SHIPBOARD ENVIRONMENTAL PROTECTION SYSTEMS

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ABSTRACT

It is a U.S. Navy objective to minimize undesirable environmental effects of ships. A brief overview is given of early efforts to reach this goal and of lessons learned, followed by studies on the dispersion of sewage discharged by moving ships, acquisition of a data base and a unique test facility, of the development of sewage treatment systems (collection, holding and transfer; evaporative toilet; biodegradation; vacuum collection/incineration) and others (trash compactors, garbage grinders), of the integration of waste management and energy conservation (showers, laundry) and of reliability/maintainability development. Mention is made of work in progress.

INTRODUCTION

Although the history of efforts to decrease harm done to the environment by man exceeds three centuries, available knowledge and technology, funding and environmental legislation were insufficient in the late sixties to permit the creation of systems and conditions that would substantially decrease water pollution caused by ships. More than a decade later we know more about water pollution abatement and its technology. Project fundings as well as regulations have both expanded. However, we still do not have a firm hold on all ship related water pollution, but optimism concerning the future is warranted. This paper briefly describes technical aspects of the U.S. Navy role in abating water pollution stemming from its ships. The subject matter, which includes shipboard wastes other than oily water, will be seen to have a significant energy conservation aspect.

In the beginning

Black water was the first of the shipboard wastes to receive attention. Managing it by using a holding tank system was not then considered practical because space on-board most Navy ships is extremely limited due to the presence of the many mission-related systems. Furthermore, there was confidence in the minds of those concerned with ship pollution abatement that the state-of-the-art of treating sewage would require but little augmentation to permit the assembly of a satisfactory shipboard treatment system. Some sewage generation rate data had been acquired. Questions on how to spend available funds were answered in favor of system development. It was realized that although pressure had been brought to bear on the Navy to proceed with water pollution abatement, wisdom in this area of work was untested. Rules for treatment (when and where to treat, degree of pollutant removal) were prepared but debated. For small craft, it was required that the treatment system effluent would contain not more than 100 total coliform bacteria per 100 ml and that the nature of the material be disguised. The chlorinator/macerator units of the era sometimes were successful in meeting this standard, until they corroded, which usually was soon. Due to the high chlorine content of their effluents they also were potent polluters. For larger vessels the requirement was that the effluent quality would not exceed:

- Suspended solids 150 ppm
- BOD5 50 ppm
- Total coliform bacteria 1000/100 ml

System development, reliably to meet this standard (or a similar one), did not succeed for more than a decade, although this is not for lack of effort. A large number of commercial and Navy organizations provided input during this period. Technological optimism was replaced by tenacity supported by increased funding which led to four novel approaches to shipboard sewage treatment. These (200 man rated) systems were based on (a) ultrafiltration coupled with biodegradation, (b) screening followed by centrifuging and incineration, (c) oil flush and incineration of the waste phase, and (d) recirculation with concentration and holding, respectively. Lessons learned include:

- Fresh shipboard (saltwater) sewage has properties that are quite different from the blackwater familiar to shoreside sanitary engineers. This ultimately resulted in the construction of a unique facility in Annapolis that can provide a 250 persons related supply of this commodity for realistic evaluations of systems designed to treat it.
- Shipboard sewage treatment prototype systems suffered from severe materials...
and reliability problems on shore, regardless of the treatment principle(s) involved.

- Such systems, when installed in a ship and used, will most likely suffer additional problems of these types. This underlines the need for a thorough prior investigation/development in the laboratory, because shipboard test time is precious.

- It is difficult or expensive to determine, in the case of flow-through systems, whether at any given time they actually can or do operate in compliance with a given set of effluent quality requirements.* The search for near real time read-out monitoring systems for fecal coliform count and suspended matters content is still underway.

- Shipboard sanitary systems do not always get the maintenance attention needed. Other systems often have higher priority.

- Personnel related components (a novel commode, an unusual type of shower) which are different from those with which the users became familiar early in life, will be viewed with reservations by many.

Sewage discharges overboard

While the development of shipboard systems for abating water pollution by sanitary waste was generally looked upon favorably in the early seventies, questions about degree-of-necessity, the when-and-where, were being asked. No reason was known why sewage discharge should not take place from a ship on the high sea. In fact, this may locally improve the organics balance beneficially. The opinions about the effects of viruses and bacteria in sewage discharges in coastal waters on, for instance, hazards to bathers, were sharply divided.9,10 At any rate, in terms of total quantities of fecal organics and numbers of bacteria discharged, fish and sea mammals far exceed the limited numbers of people travelling the seas. Nonetheless, it was recognized early in Navy pollution abatement work that information on the dispersion of sewage discharged at sea, was needed. Controlled releases were made of sanitary wastewater and tracer dye mixtures near Norfolk, Va., and San Clemente Island, Ca. These discharges were made from stationary and from moving ships. Dispersion of the waste/dye patches and wakes was monitored through aerial reconnaissance, precise radio-navigational information, and seawater sample collection at three depths. It was demonstrated that pollution (5-day biochemical oxygen demand, total suspended solids, ammonia-nitrogen, total acid-hydrolizable phosphate, and coliform bacteria) from controlled releases of sanitary waste can be detected above background concentrations for a brief span of time by using conventional methods for determining effluent water quality. A mathematical model for the dispersion of pollutants discharged from ships in the coastal zone was developed from these data. An assessment was then made of the detectability of pollutants discharged from Navy ships during normal operation. Seawater samples were also collected fore and aft of ships in normal transit and from the water around ships anchored for an amphibious operation in the coastal zone. It was determined that non-bacterial pollutants discharged from the transiting ships were not measurable above background concentrations, and only slight coliform bacteria population increases were detected in the amphibious operations area.11 These levels were still well within those prescribed as safe for bathing beaches and fisheries. Findings of this study may be used for estimating effects of sanitary waste (or other wastewater) releases by non-Navy ships and in other areas. For instance, if in the process of discharging wastewater from a transiting ship it is desired that the initial maximum concentration of a specific pollutant in the ship's wake be kept below a predetermined value, equation (1) can be used:

\[
Q = \frac{268 \, C_m \, A \, U}{C_0} \quad (1)
\]

Q = wastewater discharge (gal/min)
C_m = initial peak concentration in wake
C_0 = onboard (tank) pollutant concentration
A = submerged cross-section of ship (beam times draft, ft.²)
U = ship's speed (knots)

It is indeed possible for ships that have a holding (flow smoothing) tank, to discharge sewage such that the coliform count in the wake will not exceed, for instance, the shellfish bed limit of 70/100 ml. It has been shown that this can be achieved for different classes of Navy ships at speeds well below their normal cruising speeds.12 This method has shipboard application potential whenever the solution to a problem of pollution is dilution, as was also considered elsewhere.13

Data Base

The information on which the design of the very earliest experimental systems for shipboard sewage treatment was based, was limited. It was felt that better information would add to the chance of success in system development. Furthermore, in cases in which a ship's wastewater would be processed on shore, this information would be needed for treatment plant design or for determining treatment charges. Subsequently, all but the most minor wastewater flows were measured. Flowmeters and sample ports were installed on ships of different classes, samples taken and analyzed for thirty parameters. In one case, virtually all flows on one destroyer were measured during the same time period. Data base acquisition is a continuing process. It currently involves shipboard toxic and hazardous
The Navy Environmental Protection Support Service sponsored a computerized system for ship environmental data retrieval and statistical manipulation, for use in predicting ship outputs under various conditions. This system is now in operation at DTNSRDC, Annapolis, Md. The most significant item learned from the data base work probably is that water consumption or wastewater generation rates data need to be used or interpreted with care, and that the condition of equipment on a ship can influence wastewater generation rates considerably. In the case of an older destroyer, repair of the flumes reduced total ship wastewater output by nearly 90%. A designer of a shipboard system for treatment of any waste is therefore well advised to determine the criticality of the condition of devices that are "upstream" of his prospective treatment unit. Information on vessel emissions so far has been sent to the U.S. Army, EPA, Maritime Administration, USCG, several universities, State and local governments.

Continued sewage system development

The time frame initially projected by the regulatory authorities for compliance with shipboard sewage treatment system effluent quality standards, and the increasing realizations that the development of systems for that purpose was proving to be difficult, led to a decision to install collection, holding and transfer (CHT) systems in Navy ships. At the same time, treatment system development continued. Interesting results issued from both, ultimately of great benefit to the Fleet and ship owners/operators outside of the Navy.

(a) The original CHT systems suffered from the fact that they were not the result of a Navy development effort (such as described in a separate section) and from the lack of attention by some crew members (who often are required for work on higher priority systems). The tanks of these systems are shallow (6' to 7') compared with width and length, and pump-out usually stops at the 30% level. Problems with pumps, comminutors, level controls, coatings, grease deposits, sludge layer formation and noxious gas generation, clogging, etc. were encountered and overcome. It is not in the scope of this paper to recount this, with the exception of what probably is the most severe problem and its remedies. This concerns the anaerobic condition that will occur in sewage tanks when sludge layers are allowed to build up. It occurs wherever the fluid near the bottom is nearly or wholly stagnant. The resulting sludge will become anaerobic and will soon generate a gas that is combustible, poisonous and odoriferous. A well-established sludge layer is difficult to remove, even by hosing after tank pumpdown, and eliminating the root cause of the problem is far preferable over curing its symptoms. The best established method to prevent it is to aerate continuously using a distribution of air spargers such that the horizontal velocity component of the water near the bottom is not less than 1.2 ft/sec. This requires a residual water volume sufficient for air sparger effectiveness. In many cases, however, it is more economical, quieter and simpler to install another system. This involves circulating the sewage external to the tank. Where it re-enters, near the bottom, an air aspiration system (venturi and standpipe) can easily provide what little air is needed to prevent anaerobiosis. The momentum of the reintroduced aerated sewage prevents sludge settling if the pump is sized correctly and sewage exit and re-entry points are well chosen. When this system is applied, tank contents pump-down ceases at 10% of the tank volume.

(b) Holding tank systems are fundamentally simple but their limited capacity may lead to problems under conditions in which overboard discharge of untreated sewage is not permitted (in ports and territorial waters of the U.S. and some other countries) and when an off-loading facility (a barge, pier sewer or tank truck) is not available. In this respect, many Navy vessels are at a disadvantage compared with freighters. The latter have relatively small crews and the ships are not space critical.

Although CHT system improvement continued steadily, shipboard sewage treatment system development went forward also. Three results will be discussed.

- The Evaporative Toilet System has been designed for crews of not more than approximately 25. As with other developments described below, the pollution problem solution is first approached in this system by sharply reducing the volume of the per capita per day output. Using special commodes and urinals (flushes of 3 pints and 1 pint respectively) the per capita per day blackwater volume is kept below 2 gallons. After flushing the waste is moved to an evaporation tank by a grinding pump. The system is independent of gravity for moving the waste. The ground waste is concentrated in the steam jacketed evaporation tank until heat transfer into the fluid degrades due to its increasing viscosity. Consequently, the fluid level slowly rises and the tank must be emptied (to a pier sewer, a ship waste off-loading barge or on the high sea). The system provides an extended holding capacity (10 to 15 days). The Navy has developed this system for use of seawater for flushing. Service use approval has been given, as has U.S. Coast Guard certification as a Type I and a Type III system. Of the two versions of the system, several hundred have been delivered to or ordered by the Navy, and 50 by other government agencies.

- The LHA-1 class ships are equipped with an aerobic biodegradation system designed to serve crews of 800 using conventional toilets and urinals. The treatment approach is conventional. The wastewater is aerated in a fully mixed reactor to which sludge is returned from the settling tank following it. The clarified fluid from the settling tank is treated with hypochlorite prior

*These effects have also been observed in holding tanks of vessels owned by States (ferries) or commercial concerns.
to its discharge overboard. The system has demonstrated that its effluent meets DOD, EPA and USCG quality standards (1978). As far as is known, it is the only aerobic treatment system for shipboard use and large crews that has demonstrated its at-sea functionality, using controls that are workable under realistic conditions by shipboard personnel (settable solids volume in 30 minutes, dissolved oxygen and residual chlorine contents). Five units of the LHA-1 system have been installed.

- The vacuum collection/waste incineration system, of which 60 have been installed in the 30 ships of the DD 963 class of destroyers, is, like the Evaporative Toilet System, based on limited flush volumes. The preferred flushing fluid is not salt but fresh water. The daily per capita sewage volume is less than 2 gallons. The wastewater is moved by the pressure of the ambient air through reduced diameter pipes to a small collection tank in which a mild vacuum is maintained. Tank contents are ground and sprayed into the oil burner flame of a horizontal attitude vortex type incinerator. The waste droplets dry out, the residue incinerates in transit, and the ash settles in the quiet zone. This system has gone through a prolonged upgrading sequence and it recently successfully underwent the operational evaluation to which new Navy systems are subjected. One noteworthy problem experienced (and solved) was the short operational life of the incinerator internal components. This had been the case with all Navy experimental incinerators for human waste. No alloy (or ceramic) had been found that can sufficiently resist the hot corrosion conditions that occur with the molten ash of this waste. The solution found was to cause the incineration to take place in suspension, to improve the controls on the process such that little or no molten ash impinges on the incinerator internals, and to select an appropriate liner alloy. In the testing process in the laboratory, samples of candidate materials, mounted on a rotating table, were subjected to high temperature, combustion products and an intermittent spray of urine. An improved alloy was selected and installed.16 As a result, the vortex incinerator's operational life expectancy in combusting concentrated sewage increased to several thousand hours (from a few hundred). Another solution to the problem is to add small amounts of lime to the sewage. This raises the ash melting point by 400°F, thus avoiding hot corrosion. This approach has not yet been taken beyond the early development stage, however. The vacuum collection system for sewage (first established in Sweden and on ferries in North-Western Europe) coupled with the vortex incinerator, now is a functional reliable system in the Spruance class of ships in the U.S. Navy. It provides those ships with an independence that CHT systems cannot provide.

This is attractive for environmental and political reasons, at home and abroad.

**Garbage grinders**

- Navy surface ships garbage grinders have been plagued by reliability/maintainability problems. Consequently, two new models have been developed, a 5 HP and a 3 HP system. The former is used in dedicated garbage rooms and it has been approved for service use (ASU). The latter is for use in smaller ships in sculleries and galleys. ASU is expected in the near future.

- A requirement for a quiet reliable garbage grinder for submarines has been filled by a small low rpm unit. The first one of this type, installed in a nuclear submarine four years ago, has exceeded performance requirements (ASU is expected soon). Application of this garbage grinder has led to a 50% reduction of the use of the through-the-hull trash disposal unit, because the ground garbage slurry is transferred to a wastewater tank.

**Pollution abatement integrated with energy conservation**

In the foregoing, two systems were briefly described which, for any given crew, generate sewage at about one-tenth of the rate associated with a well maintained and calibrated conventional shipboard system. And although the total amount of pollutant is not changed thereby, the volume to be processed is sharply reduced. If the sewage is not to be treated but only held, a given holding tank would provide a commensurately increased holding period. Wastewater volume reduction can also be applied to shower and laundry systems, with a similar advantage. This has an added attraction in that fresh water saved directly relates to the use of fuel oil needed to generate steam for the on-board distilling plant.

- The Navy reduced flow hand-held shower head does not generate water when it is not held in the hand (a button on it needs to be depressed before water will flow). This means that when the person taking the shower is lathering, water does not run and is not wasted. Furthermore, when it runs, the water is used at a much lower rate than with the conventional shower types. A pressure compensated valve is used in conjunction with the hand-held shower to ensure that the user will experience a substantially constant water temperature (after making an initial choice) independent of line pressure variations. Water use in conventional showers had been measured in nine ships (8 classes, 67 data points). The overall average was 5.8 gal/min (standard deviation: 1.9 gpm; 95% confidence interval: 2.1-9.5 gpm). The duration of a shower is, under realistic conditions, difficult to determine with precision.*

*1.5" for urinal drains, 2" for commode drains.

* Observation of certain events influences their duration.
It is estimated to be 4 minutes. A conventional shower thus would consume some 23.2 gallons. During an 87-days test on USS INGRAM (DD-938) with a crew of 298, the shower water use was 2.4 gal/man-day (a saving of roughly 90%). Hand-held reduced flow showers have subsequently been installed in aircraft carrier USS SARATOGA (CV-60) for further evaluation. The ship retained them after the evaluation period. Fleet-wide distribution is planned. Resulting fuel oil savings are projected at $20,000,000 annually (at current prices). Shower unit modification cost is approximately $115, with installation by ship's force.

- Modern laundry practice, as applied at the U.S. Naval Academy, was put to use on board SARATOGA, resulting in potable water use for laundry of 2.7 gal per capita per day during a 24-week period. A previous survey (on 45 ships) had disclosed an average value of 6.3 gal per capita per day. A laundry water use saving of 57% has been achieved. So far, there are no regulations against overboard discharge of shower and laundry wastewaters while in transit in the territorial waters. In port they are discharged to a holding tank from which they are pumped to a pier sewer.

Reliability and maintainability

Millions of people commute daily by automobile without much concern about the reliability of their vehicles. The automobile is established as sufficiently reliable for the purposes of the users. This has taken decades of development and improvement. The Navy cannot wait that long before adopting a new system for shipboard use, and therefore has organized an approach to system acquisition that is intended to achieve (not just specify) system reliability via a well-defined sequence of tests. It is not in the scope of this paper to detail that process, but some of its highlights will be given for the sewage treatment systems mentioned.

- After a feasibility demonstration, usually involving a "breadboard model", has established that a novel system concept can work, a laboratory model (actually full scale) is designed on the basis of a specification. The latter includes reliability and maintainability requirements.

- The laboratory model is evaluated in a shore facility, its performance measured and its shortcomings assessed.

- An upgraded model is assembled and it may be operated in the laboratory prior to shipboard installation.

- Shipboard installation is followed by a re-evaluation of system performance; invariably, novel problems are uncovered.

- After additional improvements and testing, the system may be certified for an operational test. The personnel involved with system development and crew training, cease operating the system. The ship's crew takes over and the test is conducted under the auspices of the Operational Test and Evaluation Force.

- The Chief of Naval Operations may grant approval for service use after the system has met all operational test requirements. Among the most important of these are reliability and maintainability. For sewage systems these have been specified as follows:

  - The mean time between failures (MTBF) shall be at least 500 operating hours, at the 90% confidence level.
  - The maximum time to repair (MTTR) is to be less than 5 hours (at least 95% of repair times shall be less than 5 hours, at the 90% confidence level).

It may be assumed, on the basis of ship operating scenarios, that a shipboard sewage treatment system will rarely be required to operate for more than a few days.* Its mission time \( t_m \) will be of the order of a few days.

\[
R = e^{-\frac{t_m}{MTBF}} \quad (2)
\]

If the probability \( R \) that the system will function during the mission is .90, and if the MTBF requirement is not less than 500 hours, a calculation using equation (2) shows that \( t_m = 52.7 \) hours. Experience has shown that this coherent set of values is realistic for Navy sewage system use. Test time needed to demonstrate the desired reliability can be calculated from:

\[
t = \frac{MTBF \cdot X^2_{0.90;2r+2}}{2} \quad (3)
\]

where \( r \) = number of failures, and \( X^2_{0.90;2r+2} \) the Chi Square Statistic.18 For zero failures this statistic is 4.61 and \( t \) is then found to be 1150 hours. If one failure occurs, \( t = 1950 \) hours; if two occur, \( t = 2660 \) hours, etc. This illustrates very well that if the pre-set reliability has to be demonstrated, it doesn't pay to go on-board with a system that probably will fail before 1150 test hours (47.9 days!) have been logged. It is noted here, that the shipboard environment is generally harder on systems than conditions on land.

* When not transiting a no-discharge zone, a Navy ship will usually be serviced at a pier sewer, or by a ship waste off-loading barge, or (in some foreign ports) a sewage truck.
Whether the maintainability requirement is being met can be determined by logging repair times (twenty for the systems discussed). If the tests have not generated sufficient data for this, failures must be "introduced" by a neutral observer in the absence of assigned crew members (who then must troubleshoot and repair the system). The maximum time to repair can then be calculated using:

$$T = \bar{D} + KS$$  \hspace{1cm} (4)

where:

- $T =$ log of maximum corrective maintenance (CM) downtime
- $\bar{D} =$ mean of the logs of the observed CM downtimes
- $K =$ factor for one-sided tolerance limit for normal distribution ($P = .90$)
- $S =$ standard deviation of the logs of the CM downtimes

Values for $K$ may be obtained from the literature.9

Work in progress

Ideally, all shipboard waste streams of significance should be dealt with in an integrated automated reliable system of modules that require minimal preventive maintenance and consume energy at a low rate. Efforts are underway to achieve at least a partially integrated shipboard waste management system. Current work is focussed on module development, with integration (including overall control) to be the next undertaking. Examples of current undertakings follow.

- A shipboard 300-man related multifunctional waste incinerator for destruction of on-board generated trash, food waste, sewage concentrate and oily waste (from an oil/water separator) has been under development.20,21 Installation in a modern destroyer is being planned, after completion of the laboratory evaluation. The system has a volume of 8x8x7 feet and weighs 16,000 pounds. A substantial fraction of problems encountered and rectified concerned materials of construction. The inner surfaces are made of ceramic materials. It is expected that addition of minor amounts of lime to the sewage will be very beneficial (as described for the vortex incinerator).

- Although the use of shipboard collection, holding and transfer systems, ship waste off-loading barges and pier sewer connections is expected to lead to meeting the April 1981 DOD discharge requirements, these systems cannot provide complete coverage. Any extensive transit through territorial waters or a stay in a port without sewage off-loading facilities, beyond the time it takes to fill the CHT system tank, will result in a discharge. Work on removal of suspended solids from sewage (to $\leq 150$ ppm by weight) and on disinfection of partially clarified sewage (to $\leq 200$ fecal coliform bacteria per 100 ml) is therefore underway. A promising system for removal of suspended solids from fresh salt water sewage involves the use of a centrifugal clarifier. In this cylindrical system (with vertical shaft attitude) there is very little shear in the fluid, as system internals (a shaft carrying vanes), the outer wall and the fluid itself rotate at the same rpm. In its present form it consistently removes sewage suspended solids to $\leq 150$ ppm at flowrates up to 10 gpm (which is in excess of need for a destroyer-size crew). The concentrate from this clarifier would, in an operational situation, be returned to the sewage holding tank (to extend its holding time) or be destroyed in an incinerator. The partially clarified effluent requires disinfection. Promising approaches involve the use of a slowly alternating polarity direct current electrolysis system, of a solution of halogenated dimethyl hydantoin, and of ozone. Disinfection by ozonation of partially clarified sewage has been demonstrated by DTNSRDC on a Great Lakes ore carrier, in a project funded by the Maritime Administration.22

- Trash compactors are needed for ascertaining that solid waste, when released overboard, sinks. Available horizontal attitude compactors, assembled to produce "negative buoyancy" slugs, are large and with their ancillary equipment take up more space than is available on destroyers and frigates. Development of a vertical trash compactor is underway. The vertical attitude dictates that they be relatively small in that the distance between decks is 8 feet. The novel approach selected to overcome the buoyancy problem is to shear and slightly moisten the trash before compaction. This results in a compacted slug with few air pockets, and a stable geometry after pressure release; it readily sinks.

- In the automated processing of black and white film on board aircraft carriers, exposed during exercises, spent fixer and washwater have in the past been discharged overboard. A system for replenishing fixer solution and recuperating both washwater and silver is in an advanced stage of development. It removes the bulk of the silver from the spent fixer solution by electrolysis, after which that solution is replenished by addition of a fixer concentrate and recycled. The film washwater has a minor fixer content which is air oxidized on a catalyst column. The resulting water can be used for washing to generate film of archival quality. In the overall process, 95% of the silver is recuperated; 90% of the water that would otherwise have been used, is also saved. The use of this system will reduce water pollution, save energy and silver.

Closure

Space limitation has prevented presentation of more than summary information on a selection of topics. However, additional unclassified information/technology transfer to State and local governments, corporations and individuals, can be arranged within the framework of regulations on commercially confidential/sensitive information.
REFERENCES


