 testing. However, over-all removals increased significantly from late fall, 2008 to mid-summer, 2009.

In November, 2009, an annual check-up of the units was conducted and odor samples were taken from each unit. Samples were shipped to St. Croix Sensory, Inc. for odor panel analyses of Detection Threshold (D/T) values for the inlet and outlet of each BTF unit operating in Alpha and Beta modes. The results are as follows:

BTF Unit Mode	Inlet D/T	Outlet D/T	Odor Removal Efficiency (%)
BETA (Unit #1)	210,000	9,100	95.7
ALPHA (Unit #2)	160,000	7,900	95.1

CONCLUSIONS

The conversion of the BTFs to low pH recirculation stages and a third layer with a non-recirculated biofilter stage, was very successful in treating reduced sulfur compounds and odors. The biological system seems to improve significantly over time, perhaps due to biological acclimation. Performance of the system after one year of operation was much improved over the first six months of operation. MSD has not operated the fume incinerator for more than a year and as a result has saved more than $600,000 by treating this strong odor stream biologically. MSD continues to monitor performance daily and is prepared to add chemicals to the sludge in the summer, if peak loadings exceed the capacity of the SHOC biological units in the future. No chemicals were added in the summer of 2009.

In summary, the SHOC achieves more than 99.7% removal of high concentrations (150 ppm) of H_2S at a pH of about 1.8 (in the lower levels), and has an H_2S elimination capacity greater than 90 g/m^3/hr. The SHOC also treats methyl mercaptan at inlet concentrations ranging from 2 – 6 ppm down to non-detectable levels. Dimethyl sulfide removal efficiency is about 90% with inlet concentrations of 2 – 3 ppm, with about 50% removal in the first stage (low pH) and polishing occurring in each subsequent stage. Dimethyl Disulfide is virtually all removed in the process with an inlet concentration of about 0.2 ppm.

Odor removal efficiency (D/T) is greater than 95% for each unit after about two years in operation.

Table 3

METHYL MERCAPTAN (MM) REMOVAL IN SHOC DURING 2008 AND 2009

	November, 2008		**July, 2009**			
	ALPHA MODE SHOC #1 AND #2		**SHOC #1 BETA MODE**		**SHOC #2 ALPHA MODE**	
Location	Average MM (ppm)	Cumulative Removal Efficiency (%)	Average MM (ppm)	Cumulative Removal Efficiency (%)	Average MM (ppm)	Cumulative Removal Efficiency (%)
Inlet	3.31		2.92		4.24	
Stage 1 Outlet	2.03	38.7%	0.164	94.1%	0.085	98.0%
Stage 2 Outlet	0.93	71.9%	0.045	98.5%	0.063	98.5%
Stage 3 Outlet	0.34	89.9%	Non-Detect	>99%	Non-Detect	>99%

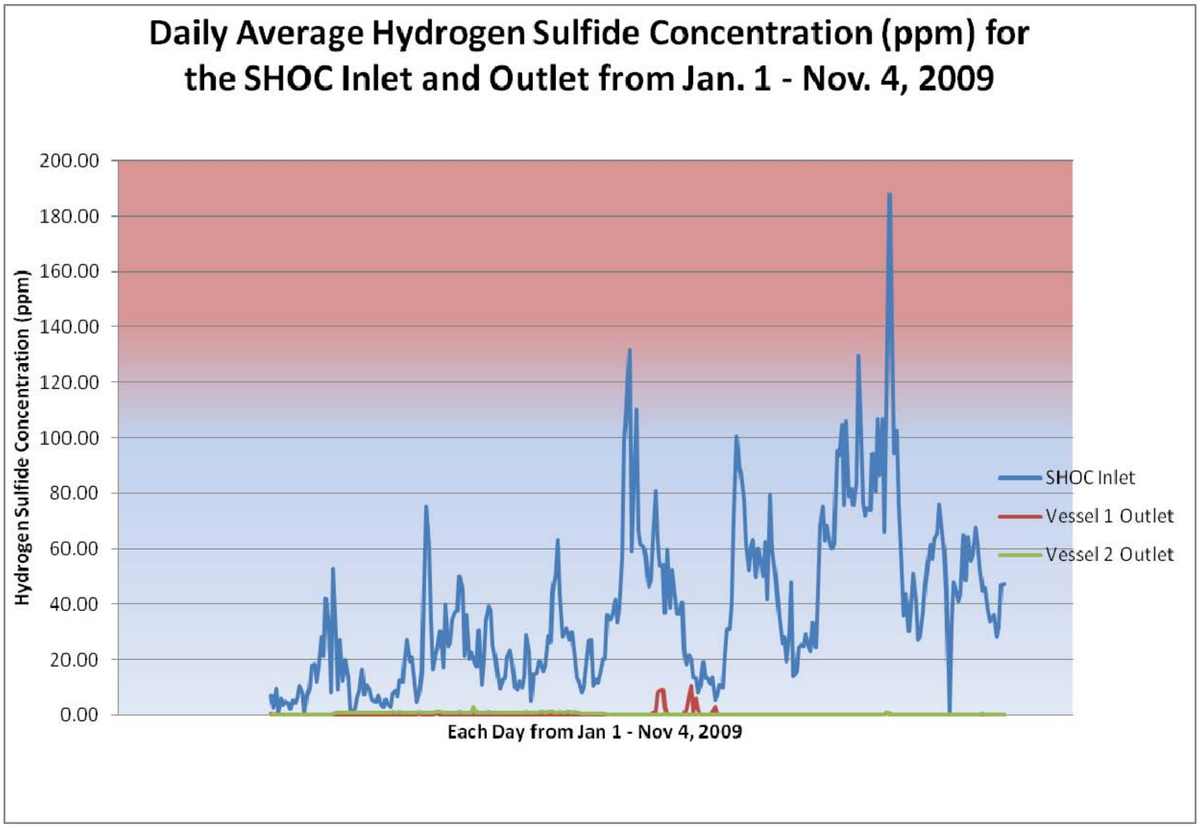

Figure 4

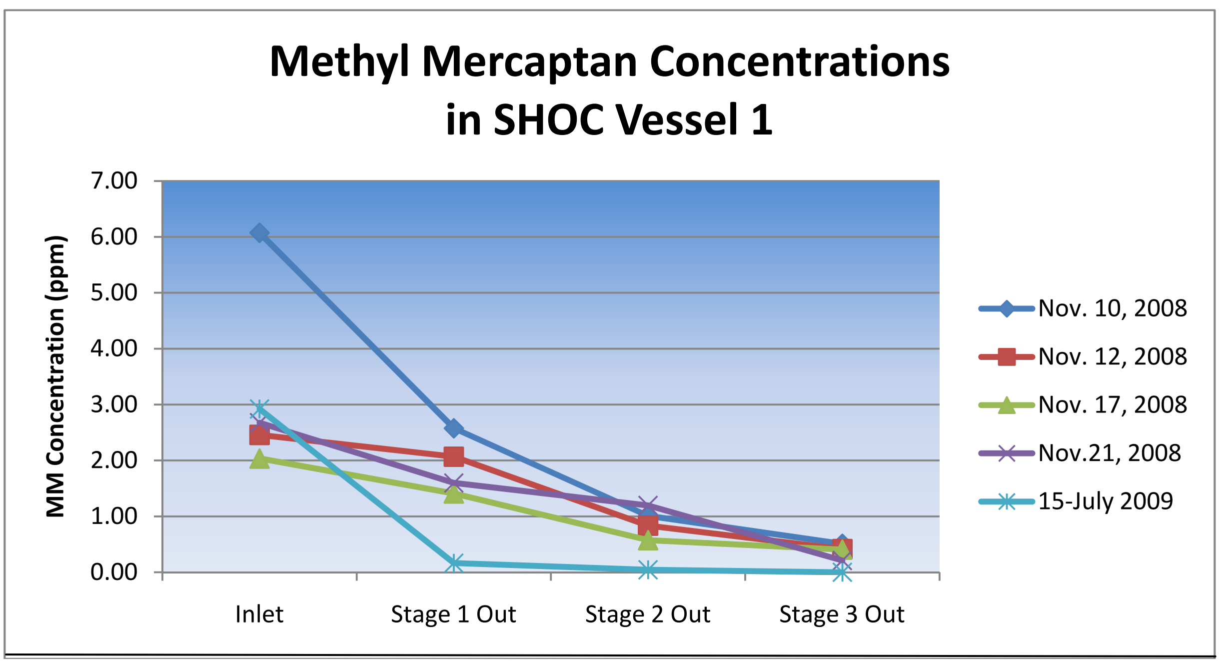

Figure 5

Table 4
DIMETHYL SULFIDE (DMS) REMOVAL IN SHOC DURING 2008 AND 2009

	November, 2008		July, 2009			
	ALPHA MODE SHOC #1 AND #2		SHOC #1 BETA MODE		SHOC #2 ALPHA MODE	
Location	Average DMS (ppm)	Cumulative Removal Efficiency (%)	Average DMS (ppm)	Cumulative Removal Efficiency (%)	Average DMS (ppm)	Cumulative Removal Efficiency (%)
Inlet	0.29		2.038		2.99	
Stage 1 Outlet	0.3	-5.7%	0.924	54.7%	1.56	47.8%
Stage 2 Outlet	0.28	3.4%	1.04	49.0%	0.665	77.8%
Stage 3 Outlet	0.23	20.7%	0.255	87.5%	0.276	90.8%

Table 5
DIMETHYL DISULFIDE (DMDS) REMOVAL IN SHOC DURING 2008 AND 2009

	November, 2008		July, 2009			
	ALPHA MODE SHOC #1 AND #2		SHOC #1 BETA MODE		SHOC #2 ALPHA MODE	
Location	Average DMDS (ppm)	Cumulative Removal Efficiency (%)	Average DMDS (ppm)	Cumulative Removal Efficiency (%)	Average DMDS (ppm)	Cumulative Removal Efficiency (%)
Inlet	0.067		0.21		0.21	
Stage 1 Outlet	0.086	-28.4%	0.039	81.4%	0.029	86.2%
Stage 2 Outlet	0.066	1.5%	0.01	95.2%	0.014	93.3%
Stage 3 Outlet	0.067	0.0%	Non-Detect	>99%	Non-Detect	>99%

Table 6

HYDROGEN SULFIDE (H_2S) REMOVAL IN SHOC DURING 2008 AND 2009

	July, 2009			
	SHOC #1 BETA MODE		SHOC #2 ALPHA MODE	
Location	Hydrogen Sulfide (ppm)	Cumulative Removal Efficiency (%)	Hydrogen Sulfide (ppm)	Cumulative Removal Efficiency (%)
Inlet	141.8		166.7	
Stage 1 Outlet	0.248	99.83%	0.212	99.87%
Stage 2 Outlet	0.168	99.88%	0.197	99.88%
Stage 3 Outlet	0.179	99.87%	0.152	99.91%

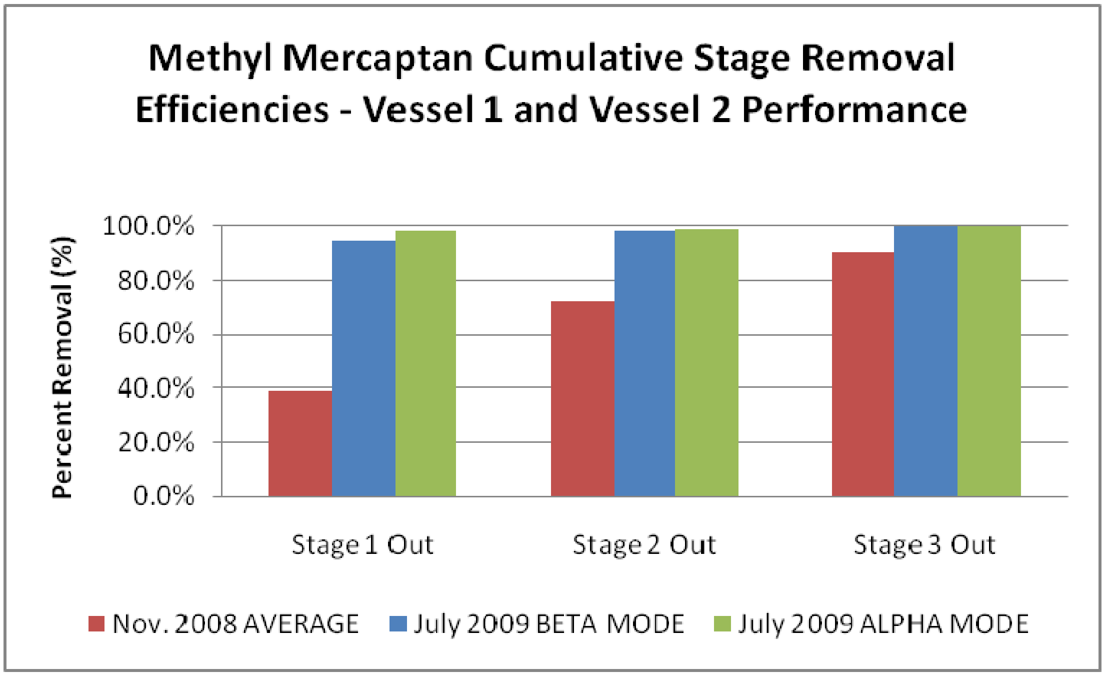

Figure 6

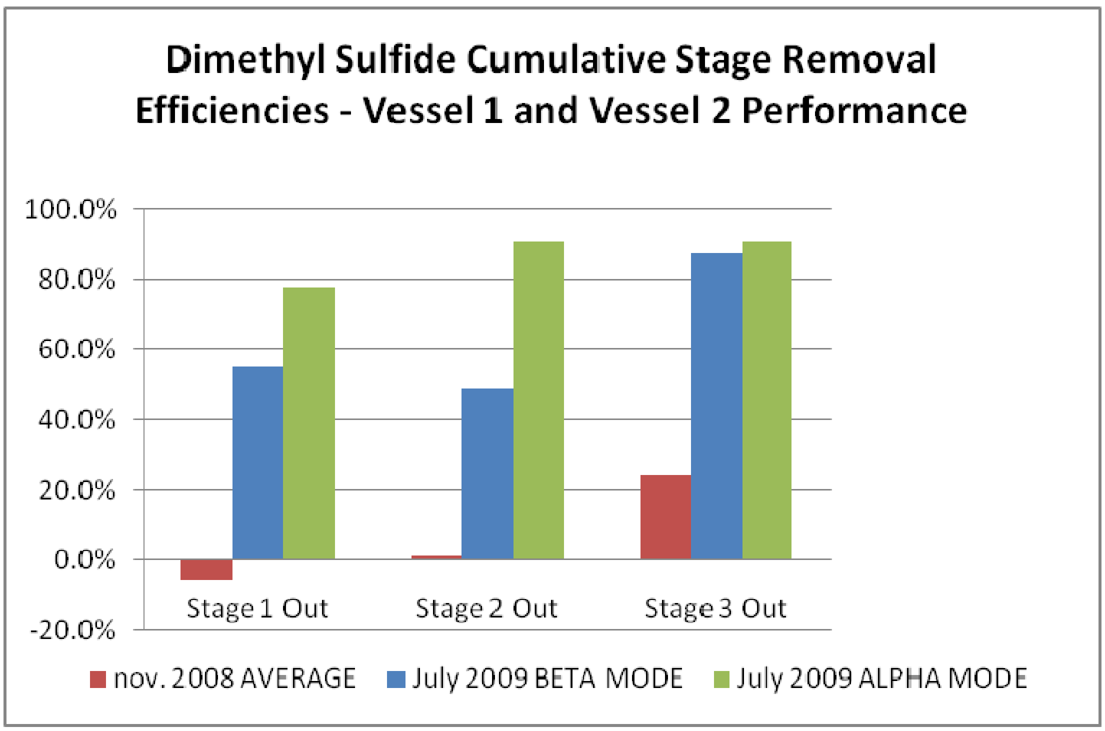

Figure 7

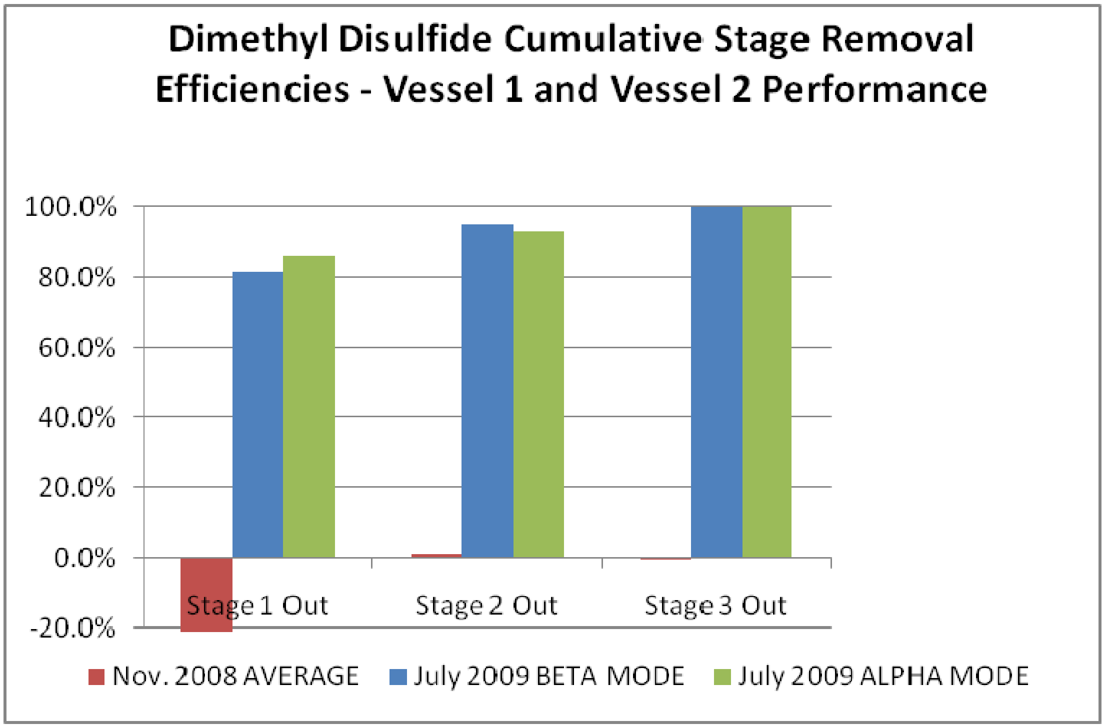
Dimethyl Disulfide Cumulative Stage Removal Efficiencies - Vessel 1 and Vessel 2 Performance
100.0%
80.0%
60.0%
40.0%
20.0%
0.0%
-20.0%
Stage 1 Out
Stage 2 Out
Stage 3 Out
Nov. 2008 AVERAGE
July 2009 BETA MODE
July 2009 ALPHA MODE

Figure 8