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Analysis of Wash Water Treatment Efficiency for Copper and Zinc

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

in cooperation with
National Steel and Shipbuilding Company
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Analysis of Wash Water Treatment Efficiency for Copper and Zinc

FINAL REPORT

**For the
National Shipbuilding Research (NSRP)
Environmental Science and Technology Program**

by



**222 East Main Street
Norfolk, VA 23506
Tel. (757) 622-2137, Fax. (757) 622-2490
E-Mail: casrm@infi.net**

**Dr. Thomas J. Fox
Thomas Beacham
Dr. Gary Schafran**

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Treatability Study of Copper and Zinc Contaminated Wash Water

Introduction

The pressure washing of the exterior hull of a ship immediately after it is drydocked is a required operation to remove marine growth and salt contamination before the surface of the hull dries. Depending upon the area of the ship's hull and the flow rate of the pressure washers, this process may generate a wastewater stream in volumes ranging from tens of thousands to over a hundred thousand gallons. This wash water will, to some extent, be contaminated with metals commonly found in antifoulant coating systems, including tributyltin, copper and zinc.

In 1997 The Commonwealth of Virginia established an effluent discharge limit of 50 parts per trillion for tributyltin ("TBT"). This regulatory action led to an intensive research effort to develop a treatment method for ship's wash water waste stream that could consistently remove TBT to levels below this discharge standard. This work is currently being performed by the Center for Advanced Ship Repair and Maintenance ("CASRM"), in conjunction with Old Dominion University. The study consisted of the testing of various treatment methodologies on wash water derived from various ships' hull pressure washing operations, in order to determine optimum treatment parameters.

During the course of the TBT treatment study, it was decided it would be advisable to test the wash water for copper and zinc. This was done to determine if the treatment parameters that maximized TBT removal also effectively remove other metal contaminants. This report presents the results of this wash water treatability study for copper and zinc.

Water Samples

The original project plan anticipated that TBT wash water would be obtained from 10 different dry-dock events in Hampton Roads shipyards during the time span of this project (July 1999-June 2000). This assumption was based on historical experience of the number of TBT dry-dockings performed in the region over recent years. However, for a variety of reasons, the 12-month period chosen had a much lower than expected TBT activity in local yards.

In order to sample the planned number of ship wash waters, a decision was made with the agreement of the project sponsor, Virginia DEQ, to solicit samples of wash water from shipyards outside the region. These TBT water samples (20 gallon typical) were taken under conditions equivalent to NPDES samples by shipyard environmental managers, and were shipped by Federal Express with chain-of-custody papers directly to Old Dominion University for analysis.

A list of the samples and their origin is provided below.

Source of Wash Water Samples:

Sample	Source Location	Comments
CV3	Hampton Roads	Oceanographic Science Ship
CV4	Gulf Coast	Cruise Ship
CV5	Hampton Roads	Cruise Ship
CV6	Hampton Roads	Private Yacht
CV7	West Coast	Fishing Vessel

CV8	West Coast	Cruise Ship (FWD End)
CV9	West Coast	Cruise Ship (AFT End)
CV10	Gulf Coast	Cruise Ship
CV11	Hampton Roads	TBT Painted Plate

CV8 and CV9 were also taken from the same dry-dock event. In this case, CV8 was taken from the forward end of the ship, and CV9 was taken from the aft end, where it was anticipated that the paint and slime build-up would be different.

CV11 was prepared by painting a steel plate and washing it down with water using the same conditions that would be used on a hull wash-down.

Batch Treatability Test Methodology

These studies were made in batch mode to study the effects coagulation on removal of copper and zinc from the wash water samples.

Coagulation studies have concentrated on evaluating the performance of two metal-salt coagulants and their ability to remove copper and zinc with the large amount of the particulate material that is typically present in shipyard wash waters. The primary variables that control particulate material removal, and also the adsorption of adsorption-amenable organic compounds, are coagulation, pH and coagulant dose. Particle removal is typically accomplished by either charge neutralization or sweep-floc coagulation, where an excess amount of coagulant is added to enmesh and coprecipitate particulate material from solution. After chemical amendment, particle removal from water occurs during the clarification process. In the laboratory studies, sedimentation is being used to separate particulate material. In the full-scale, barge-mounted treatment plant, dissolved air flotation, DAF, is being used for clarification. While different clarification processes are being used, it is well recognized that the chemical conditions for coagulation determined with particle sedimentation are the same for particle removal via DAF.

Commodity-grade alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$: General Chemical) and ferric sulfate ($\text{Fe}_2(\text{SO}_4)_3$: Midland Resources) were used to assess the removal of copper and zinc under three coagulant doses and three pH values. Target coagulation pH values of 6, 8, and 10 were used in these efforts.

Coagulation tests were conducted on wash water samples CV5-CV11. The pH and coagulant dose conditions for these tests are provided in Table 1 below.

Table 1: Batch Coagulation Treatment Conditions: pH and Dose (all coagulant doses in mg/L).

Coagulation Conditions	Coagulation Conditions											
	Ferric Coagulation						Alum Coagulation					
	1	2	3	4	5	6	1	2	3	4	5	6
Ship CV5 Coag Dose	20	41	82	20	41	41	29	57	115	29	57	57
pH	6.6	6.6	6.5	5.3	7.8	8.9	6.3	6.6	6.6	5.3	7.8	8.7
Ship CV6 Coag Dose	41	82	163	41	41	82	57	115	230	57	115	115
pH	6.5	6.8	6.2	5.3	8.5	7.9	6.5	6.6	6.6	5.4	8.0	8.8
Ship CV7 Coag Dose	20	41	82	20	41	41	29	57	115	29	57	57
pH	6.4	6.7	6.3	5.6	8.3	9	6.6	6.3	6.5	5.4	8	8.8
Ship CV8 Coag Dose	41	82	163	41	82	82	57	115	230	57	115	115
pH	6.3	6.3	6.7	5.6	7.9	8.7	6.2	6.4	6.5	5.7	7.8	9.2
Ship CV9 Coag Dose	41	82	163	41	82	82	57	115	230	57	115	115
pH	6.3	6.6	6.6	5.5	7.8	8.7	6.4	6.4	6.4	5.7	7.8	8.9
Ship CV10 Coag Dose	20	41	82	20	41	41	29	57	115	29	57	57
pH	6.6	6.6	6.5	5.4	8.1	8.9	6.3	6.6	6.5	5.5	7.9	8.8
Ship CV11 Coag Dose	15	31	61	15	31	31	22	43	87	22	43	43
pH	6.3	6.6	6.4	5.6	8.1	9	6.3	6.7	6.5	5.4	8	8.9

Batch Treatability Test Results

The results of the batch coagulant and pH tests indicate that the levels of copper and zinc in hull wash water can be significantly reduced using coagulants. The effect of the coagulant is significantly enhanced with increasing pH. As an example, Figure 1 and 2 below show the typical effect of increasing coagulant dose and increasing pH, respectively, on the percent reduction of copper from Sample CV6.

Figure 1: Effect of Ferric Dose on Percent Reduction of Copper (Coagulation pH = 6.6).

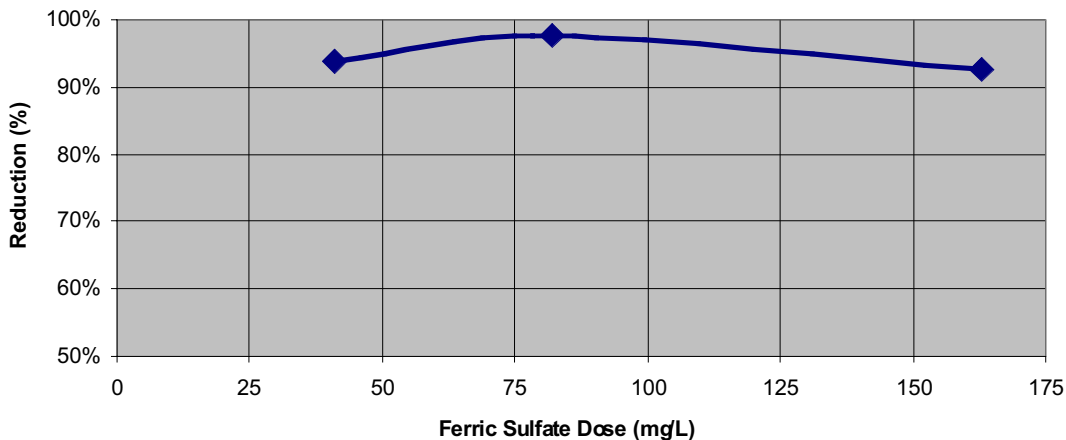


Figure 2: Effect of pH on Percent Removal of Copper

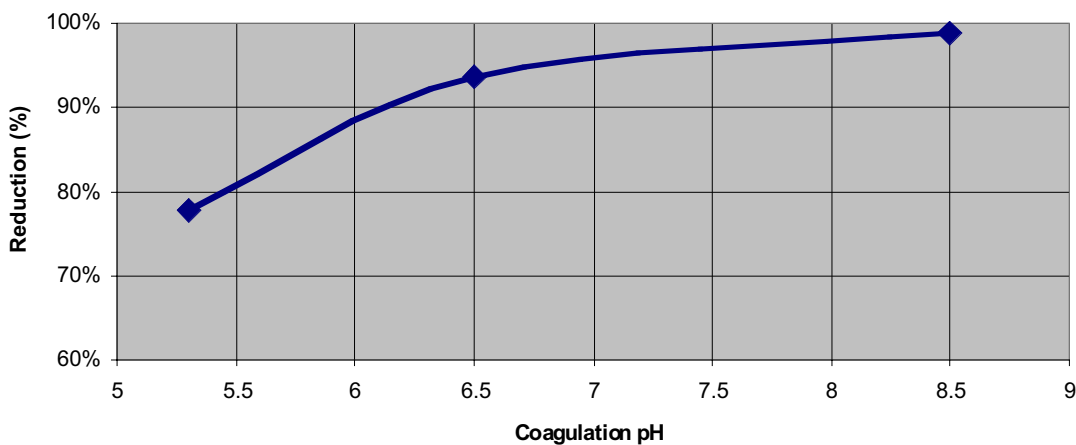


Figure 1 above illustrates the effect of coagulant dose (ferric sulfate at coagulation pH = 6.6) on the removal of copper during the coagulation experiments. At all doses (41, 82, and 163 mg/L) copper removal is found to be high (>90%) with little obvious correlation with dose. These results suggest that particulate-copper amenable to removal through coagulation was efficiently removed at the lowest (41 mg/L). The higher removal at a coagulant dose of 82 mg/L may be

due to greater particulate material or a function of slight differences in the handling of washwaters high in particulate content that was difficult to keep in suspension. Other coagulation copper data illustrated a trend of increasing removal with increasing coagulant dose eventually approaching a maximum percent removal. The maximum percent removals observed were generally a function of the coagulation pH related to copper and zinc solubility. The effect of coagulation pH is illustrated below.

Figure 2 above demonstrates that increasing pH levels enhanced the removal efficiency of the coagulant. For example, increasing the pH from 5.3 to 6.5, while maintaining the coagulant dose at 41, increased the removal efficiency from 78% to 94% of initial copper concentration. Increasing the pH level to 8.5 further increased removal efficiency to 98% of the initial copper concentration. These results are consistent with copper solubility which is typically minimum at pH of approximately 9.5 to 10. The results shown in Figures 1 and 2 demonstrate that overall copper removal efficiency can be maximized by optimization of both dose and pH.

The result of all wash water samples tested for coagulant dose and pH effects are provided in Table 2 below.

Table 2: Results of Batch Coagulant and pH Tests

Sample CV5	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of Ferric dose at pH 6.6	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	20	546	91	83%	8,500	2,212	74%
	41	546	49	91%	8,500	3,776	56%
	82	546	51	91%	8,500	1,781	79%

Sample CV6	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of Ferric dose at pH 6.6	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	41	13890	876	94%	72,000	7,142	90%
	82	13890	317	98%	72,000	7,045	90%
	163	13890	1,022	93%	72,000	9,358	87%

Sample CV5	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of pH at Ferric dose of 41	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	6.6	546	49	91%	8,500	3,776	56%
	7.8	546	59	89%	8,500	752	91%
	8.9	546	48	91%	8,500	166	98%

Sample CV6	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of pH at Ferric dose of 41	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	5.3	13890	3,094	78%	72,000	9,187	87%
	6.5	13890	876	94%	72,000	7,142	90%
	8.5	13890	159	99%	72,000	350	99%

Sample CV7	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of Ferric dose at pH 6.6	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	20	67	45	33%	600	458	24%
	41	67	153	-%	600	250	58%
	82	67	94	-%	600	469	22%

Sample CV8	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of Ferric dose at pH 6.6	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	41	15300	795	95%	34,000	6,366	81%
	82	15300	641	96%	34,000	6,388	81%
	163	15300	496	97%	34,000	4,293	87%

Sample CV7	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of pH at Ferric dose of 41	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	6.7	67	153	-%	600	250	58%
	8.3	67	227	-%	600	73	88%
	9	67	62	7%	600	77	87%

Sample CV8	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of pH at Ferric dose of 82	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	6.3	15300	641	96%	34,000	6,388	81%
	7.9	15300	420	97%	34,000	665	98%
	8.7	15300	447	97%	34,000	247	99%

Sample CV9	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of Ferric dose at pH 6.6	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	41	13,500	931	93%	23,000	3,964	83%
	82	13,500	770	94%	23,000	4,585	80%
	163	13,500	577	96%	23,000	3,219	86%

Sample CV10	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of Ferric dose at pH 6.6	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	20	250	98	61%	1,100	802	27%
	41	250	90	64%	1,100	738	33%
	82	250	82	67%	1,100	680	38%

Sample CV9	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of pH at Ferric dose of 82	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	6.6	13,500	770	94%	23,000	4,585	80%
	7.8	13,500	780	94%	23,000	381	98%
	8.7	13,500	812	94%	23,000	231	99%

Sample CV10	Copper			Zinc			
	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction	
Effect of pH at Ferric dose of 41	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	
	6.6	250	90	36%	1,100	738	33%
	8.1	250	71	28%	1,100	114	90%
	8.9	250	78	31%	1,100	64	94%

Sample CV11	Copper			Zinc		
Effect of Ferric dose at pH 6.6	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction
	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)
15	270	72	73%	1,500	1,147	24%
31	270	57	79%	1,500	845	44%
61	270	54	80%	1,500	998	33%

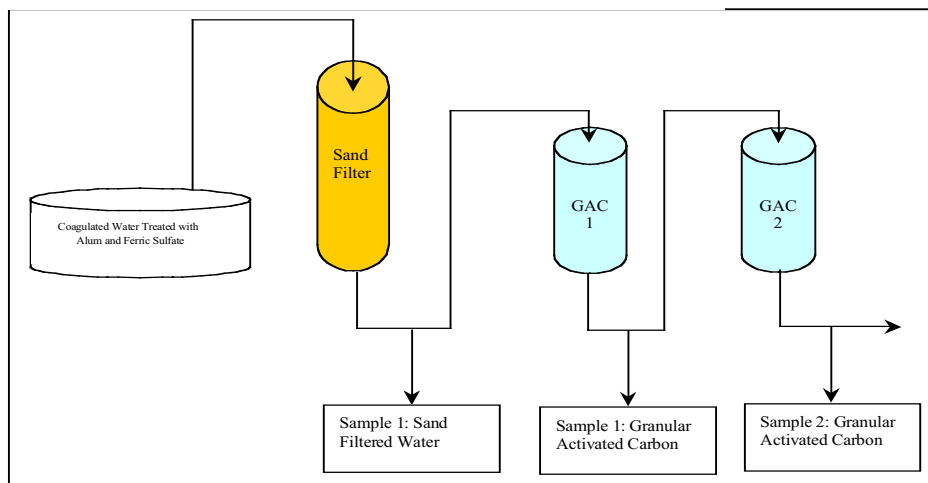
Sample CV11	Copper			Zinc		
Effect of pH at Ferric dose of 41	Initial Conc.	Final Conc.	Reduction	Initial Conc.	Final Conc.	Reduction
	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)
6.6	270	57	79%	1,500	845	44%
8.1	270	51	81%	1,500	133	91%
9	270	48	82%	1,500	43	97%

Continuous Flow Treatment Tests

A bench-scale, water treatment process train was set up in the Environmental Engineering Laboratory at Old Dominion University to simulate the CASRM barge-mounted, pilot-plant treatment system that is used for treating wash water at shipyards in southeastern Virginia (described in a later section). The Old Dominion University laboratory pilot process train consisted of a sand filter column followed by two activated carbon columns in series. The laboratory pilot process train used the same sand (mixed media) and activated carbon grades as used on the CASRM barge. The system and flow rates are scaled to give similar water-carbon contact time and water mass-carbon mass ratio as the pilot plant. Water treated first by batch coagulation was passed through the laboratory system. Samples were taken from the influent stream, after the sand filter, and after each carbon column.

A schematic of the Pilot Process Train is given in Figure 3. Data from the Pilot Process Train Studies is presented in Table 3.

Figure 3: Pilot Process Train



In this series of tests the sample wash water (influent) was first treated by batch coagulation, the resultant flocculent removed, and the clarified supernatant (coagulated influent) fed into the process train. Three samples were removed from the process train as the wash water sample was processed. Sample 1 was removed after the sample had passed through the sand filter, and Samples 2 and 3 were taken after the sample had passed through the respective activated carbon columns. The purpose of the sand filter was to determine if additional removal of fine particulates from the sample could significantly reduce the copper and zinc levels. The purpose of the carbon columns was to determine if these metals could be removed by the adsorption of organically-complexed metals. Five samples at each of the three sampling points were taken during each test (i.e. each wash water treated).

The results of the Process Train testing of the samples is shown in Table 3 below.

Table 3: Pilot Process Train Test Results
Copper and Zinc Removal Data
Process Train Tests

 Sample
 CV8

Total Copper					
	Influent	Coag. Infl.	Sand Filter	GAC1	GAC2
1	15300	431	213	18	25
2			243	15	17
3			274	23	25
4			291	25	24
5			289	24	17
Average			262	21	22

 Sample
 CV8

Total Zinc					
	Influent	Coag. Infl.	Sand Filter	GAC1	GAC2
1	34000	4800	3750	102	114
2			3870	165	76
3			4050	465	77
4			4100	721	78
5			4120	881	79
Average			3978	467	85

CV9

Total Copper					
	Influent	Coag. Infl.	Sand Filter	GAC1	GAC2
1	13500	647	495	38	43
2			530	38	37
3			532	32	40
4			551	29	45
5			552	34	39
Average			532	34	41

CV9

Total Zinc					
	Influent	Coag. Infl.	Sand Filter	GAC1	GAC2
1	23000	2221	194	107	328
2			51	136	88
3			52	242	94
4			52	368	96
5			52	511	100
Average			80	273	141

CV10

Total Copper					
	Influent	Coag. Infl.	Sand Filter	GAC1	GAC2
1	250	73	70	50	38
2			68	48	45
3			66	48	50
4			75	40	52
5			75	48	48
Average			71	47	47

CV10

Total Zinc					
	Influent	Coag. Infl.	Sand Filter	GAC1	GAC2
1	1100	202	115	845	257
2			125	734	178
3			131	676	147
4			135	629	145
5			138	587	141
Average			129	694	174

CV11

		Total Copper			
	Influent	Coag. Infl.	Sand Filter	GAC1	GAC2
1	270	53	41	41	34
2			51	34	41
3			45	29	26
4			38	40	38
5			31	34	35
Average			41	36	35

CV11

		Total Zinc			
	Influent	Coag. Infl.	Sand Filter	GAC1	GAC2
1	1500	1028	658	229	666
2			760	280	267
3			768	327	248
4			781	372	240
5			781	404	235
Average			750	322	331

Table 4 below shows a summary of the process train results in units of percent reduction of the metal from initial concentration of the incoming water (coagulated influent). For these calculations, a higher percent reduction (i.e. metal removal) value indicates greater treatment efficiency. Note the percent removal indicated for the coagulated influent is from the initial concentration of copper and zinc. The percent removal for the sand, GAC1, and GAC2 column samples is based on the copper and zinc concentrations present in the coagulated influent (not the original wastewater).

Table 4: Process Train Results Summary

Sample	Percent Reduction of Total Copper from Initial Concentration				Sample	Percent Reduction of Total Zinc from Initial Concentration			
	Coag. Infl.	Sand	GAC1	GAC2		Coag. Infl.	Sand	GAC1	GAC2
CV8	97%	39%	92%	92%	CV8	86%	17%	88%	98%
CV9	95%	18%	94%	92%	CV9	90%	96%	n/a	n/a
CV10	71%	3%	34%	34%	CV10	84%	36%	n/a	n/a
CV11	80%	22%	14%	16%	CV11	31%	27%	57%	56%
Average	86%	21%	58%	58%	Average	72%	44%	73%	77%

A review of Table 4 indicates that on average, coagulation treatment was most effective, reducing copper and zinc levels to 86% and 72% their initial concentration, respectively. The sand filter was able to reduce copper and zinc concentration to 21% and 44% of their incoming concentrations. The activated carbon columns also yielded a significant reduction in metals concentrations averaging 58% for copper and 73 to 77% for zinc. Note the negligible difference in removal efficiency between the activated carbon columns GAC1 and GAC2. This result demonstrates the maximum possible removal of the metals occurred in the transport through the first activated carbon column and that additional residence time gained in GAC2 did not appreciably affect metal removal.

The results of the Process Train tests are shown in the Figures 4, 5 and 6 below:

Figure 4: Process Train Results-Sand Filter: Percent Removal of Copper and Zinc Occurring in the Sand Filter

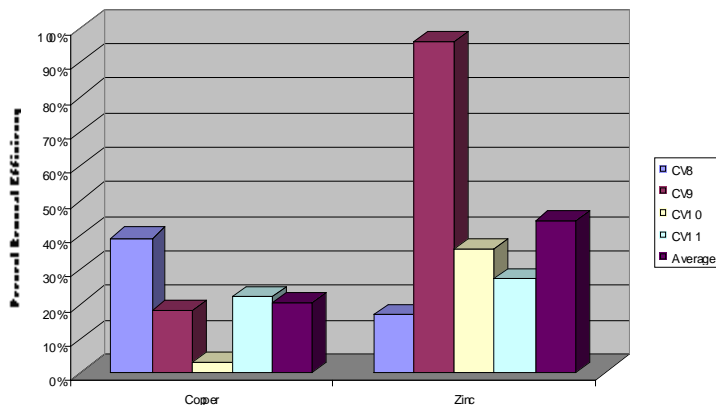


Figure 5: Cumulative Copper Removal Through the Sand Filter and GAC1 and GAC2.

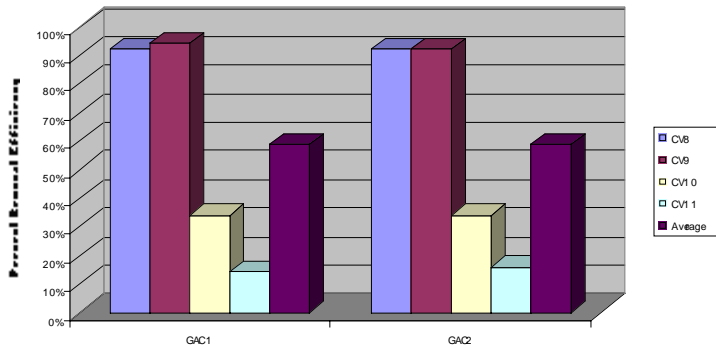
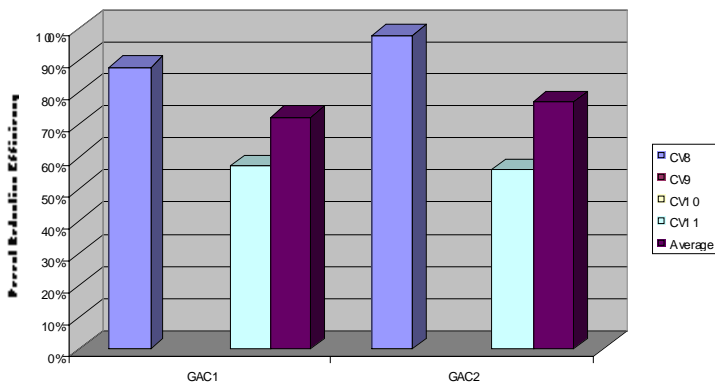


Figure 6: Cumulative Zinc Removal Through the Sand Filter and GAC1 and GAC2.



Pilot Plant Studies

The CASRM barge-mounted pilot plant was constructed as part of an effort toward aiding Virginia shipyards to achieve compliance for discharge of wastewater containing TBT and other metals. The barge is completely self-contained. It can be towed into place before the ship is dry docked, and can collect and treat water as soon as production begins. The system was designed for use in a marine environment at shipyards. It can be operated day and night year round.

Mounted on the barge is a variety of equipment to enable the unit to perform its mission. This equipment includes:

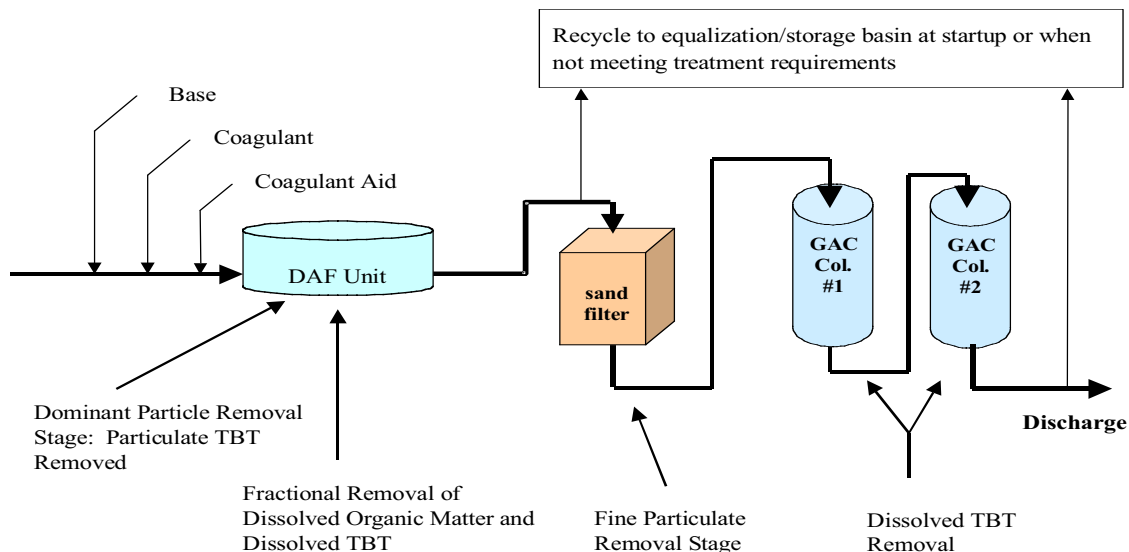
- A water treatment system
- Water storage tanks

- Storage space and office
- A piping system
- An electrical distribution system
- A monitoring and computer data logging system
- Lighting

Major components can be removed from the barge by crane in a shipyard. This arrangement was added to allow operation of the system on the barge or on shipyard property, as necessary. The pilot plant equipment is mounted on skids, each with lifting eyes and tie downs. A specially designed and constructed lifting frame is used for safe lifting of heavy skids.

The pilot plant treatment process train, shown in Figure 7 below, consists of a dissolved air flotation unit (DAF), a sand filter and two activated carbon columns, containing 7000 lbs of carbon total. The system has provision for pH control, addition of coagulant and flocculating polymer before the DAF and hydrogen peroxide before the carbon canisters. The system is currently being used to investigate optimal treatment methods for the removal of TBT from shipyard wastewater. The system can easily be set up for removal of copper and other metals from wastewater streams. The pilot plant can treat up to 100 gallons of water per minute.

Figure 7: CASRM Barge-Mounted, Pilot Plant Treatment Schematic



Pilot Plant Test Results

The wash water from ship CV5 was treated using the barge-mounted, pilot-plant process train

during the period from April 26–28, 2000. Samples were taken following individual unit processes in the treatment train, similar to the laboratory-scale, continuous-flow treatment tests described previously. The samples were analyzed for copper and zinc to determine the treatment removal efficiency of the barge-mounted, pilot plant. The results of these tests are provided in Table 5 below:

Table 5: CASRM Barge-Mounted, Pilot Plant Process Test Results

CV5 Date	Total Copper (ppb)					Total Zinc (ppb)				
	Influent	DAF	Sand Filter	GAC1	GAC2	Influent	DAF	Sand Filter	GAC1	GAC2
4/26/00	422	76	84	47		2100	194	93	224	
4/26/00	463	96	112	43	44	2200	76	96	210	294
4/27/00	587	91	116	57		2000	183	157	144	
4/27/00	662	170	175	56		2000	1013	145	137	
4/28/00	591	152	107	48	54	2200	1056	787	199	101

A review of the copper results in Table 5 indicates the average concentration of wash water influent was 545 ppb. After treatment in the DAF unit the average concentration of copper had been reduced to 117 ppb, a reduction of 79% from the initial copper concentration. The sand filter showed no significant reduction in copper concentration over the DAF unit, yielding an average copper concentration of 119 ppb. The average copper concentration was reduced to 50 ppb following treatment in the activated carbon columns. The overall copper removal efficiency of the entire pilot plant was calculated to be 91% of the average initial copper concentration.

In the case of zinc, the pilot plant demonstrated similar metal removal efficiencies. Starting with an average influent zinc concentration of 2100 ppb the DAF unit reduced the zinc concentration to 504 ppb. Treatment through the sand filter reduced the average zinc level to 256 ppb, and finally the activated carbon columns reduced zinc levels to an average of 190 ppb. The overall zinc removal efficiency of the entire pilot plant was calculated to be 91% (the same as for copper) of the average initial zinc concentration.

Comparing differences between the copper and zinc treatment efficiencies of the pilot plant it can be noted that the only difference is in the effect of the sand filter. The sand filter had no measurable effect on reducing copper concentrations of the sample incoming from the DAF unit. In the case of zinc however, the sand filter reduced its concentration by almost 50%. Note, this effect was highly variable and may in fact reflect the capture and later release of particulate metals to the sand filter effluent. However, the difference between the post-sand results for the two metals would appear to indicate a difference between copper and zinc removal from fine particulate material, the removal of which would be seen after the sand filter.

Conclusions

The data presented above demonstrate that the treatment technology being developed by CASRM to reduce the concentration of TBT in ship hull wash waters is also effective for the removal of copper and zinc.

The treatment technologies of coagulation, clarification with a DAF unit, and removal of fine particulate material via a sand filter were the most effective methods of reducing the metals concentration. Adsorption by activated carbon did, in some circumstances, effectively remove metals, more so for copper than zinc.

Treatment efficiencies of both copper and zinc can be optimized by the proper selection of coagulant dose and pH. The most optimum combination of coagulant dose and pH for removal of copper and zinc could be less efficient for removal of TBT. No effort was made in this study to attempt to find the optimal (or acceptable) process train operational condition for removal of copper, zinc, and TBT. The barge-mounted treatment plant could potentially be operated to maximize copper and zinc removal in one (or more) stages in the treatment process train while operating other/later treatment stages under different conditions that maximize TBT removal. The conditions that would likely favor maximizing copper and zinc removal as well as TBT would be operating at higher pH in the coagulation and filtration stage followed by post-DAF pH adjustment (to neutral pH) for removal of TBT on granular activated carbon.

For more information contact:
National Shipbuilding Research and Documentation Center:

<http://www.nsnet.com/docctr/>

Documentation Center
The University of Michigan
Transportation Research Institute
Marine Systems Division
2901 Baxter Road
Ann Arbor, MI 48109-2150

Phone: 734-763-2465
Fax: 734-763-4862
E-mail: Doc.Center@umich.edu