Evaluation of New Technology for Shipboard Wastewater Treatment

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***Abstract* - In 2000, the Alaska Cruise Ship Initiative found that traditional marine sanitation devices (MSD) on passenger ships, both large and small, were unable to effectively treat sewage (blackwater). In addition, untreated shower and galley water (graywater) contained bacteria and suspended solids concentrations equal to or exceeding blackwater. Since that discovery, cruise ship owners and operators operating in Alaska have worked aggressively to improve the performance of traditional MSDs or replace them with new treatment technologies to meet new Federal and state effluent standards. The efforts to improve the traditional MSD proved unsuccessful so large ships moved toward replacing them. Member lines of the North West Cruise Ship Association (NWCA) evaluated different technologies and systems and shared the lessons learned in the interest of developing an accelerated program to treat both blackwater and graywater discharge. Five different treatment methods were strenuously tested or evaluated. As of 2003, shipboard systems employing a combination of biological aerobic digestion and fine filtration were the most commonly employed systems capable of meeting stringent Federal standards for continuous discharge. These new technologies have improved the quality of wastewater discharged into Alaska water and have potential to reach other applications within and outside the marine industry.**

I. INTRODUCTION

Due to concerns regarding the quality and quantity of commercial passenger ship wastewater discharged into Alaska marine waters and the potential effects of those discharges, environmentalists, government agencies, the cruise ship industry, and other stakeholders formed the Alaska Cruise Ship Initiative in 1999 [1]. In 2000, this work group began a voluntary sampling program to test the effluents of large cruise ships that discharge in Alaska waters. Large cruise ships were defined as ships that have overnight accommodations for 500 or more people.

Commercial passenger ships produce two types of wastewater: blackwater and graywater. Blackwater is wastewater from ship's toilets. Graywater is water produced from showers, sinks and laundry. Graywater comes from three main sources: (1) galley or kitchen areas, (2) passenger/crew accommodations, and (3) laundry facilities. For regulatory purposes, a mix of blackwater and graywater is considered blackwater.

Sampling of large cruise ships in 2000 yielded unexpected results. Total suspended solids (TSS) and fecal coliform concentrations in treated blackwater were high, in most instances far exceeding the MSD manufacturer's performance certifications, which required effluent concentrations not to exceed 150 mg/l TSS and 200 fecal coliform bacteria per 100 ml. In addition, graywater analysis indicated that bacteria concentrations, suspended solids, and biochemical oxygen demand of this effluent equaled or often exceeded treated blackwater. Table I summaries typical year 2000 findings.

TABLE I
2000 SAMPLE RESULTS FOR LARGE CRUISE SHIPS OPERATING IN ALASKA [2]

Type of Water	# of samples	Tank Type	Fecal Coliform (MPN/ 100 ml)	TSS Mg/l
Galley	14	CT	13,750	420
Galley	10	DB	784,072	512
Mixed Graywater (GW)	24	CT	118,052	124
Accommodations	3	CT	104	297
Laundry	10	CT	8	38
Accommodation .& Laundry	3	CT	6.13	77.5
Blackwater (BW)	22	MSD	18,213	478
Mixed BW & GW	11	DB	12,824	119

Sample results are presented as a geometric mean.
CT – Collecting tank; DB – Double bottom; MSD – Marine sanitation device; MPN – Most Probable Number.

The 2000 data yielded results that were higher than expected because the regulations required the MSDs to be certified by manufacturer "in shop". There is no data available that indicates these systems ever met the standards in the field.

There are several possible explanations for the inability of traditional marine sanitation devices to effectively treat cruise ship blackwater The systems, using shore-based processes, may not have been adequately modified for shipboard operation. The systems may have been compromised by inadequate maintenance, ship movement, concentrated waste because of the use of low flush toilets on ships, the adverse effect of shipboard cleansers on aerobic bacteria, and inconsistent nutrient input to the aerobic biological digesters and the inability to control what passengers throw down the toilet The authors are not aware of data that proves any of these explanations or conclusively promotes one cause over that of another.

With regard to the high concentrations of fecal coliform in graywater, whether in large or small cruise ship discharge, there has been much speculation as to the source. These potential sources include bacteria from humans in shower water, growth of bacteria in the bends and elbows of graywater drain lines, graywater lines or holding tanks previously used for blackwater, and rapid bacteria growth within highly concentrated food pulp from the galley food waste grinders.

Large cruise ship owners and operators that discharge wastewater in Alaska have abandoned traditional MSDs in favor of newer "advanced" wastewater treatment technologies. Member lines of the North West Cruise Ship Association (NWCA) evaluated different technologies and systems and shared the lessons learned in the interest of developing an accelerated program to treat both blackwater and graywater discharge. Six different treatment methods were strenuously tested or evaluated. By 2001, one large cruise ship began using the one of the most promising of the systems. Another ship already had another promising system tested in 2000.

By the 2002 Alaska cruise ship season, six vessels were treating combined graywater and blackwater meeting the most stringent regulatory standards[1]. As of June 2003, sixteen large cruise ships were operating advanced technology systems in compliance with the Coast Guard regulations. Table II presents typical effluent constituent concentrations of wastewater treated with advanced treatment technology in order to meet stringent Alaska in-port standards.

II. TRADITIONAL TREATMENT SYSTEMS

Two processes have traditionally been used to treat sewage on ships: maceration-chlorination and biological-chemical disinfection. Process comparisons for both systems appear in Figure 1.

A. Macerator-chlorinating systems

This system reduces biosolids through oxidation, dilutes the effluent with ambient seawater, and disinfects. The macerator pump breaks up solids in the sewage influent to a maximum particle size of 1.5 mm. The wastewater is then mixed with ambient seawater and passed between the charged cell plates where a number of reactions occur simultaneously. The reactions cause the electrolytic breakdown of the organic molecules and the production of sodium hypochlorite, which will continue to oxidize the stream in a contact tank. Disinfection by chlorine occurs using this "electrocatalyst" process that produces sodium hypochlorite disinfectant from the salt in the seawater, with a design 90-95% oxidation rate and a total bacterial kill within minutes [3]. The treated water remains in the contact tank, usually for a minimum of 30 minutes. Some operators add chlorine to tank to ensure disinfection is complete when in brackish water or add salt to the effluent since the ambient water has low salinity. Material not oxidized (cellulose) is returned for further treatment. Gases produced from reactions are mixed with ambient air and exhausted.

One of the system's detractors is that operators tend to "over-chlorinate" in excess of the manufacturer's recommendations to meet the Alaska fecal coliform standards, resulting in high levels of residual chlorine in the discharge. The chlorine concentration in ambient water must be less than 2 µg/l (ppb) to protect aquatic life. The Alaska Department of Environmental Conservation (ADEC) conducted Whole Effluent Toxicity (WET) Testing in July 2002 [4]. This test provided evidence that chlorine in the effluent is highly toxic to marine life. The chlorine works as it should to ensure human disease carrying organisms are not discharged to the environment, however the residual is lethal to marine organisms.

B. Biological and chemical disinfecting systems

The marine biological treatment systems are similar to land based secondary municipal treatment systems. This treatment system has three steps: (1) aeration; (2) clarification & filtration; and (3) final chemical disinfecting.

The raw sewage passes through a screen, which removes grit, then enters the MSD aeration chamber. In the aeration chamber the raw sewage mixes with a large concentration of active aerobic bacteria. The bacteria start to consume the organic waste material in the sewage [5]. The chamber contains air diffusers that provide oxygen to keep the aerobic bacteria at optimum health and support reproduction.

The wastewater flows from the aeration chamber into the clarification and filtration chambers. The filter media removes larger pieces of organic waste not consumed by bacteria in the aeration chamber. The aerobic bacteria also consume the biomass on the filter.

After clarification and filtration, the treated water flows through the internal piping into the chlorine contact chamber. This chamber disinfects the wastewater by combining the treated water with chlorine. Some systems use ultraviolet light for disinfecting in areas where chlorinated effluent is not allowed. The wastewater stays in this chamber until virtually all the bacteria that were allowed to pass through the previous chambers are killed off. The chlorine residual levels usually control this. A chlorine residual of 1-2 PPM is sufficient to kill most of the bacteria.

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[1] If the effluent meets the most stringent standards under Coast Guard regulations (33 CFR 159 Subpart E), the vessel may discharge at less than 6 knots and within 1 mile of the shoreline (sometimes called the "in-port" approval). In general, these standards are:

Fecal coliform	not to exceed 20/100 ml (30-day geometric mean)
Total residual chlorine	not to exceed 10 mg/l
BOD	not to exceed 30 mg/l (30-day average)
Suspended solids	not to exceed 30 mg/l (30-day average)
pH	6.0 – 9.0

The details and specifics of these requirements may be found in 33 CFR 159.309(b), 40 CFR 133.102, and enclosure (1) Captain of the Port Southeast Alaska letter 16455 of January 1, 2002.

Biological on board systems do not have the advantages that land based treatment units have of high dilution from graywater and ground water infiltration. Salt-water infusion can kill the treatment organisms, so fresh water, rather than salt water has to be used for flushing toilets. Biological systems thrive on a constant, even flow of nutrients and constant pH. Ships' treatment system demand is intermittent with periods of low or no flow. Biological systems need a constant flow to "feed" the microorganisms.

III. ADVANCED TECHNOLOGY TREATMENT SYSTEMS

Large cruise ship operators have evaluated several advanced wastewater treatment designs. These include chemical treatment and mechanical decanting; activated oxidation and oxidant disinfection; reverse osmosis filtration, and bio-reactor/filtration. These processes are briefly described below and generally compared in Figure 2. The authors have only compared processes. The overall value and efficiency of each system, which includes evaluation of the required initial expense, maintenance, operator training and monitoring, continues to be a subject of research by the cruise lines.

A. Chemical treatment and mechanical decanting

This system uses chemical treatment and a mechanical decanter, followed up by a UV purifier. The design is used successfully for shore-based applications and showed promise in large-scale laboratory tests. However, the pilot cruise ship installation determined that modifications were necessary for a fully operational treatment system.

B. Activated Oxidation Process

This non-biological treatment system has consistently provided high-quality effluent that under test conditions. The treatment process has four major components: (1) a primary screening system, (2) a primary solids separation and oxidizing system, (3) a secondary oxidation tank, and (4) controls and oxidant generation equipment. Electrically produced oxidants eliminate the need for chlorine disinfection. A polymer is added to the preliminary stage to remove sludge before the effluent enters the system. The sludge can be de-watered and incinerated onboard. This treatment system has been installed on one cruise ship and the manufacturer is conducting the tests and analysis on this ship to meet Coast Guard in-port discharge standards. This system has not received USCG certification as of June 2003.

Ozone residuals are toxic to marine life but the residuals dissipate so quickly they are usually gone by the time it reaches the receiving water.[6] Ozone byproducts have been generated during disinfection experiments. These byproducts may be toxic and carcinogenic depending on the wastewater quality, but little is presently known about these products because this technology is not used extensively on wastewater as a treatment. However, ozone presents fewer known potential environmental and health effects than chlorine and its byproducts [7]. There is more information regarding treating drinking water with ozone that wastewater. Again, there is the potential for hazardous byproducts from treating the sewage with ozone but there is little research material available on the subject, except for manufacturer's claims.

C. Reverse Osmosis Filtration

Osmotic theory implies pure water will move across semi-permeable membrane into wastewater until the contaminant concentrations of both liquids are equal. However, if external pressure is exerted on the "contaminant" solution, water will flow in the reverse direction from the wastewater into the pure water. This phenomenon, known as reverse osmosis (RO), can separate pure water from contaminated matrices. Reverse osmosis treatment systems employing this process have installed on two ships operating in Alaska, with one approved for in-port discharge. This system has ultraviolet (UV) disinfection after the RO. Analysis of the effluent from the fully operational RO/UV units indicated that suspended solids and fecal coliform met the USCG stringent standards. The presence of some BOD and a slightly low pH requires some buffering and a final run through activated charcoal canisters before discharge. This system produces some sludge that must be incinerated, discharged at sea where legal, or landed ashore.

D. Bio-reactor/filtration

These units employ an integrated system of enhanced aerobic digestion and low-pressure membrane filtration to treat blackwater and graywater. Currently, fourteen ships operating in Alaska have installed this process using three different vendors. Essentially, on each of these systems the designers have enhanced traditional treatment methods (biological digestion, filtration) with advanced engineering. Each of the three units emphasizes one of the two treatments over the other. For example, one system, after only a brief holding period in the bio-reactor, passes the influent through membrane filtration modules that have very large surface area and a extremely small nominal pore size (0.035 micron or 0.035 X 10^{-6} meters). Another, apparently equally effective unit, does not rely of ultra-filtration as much. This unit enhances the capacity and effectiveness of the bio-reactor with plastic carrier elements (biofilm) suspended in the wastewater to increase reactor surface area. All bio-reactor/filtration units also use ultraviolet irradiation before discharge overboard or to a holding tank. As with the reverse osmosis system, bio-reactor/filtration produces solid sludge that must be properly handled and disposed.

TABLE II
SOME 2002 and 2003 SAMPLE RESULTS FOR LARGE CRUISE SHIPS OPERATING IN ALASKA AND USING ADVANCED WASTEWATER TREATMENT TECHNOLOGY FOR CONTINUOUS DISCHARGE

Treatment	#	Fecal coliform MPN/100 ml	TSS mg/l	BOD Mg/ml	Cl mg/l
Reverse Osmosis (April 2003)	12	<1	<1	0.98	ND
Bio-reactor ultrafiltration	21	2	3.8	3.2	0.1
Bio-reactor filtration	10	ND	<5	3	ND

Concentrations are averaged.

IV. SUMMARY

At significant expense and effort, the cruise industry has been able to re-engineer traditional treatment methods to clean wastewater. Generally, cruise ships using advanced technology have combined enhanced aerobic digestion with physical filtration to clean shipboard wastewater. These systems do not use chlorine for disinfection, which is toxic to marine life. They do produce solid sludge, which requires proper disposal. If sludge production becomes problematic, the wastewater residence time in the aerobic bacteria digesters could possibly be increased. The ship owners and operators have greatly improved the quality of their ship's wastewater discharged in Alaska water. Cruise lines demonstrated innovation and ingenuity; quickly researching, installing and operating these systems on existing ships. Both authors agree that these systems have potential to reach other applications within and outside the marine industry. The authors hope that as the overall efficiency of these systems improve, (a combination of initial expense, energy demand, amount of required training, monitoring and maintenance) they can be applied to the landside sanitation challenges of the developing world, where 3 billion people lack access to basic sewage systems [8].

References

[1] *Alaska Cruise Ship Initiative: Historical Information;* http://www.state.ak.us/dec/press/cruise/documents/cruiseshipinitiative.htm

[2] C. Morehouse, "Wastewater sampling and analysis for commercial passenger vessels," in *The Impact of Cruise Ship Wastewater Discharge on Alaska Waters*, Table II-5, pp. II-14, ADEC Nov. 2002

[3] Information obtained on manufacturer's website http://www.alfatec.com/exceltec.asp

[4] Whole Effluent Toxiicity Test Results, July 2002, Alaska Department of Environmental Conservation at http://www.state.ak.us/dec/press/cruise/documents/wetfinal.htm

[5] Information from Red Fox Manufacturer's website http://www.redfoxenviro.com/foxpacmarinemsd.html

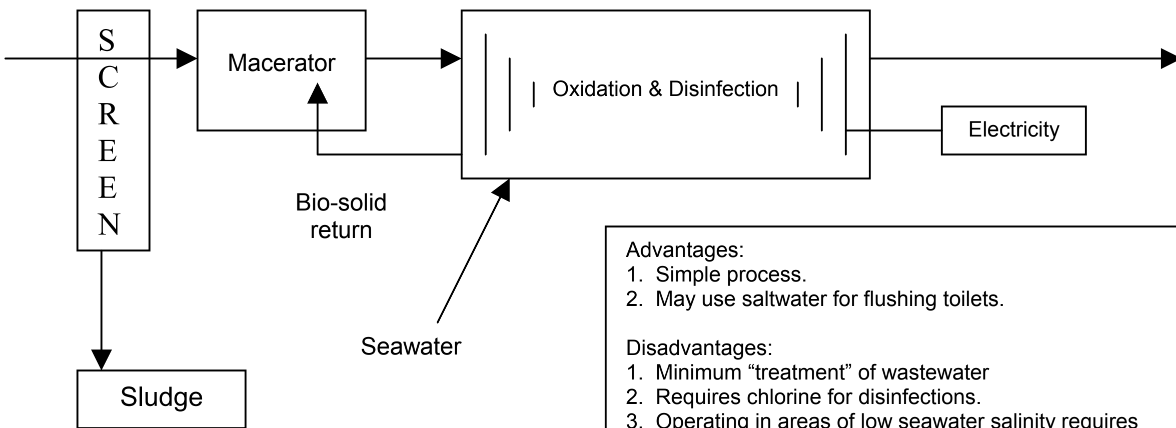
[6] EPA 832F99063,EPA Ozone Fact Sheet, September 1999.

[7] EPA/625/1-86/021 EPA Design Manual Municipal wastewater disinfection

[8] D.B. Brooks, *WATER: Local-level Management*, International Development Research Centre Canada (IDRC 2002), ISBN 0-88936-996-8

FIGURE 1
TRADITIONAL MARINE WASTEWATER TREATMENT SYSTEMS
Simplified schematics

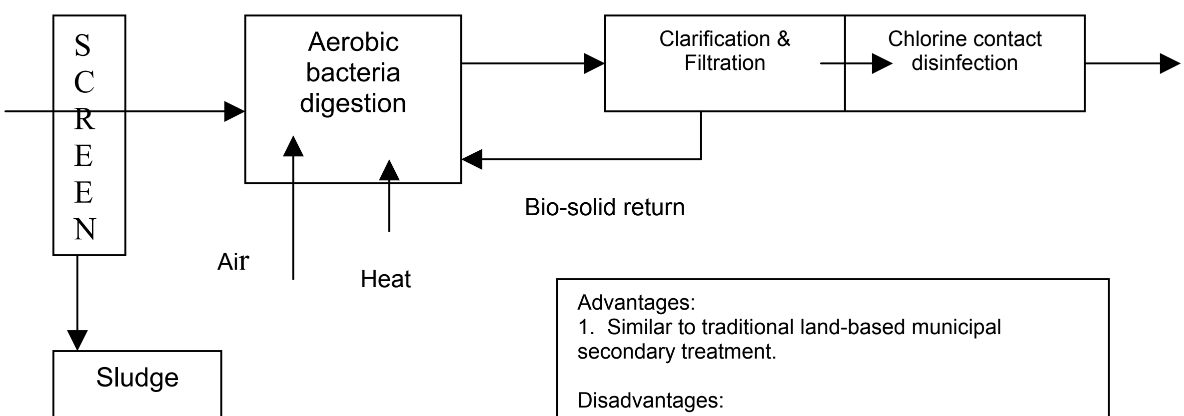
Macerator-Chlorinator



Advantages:
1. Simple process.
2. May use saltwater for flushing toilets.

Disadvantages:
1. Minimum "treatment" of wastewater
2. Requires chlorine for disinfections.
3. Operating in areas of low seawater salinity requires chemical make-up or salt tablets.

Biological-Chemical Disinfection



Advantages:
1. Similar to traditional land-based municipal secondary treatment.

Disadvantages:
1. Requires fresh water influx.
2. Disrupted by intermittent flow common to shipboard life.
3. May require chemical disinfections.

FIGURE 2
ADVANCED WASTEWATER TREATMENT SYSTEMS
Simplified schematics