Risk Analysis of Shipboard Drinking Water Chemical Contaminants

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Abstract

A survey of eleven United States Navy ships was conducted to identify the risk of chemical contamination in their drinking water supply systems. Survey results indicate there is a moderate risk of chemical contamination of the drinking water production, storage, and distribution systems with volatile organic compounds, total petroleum hydrocarbons, disinfection by-products (total trihalomethanes), and lead.

Administrative Information

This project was authorized by the Naval School of Health Sciences, Code OS, Washington, D.C., the Navy Environmental Health Center, Norfolk, Virginia and The Ohio State University, School of Public Health, as a summer practicum for graduate credits towards the completion of MPH Degree requirements, for the author.

Summary

Purpose

To identify the risk of chemical contamination in drinking water supply systems on United States Navy ships and submarines.

Findings

Surveys and interviews with key personnel onboard eleven United States Navy ships were conducted. Findings include:

- Moderate risk of chemical contamination of the drinking water production, storage, and distribution systems onboard ships.

- Most likely source of chemical contamination of shipboard drinking water is volatile organic compounds, total petroleum hydrocarbons, disinfection by-products (total trihalomethanes), and lead.

Recommendations

Installation of additional shipboard monitoring equipment and procedures when ships and submarines are required to operate in littoral or contaminated waters.

Periodic testing of shipboard/submarine water tanks, production systems, and distribution systems for volatile organic compounds, total petroleum hydrocarbons, disinfection by-products, and lead.

Testing should be accomplished immediately upon returning from major deployments/operations (approximately once every two years).

Purpose

The objective of this study was to identify the risk of chemcial contamination in drinking water supply systems on United States Navy ships and submarines. Oversight and administrative/technical support were provided by the Environmental Health Department of the Navy Environmental Health Center.

Background

United States Navy ships and submarines produce water while at sea (and at times, in littoral waters) through distilling and reverse osmosis processes. When in port, Navy vessels receive water from local municipalities, contracted agents, and/or watering points ashore.

Shipboard personnel monitor water produced onboard and water received from most foreign sources for bacteriological quality and halogen residuals (chlorine, chloramine, and bromine). Water received from local municipalities, contracted agents, and/or watering points within or under the cognizance of the United States and her territories, United Kingdom, Australia, and Canada may or may not be routinely monitored for bacteriological quality and halogen residual (drinking water standards meet minimum requirments and testing is assumed to be accomplished by local authorities overseeing these sources of water).

An important aspect of the drinking water produced onboard ships and submarines is, its source. Ships and submarines routinely do not produce water unless they are at least twelve miles from the shoreline. Being so far from shore, the sea water that is utilized is not directly subjected to the contaminates identified in the Environmental Protection Agency (EPA) Primary and Secondary Standards under the Safe Drinking Water Act (SDWA), and therefore, are not currently monitored by shipboard personnel. However, the operational environment for ships and submarines is changing and more missions are requiring operations in littoral waters for extended lengths of time.

Littoral waters are more likely to be at risk for primary and secondary contaminates.

Watering points for military units under the cognizance of the United States, her territories, and her allies are governed by EPA regulations and international agreements that adopt minimum requirements for potability of drinking water that meet or exceed EPA requirements. An exception to this may be when water is issued for drinking purposes under strict emergency conditions, (i.e., when there is no safe supply of water available and water has to be obtained, either direct or indirectly, from sources which are unknown or imperfectly known). Monitoring of EPA Primary and Secondary Standards of water received from these points is also not currently being accomplished by Navy personnel.

The drinking water distribution system on ships/submarines is relatively isolated (by physical separation of piping and minimization of cross-connections/backflow connections) from other distribution systems such as fuel, chill water, and the firemain (which contains seawater). However, many chemicals and hazardous materials are being utilized for processes throughout the ships/submarines that could possibly contaminate the drinking water system, if not handled properly. Another concern is, if the source water for water production (sea water) is contaminated (e.g., with fuel or oil), there may be an associated risk of chemical contamination of the final drinking water product.

Types of Water Production Plants

Flash-Type Distilling Plant: The flash-type distilling plant is widely used throughout the Navy. Flash-type plants are fundamentally different from other type of distilling plants. The most important difference is that the feed is flashed into vapor (steam) by pressure reduction, rather than boiling inside an evaporator shell. Vapor is also produced by pressure reduction in each successive stage that the feed/brine enters. Two- through six-stage flash-type distilling plants are used in Navy surface ships. To achieve greater distillate output capacities in the most efficient manner, multiple-stage units are used. These plants use the same principles as two-stage plants, with additional stages added between the feed inlet and the brine outlet.

In flash-type plants, seawater is heated in a series of heat exchangers and subsequently discharged into the first-stage flash chamber. Since the pressure in the first-stage flash chamber is lower than the saturation pressure corresponding to the temperature of the feed, a portion of the feed flashes or vaporizes as it passes through the first-stage flash chamber. The vapor rises through a moisture separator or mesh-type demister and is condensed on the first-stage condenser tubes by the cooler seawater flowing through them. The condensed vapor (or distillate) then falls into the first-stage distillate trough. The remaining unflashed feed (brine) enters the second stage through restrictions in the bottom of the flash chamber. Since the brine is now at the saturation temperature of the first-stage vacuum and the second-stage flash chamber is at a lower pressure, a portion of the brine again flashes. Distillate is formed and collected in the second-stage distillate trough in the same manner as in the first stage. The distillate pump removes the distillate (formed in both stages) from the second-stage distillate trough. The remaining brine in the bottom of the second-stage flash chamber is pumped overboard.

The ratio of distillate produced to feed through a flash-type distilling plant is approximately one gallon of distillate per 10 to 20 gallons of feed. This ratio is independent of the number of stages but varies directly with the seawater temperature. Flash-type distilling plants on Navy surface ships range in capacity from 6,000 to 100,000 gallons per day.[1]

Reverse Osmosis: In the late 1970's, a process of directly desalting seawater without the use of heat or a phase change became a practical commercial process. This process, known as reverse osmosis, revolutionized the desalting industry. High-quality water could now be produced at substantially lower energy costs and with substantially less complexity than with conventional distillation systems. The reverse osmosis process can be thought of as similar to the conventional filtration process - pressurized seawater is passed over a semipermeable membrane that passes pure water but excludes salt species. There are, however, three important differences between reverse osmosis and conventional filtration processes:

a. Osmotic Pressure. In the reverse osmosis process, a natural osmotic pressure exists between the saline and the pure water sides of the membrane. For seawater reverse osmosis, an osmotic pressure of 350 to 400 pounds per square inch (psi) exists across the membrane, requiring fairly high pressures (700 to 1000 psi) of operation. Conventional filtration processes typically operate from 10 to 25 psi.

b. Crossflow Operation. In the conventional filtration process, all the process fluid (seawater) normally passes through the filtration media. In the reverse osmosis process, the process fluid passes over the membrane, but only a small portion (20 to 30 percent) passes directly through it. This allows the salt to remain in the concentrating feed solution, which is discharged overboard. The membrane is therefore free of rejected substances. In contrast, the conventional filtration process retains the rejected material, requiring repeated filter replacement.

c. Particle Size. In the conventional filtration process, the filter media acts as a seive, retaining particles as a result of size and spatial incongruities. In the reverse osmosis process, ions (charged molecular particles) are separated because of their limited diffusion through the membrane. Particulates as such cannot pass through the membrane mechanically unless the membrane is defective.

The term reverse osmosis was developed because the process is often thought of as the reverse of the natural process of osmosis. If two solutions having different concentrations of solute are separated by a semipermeable membrane (permeable to the solvent but not to the solute), solvent from the weaker solution tends to pass through the membrane, decreasing the concentration of the stronger concentrated solution. The equilibrium pressure head developed by an increase in column height is called the osmotic pressure. This process is known as normal osmosis.

If the weaker solution is pure water (solvent) and the concentrated solution is seawater, the resulting osmotic pressure will be about 350 psi. The process can be reversed by applying pressure to the seawater in excess of the osmotic pressure. Water will then pass through the membrane from the concentrated side to the weaker side. The membrane rejects the sea salt and dissolves it back into the remaining seawater.

The greater the difference between the applied pressure and the osmotic pressure, the faster the water will permeate the membrane and the purer the permeated potable water will be. In practice, a pressure of 700 to 1000 psi is required to obtain an acceptable flow of water through the membrane.[2]

The solution-diffusion theory, which as its basis is supported by actual operational data, helps to explain membrane operation. This theory proposes that the water and salt are dissolved directly into the membrane from the saline water side. Their mechanisms of passage through the membrane, however, are distinctly different. The salt diffuses through the membrane from the seawater side to the freshwater side at a given rate consistent with the principles of diffusion. That is, the migration of salt through the membrane is proportional to the difference of the salinity between the saltwater and freshwater on adjacent sides of the membrane. It is theorized that this diffusionary process is a function of the electrical interaction of the salt ions and the active ionic groups in the polymeric structure of the membrane. Pure water, on the other hand, passes through the membrane under hydraulic pressure (its rate of permeation being directly proportional to the hydraulic pressure drop across the membrane). A good reverse osmosis membrane provides maximum waterflow with very low salt diffusion. Salt separates as the waterflow rate through the membrane greatly exceeds the salt diffusion rate. This solution-diffusion concept can be demonstrated on any reverse osmosis plant simply by increasing the pressure. The permeation rate will increase, and the permeate salinity will appear to decline. What actually happens is that the salt diffusion rate remains constant, and the greater water permeation rate results in a greater salt dilution.[2]

The ratio of distillate produced to feed through a reverse osmosis plant is approximately one gallon of distillate per 3 to 5 gallons of feed (or 20 percent to 30 percent). Reverse Osmosis on U. S. Navy surface ships range in capacity from 2,000 to 12,000 gallons per day.

Methods

Shipboard Surveys

Ships surveyed during July/August 2000 for this study, included (with date of commissioning): USS John F. Kennedy (CV-67) September, 1968; USS Mount Whitney (LCC/JCC-20) January, 1971; USS Ponce (LPD-15) July, 1971; USS La Moure County (LST-1194) December, 1971; USS Peterson (DD 969) July, 1977; USS Nassau

(LHA-4) July, 1979; USS Carr (FFG-52) July, 1985; USS Theodore Roosevelt (CVN-71) October, 1986; USS Arleigh Burke (DDG-51) July, 1991; USS Vella Gulf (CG-72) September, 1993; and USS Bataan (LHD-5) September, 1997. No submarines were surveyed during this period.

The surveys conducted onboard these ships consisted of interviews with medical; engineering; lithography/photography; and maintenance personnel who were responsible for monitoring of drinking water quality, production of drinking water, processing/developing of film/x-rays, and industrial processes, respectively. A walk-through survey of selected shipboard spaces (engineering, maintenance, medical, and photography) was also conducted on all listed ships.

Water samples were not collected for chemical testing at this time. However, a brief overview of water sampling procedures, methodology, and results obtained was conducted to ensure that current testing requirements by shipboard personnel (bacteriological and halogen residual) were understood, being completed, and that the water being produced onboard met current requirements.

Review of Existing U. S. Navy Studies

A review of existing U. S. Navy studies identified by Navy Environmental Health Center personnel and/or the investigator covering current water production and treatment/disinfectant technologies utilized, was done. Identified literature was limited to three studies that are restricted in distribution: *Rejection of Selected Chemical Contaminants by Reverse Osmosis Desalination Modules*; *Developmental Test and Evaluation of a Potable Water Electrolytic Disinfectant Generator*; and *Flash Type Distilling Plant Crude Oil Contamination Test*.

Review of Shipboard Water Production Processes

Two methods of shipboard water production processes were identified and utilized on the ships surveyed: Flash-Type Distilling Plants and Reverse Osmosis (RO) Plants. A basic understanding of these processes was necessary to identify vulnerbilities in the system where contaminates could enter the water. One such weakness was noted in the *Flash Type Distilling Plant Crude Oil Contamination Test* study where the inability of the flash-type distilling plants to sepearate fuel and crude oil contamination from the final distillate product was documented.

Discussion of Results

The eleven surface ships surveyed ranged in size from a frigate (USS Carr (FFG-52)) to aircraft carriers (USS John F. Kennedy (CV-67) and USS Theodore Roosevelt (CVN-71)); and in manning from 300 to over 5,000 personnel when the ships are deployed. As expected, the drinking water production and storage capacity varied according to the size and manning of the ship.

All ships surveyed (except the USS Arleigh Burke (DDG-51), which had two reverse osmosis plants) had at least two flash-type evaporator plants for the production of drinking water. The evaporators varied in size (one, two, three, and six stages) and production capacity (6,000 to 1000,000 gallons of water per day per evaporator). The flash-type distilling plants provide both drinking water and make-up feedwater for shipboard steam plants.

Disinfection Systems. There are two primary shipboard water disinfection systems: bromine cartridges and calcium hypochlorite. The USS Theodore Roosevelt utilized an electrolytic disinfectant generator (EDG), a relatively new technology, to disinfect water. The EDG uses brine electrolysis to produce sodium hypochlorite (NaOCL) as the disinfectant. The EDG has been identified as a system that may be installed on all new surface ships to replace bromine and calcium hypochlorite as water disinfecting agents.

The methods of disinfecting the drinking water supply onboard ships (bromination, batch chlorination, and use of the electrolytic disinfectant generator) was found to be satisfactory. The required halogen residuals for the disinfection process were obtained/maintained (0.2 ppm after 30 minutes contact time for potable water obtained from approved sources or water produced onboard and 2.0 ppm after 30 minutes contact time for water received from an unapproved source, a source of doubtful quality, or an area where amebiasis or infectious hepatitis is endemic). Even though the focus of this study was chemical contamination, the risk of bacterial contamination was looked into. Due to the above mentioned methods of production and disinfection, the risk of bacterial contamination is minimal.

Potable Water Tanks. Access to potable water tanks is limited to select personnel (engineering and medical). Water tanks are usually "skin tanks" (sharing a bulkhead with the hull of the ship) and are located on the bottom and sides of the ship. Physical access to water tanks are limited to small openings (hatches) that may be located in the ship's bilge and sounding tubes (used to monitor tank levels in conjunction with mechanical/computerized tank level indicators). Some drinking water storage tanks (especially on older ships) may also share a common bulkhead with fuel/oil storage tanks and ballast tanks (which may contain sea water). The risk of chemical contamination of drinking water storage tanks due to rusting, wear/tear, and leakage between the water and adjacent fuel/oil storage tanks either through common bulkheads and/or the hatches that are covered by bilge water (the bilge collects "dirty" water, oil, hydraulic fluids, and other liquid wastes) is possible.

Another concern is the inner coating of the potable water storage tanks (either during construction or during yard periods to repair/rehabilitate the tanks). Within the past year, two U. S. Navy ships have been identified where lead-based paint was used as the inner surface coating of potable water tanks. Even though the use of lead-based paints for this purpose is not authorized, the use has obviously occurred and the possibility of similar uses on other ships and submarines should not be ignored. Due to this fact, the risk of lead contamination of the water supply is possible.

Sounding Tubes. The most frequent physical access to water tanks occcurs through the sounding tubes. Sounding tubes provide immediate/direct access to finished drinking water and are used to monitor water tank levels and to introduce chlorine when batch chlorinating a specific water tank is necessary. "Sounding tapes" are fed through the sounding tubes to "sound" (measure) the water levels. The sounding tapes are also designated for potable water tank use only (tapes are also utilized to "sound" fuel/oil tanks) and are required to be disinfected with a chlorine solution before being introduced to the sounding tubes/water tanks. Due to the small surface area of the sounding tapes, procedures to disinfect the tapes before use, and large quantity of water involved, the risk of chemical contamination through the use of the sounding tapes is minimal.

The sounding tubes are also required to be capped and secured (locked) when not in use and are located throughout the ship (i.e., engineering, berthing, and other common spaces). Unsecured sounding tubes were noted on a number of occassions in different spaces. Contamination of drinking water may occur through unsecured tubes with machinery-type of fluids (i.e., hydraulic, oil, fuels, etc...) in engineering spaces, cleaning solvents and dust/dirt in berthing spaces, or through accidents/intentional actions in any space. Due to the direct access of sounding tubes to the finished drinking water supply, the risk of chemical contamination of the drinking water due to unsecured sounding tubes is possible.

Industrial Processes. Industrial processes that utilized chemicals and/or hazardous materials appeared to be completed in a manner that prevented and/or contained any spills. For example, parts washers (basically a dishwasher for machinery parts) utilized biodegradable detergents and were self-contained. No cross-connections with the drinking water system in the areas surveyed were noted. The numbers of chemicals and hazardous materials authorized/utilized onboard ships have also decreased dramatically the past decade and the guidelines that govern and track their use have become more stringent. The chemical contamination risk of drinking water regarding industrial processes that utilize chemicals and/or hazardous materials is minimal since these processes are separate and do not come into physical contact with the drinking water system.

Photography. Another area of concentration was photography processes. The large majority of film processessors identified during the surveys were self-contained, stand-alone units (i.e., no direct, "hard-plumbed" water source to the processessor). This type of set-up eliminates any chance of cross-connections and/or back siphonage of photography chemicals into the drinking water system. Medical processessors for x-rays did have a direct water connection, however, these processessors have cross-connection/back-flow prevention devices installed and/or incorporated into the design of the processessor. Manual processing of film was identified on one ship. Film processing chemicals were utilized in "processing pans" and disposed of as hazardous waste once the film was developed. The chemical contamination risk of drinking water in regards to photography processes is minimal since the process is separate from the drinking water system.

Disinfection By-Products. Surface and ground water contain organic materials (measured as total organic carbon) that may react with disinfectants to form disinfection by-products (DBPs). As mentioned above, the source water that is routinely utilized by U. S. Navy ships and submarined are not influenced by waters that contain organic materials. However, there are situations that the source water for water production may be influenced by water containing organic material (i.e., operations in littoral waters and source/finished water contaminated with fuel, oil, or other petroleum based products).

The two methods of shipboard water production (distillation and reverse osmosis) will not remove all organic chemicals. In fact, it has been demonstrated that volatile hydrocarbons will carry-over through the distilling plants into the distillate when the sea (source water) is contaminated with low levels of fresh crude oil.[3] It has also been demonstrated that fuels and oils were, at best, moderately rejected by reverse osmosis.[4] Accumulation of disinfection by-products and therefore, total trihalomethanes (TTHMs), may be expected if these organic chemical contaminates are present. The chemical contamination risk of drinking water with disinfection by-products and total trihalomethanes is possible since the current shipboard water production methods do not remove all organic chemicals that may contaminate the source water.

Volatile Organic Compounds/Total Petroleum Hydrocarbons. Two studies conducted by the Naval Sea Systems Command have been identified that demonstrates that the current shiboard water production methods do not remove all organic chemicals that may contaminate the source water (sea water). In regards to the flash-type distillers, full scale distilling plant testing with crude oil contamination has demonstrated light hydrocarbons and toxic aromatic hydrocarbons will be distilled and carry over into the distillate. Light distillate fuels such as JP-5 (jet fuel) and naval distillate (diesel fuel) will also be distilled and carry over into the final water product. Other than petroleum odors coming from the air ejector vent and oil droplets splashing on the stage port hole windows, there was no other indication of contamination occurring. Low levels of light oil and aromatic hydrocarbon carry over into the distillate, will be difficult to detect visually or by odor.[3]

Weathering of the crude oil on the sea surface will have an effect on the carry over of light fractions into the distillate. However, the most toxic hydrocarbons such as benzene and toluene will disolve into the water column beneath the water slick and remain for up to two days until they are completely evaporated. Based on the results of the testing, it can be expected that one percent of the benzene and three percent of the toluene will be distilled in shipboard distilling plants and carry over into the distillate.[3]

Testing of reverse osmosis systems have indicated a moderate to good rejection of cyclic hydrocarbons, cleaning agents, and fuels/oils. There were several inorganic materials (cyanide, arsenic, cadmium, chromium, and magnesium) which were either poorly rejected by the reverse osmosis membrane and/or the solubility in sea water is high. The possibility exists that the materials could be present in sufficiently high concentrations to result in unacceptable levels in the final product water.[4]

Another consideration is while ships are transiting oil slicks, the amount of oil in the sea water that will be drawn into the distilling/reverse osmosis sea chests, and therefore, the amount of contamination that will result, is difficult to determine. Variables include depth and location of the sea chests; ship speed and formations; weathering of the oil; and thickness of the oil slick emulsion. The chemical contamination risk of drinking water with volatile organic compounds/total petroleum hydrocarbons, disinfection by-products, and total trihalomethanes is possible. The current shipboard water production methods do not remove these type of contaminates and the possibility of the source water and/or the final water product (i.e., through indirect/ direct contamination of sounding tubes, leaking water tanks, etc...) being contaminated is possible.

Conclusions

Even though, drinking water produced onboard ship is of high quality there is moderate risk of chemical contamination of the drinking water production, storage, and distribution systems.

The most likely risk identified and the source of chemical contamination of shipboard drinking water is volatile organic compounds, total petroleum hydrocarbons, disinfection by-products (total trihalomethanes), and lead through the use of lead-based paints as sealants/coatings on the interior of potable water tanks.

Recommendations

- Installation of additional shipboard monitoring equipment (i.e., oil content meter to monitor inlet sea water) and procedures to reduce the possibility of oil or aromatic contamination of drinking water for ships and submarines expected to operate in littoral or contaminated waters.

- Periodic testing of shipboard/submarine water tanks and distribution systems for volatile organic compunds, total petroleum hydrocarbons, disinfection by-products (total trihalomethanes), and lead.

- Testing should be accomplished immediately upon returning from major deployments and/or operations (approximately once every two years), prior to hook-up, and use of any water source foreign to the shipboard water production plants. Estimated cost of testing is $750 to $1,000 per ship based on figures provided by local EPA certified labs.

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[1] *Naval Ships Technical Manual Library NSTM015, Chapter 531-Volume 1-Desalination Low-Pressure Distilling Plants* (February, 1999), Naval Sea Systems Command

[2] *Naval Ships Technical Manual Library NSTM015, Chapter 531-Volume 3-Desalination Reverse Osmosis Desalination Plants* (February, 1999), Naval Sea Systems Command

[3] Steck, Richard W. (1992), "Flash Type Distilling Plant Crude Oil Contamination Test."

[4] Pizzino, J. F. and Titus, M. W. (1983), "Rejection of Selected Chemical Contaminates by Reverse Osmosis Desalination Modules."

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