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Evaluation of Nonpolluting Biofouling Control Methods for Titanium Seawater Piping

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I. Introduction

Corrosion and biofouling of shipboard seawater piping and cooling systems reduce readiness, impact operations and are costly to prevent and to remediate (Jones and Little, 1990). The materials most widely used currently by the Navy in these systems are copper-nickel alloys, which are susceptible to erosion corrosion and microbiologically influenced corrosion (Little *et al.*, 1990; Little *et al.*, 1991). Titanium has been proposed for more extensive use by the Navy in seawater piping and heat exchanger applications because of its high corrosion resistance, high strength, and light weight. Titanium is susceptible to biofouling, however, and currently used chemical fouling control methods, such as chlorination, may soon be phased out due to their adverse environmental impact.

Alternative biofouling control technologies are available, and new technologies currently are under development. Ultraviolet (UV)sterilization and ozone disinfection are two technologies that have been used successfully to maintain control of microbial populations in a wide variety of both freshwater and seawater applications. Ozone has the added advantage of removing dissolved and suspended organics, color and odor from the water. Both ozonation and ultraviolet irradiation are non-polluting and are economically competitive with chlorination for water treatment when the expense is considered of dechlorination chemicals and injection equipment that are necessary in order to meet strict government regulations for effluents.

We have been testing the effectiveness of several potential alternative methods to chlorination for environmentally safe control of biofouling in seawater piping. NSWC/Code R33 has a titanium test loop at Ft. Lauderdale, Florida. Through a Cooperative Research and Development Agreement (CRADA) with Ingalls Shipbuilders in Pascagoula, Mississippi (POC: Mr. Robert Erskine), an ozone generator and an ultraviolet sterilizer were incorporated into the loop in order to test their effectiveness in reducing microbial and larval populations in the seawater and in decreasing fouling of the piping. A summary of the results of these CRADA-supported studies are reported here.

In addition, we have conducted an independent, preliminary study of biofouling control using pulsed acoustic waves in seawater. A separate test loop, constructed of PVC plastic pipe, was built at the Ft. Lauderdale test site. Biofouling was shown to be significantly reduced in the portion of the loop that received pulsed power treatment, compared to an untreated control. Results of that test also are summarized in this report.

II. Evaluation of Ozonation and UV Sterilization

Study Design

A test loop was constructed of Grade 2 Titanium at the NSWC/Code R33 corrosion test facility located in Ft. Lauderdale, Florida. This test site is located at the mouth of the Port Everglades shipping channel. Seawater is pumped directly from the channel, passed through a course duplex strainer (3/16-inch pore diameter) to filter out large shells and, from there, is pumped through the test loop and back into the channel. The loop was designed originally to test, among other things, the effects of different flow rates on the extent of fouling in various areas of the piping. Legs of varying diameter piping were incorporated into the loop to achieve flow velocities of 3, 8, and >10 $ft \cdot sec^{-1}$. A blank-off and stagnant leg were also included. More recently the test loop was modified to include an ozone generator (Trailsgraz Ozone Co.), an ultraviolet treatment unit (Aquafine Corp.), and two titanium heat exchangers: a plate heat exchanger obtained from Alfa-Laval, and a shell and tube heat exchanger provided by CDNSWC/Annapolis, MD. These were built into the test loop such that the plate heat exchanger was treated by ozonation, and the shell and tube heat exchanger was treated by UV irradiation. The two treatments were installed into separate parallel legs of the loop but used the same source water (Figure 1).

As part of the CRADA with Ingalls Shipbuilders, a detailed, three-week evaluation of ozone and UV treatments was performed during the summer of 1993. Flow rates through the legs of the loop that contained the heat exchangers were maintained at 5.7 $ft \cdot sec^{-1}$ for the ozonation and 3.1 $ft \cdot sec^{-1}$ for the UV. The test involved 10 days of continuous treatment (ozonation or UV irradiation)[1] in each of the two legs of the loop, followed by 10 days of no treatment as a control.

Both biological/organic and physical/chemical parameters were measured before and after treatment. Physical/chemical parameters measured included: dissolved oxygen, water temperature, air temperature, pH, salinity/conductivity, metals content (by atomic absorption spectrophotometry), flow rate, and ozone injection rate/UV

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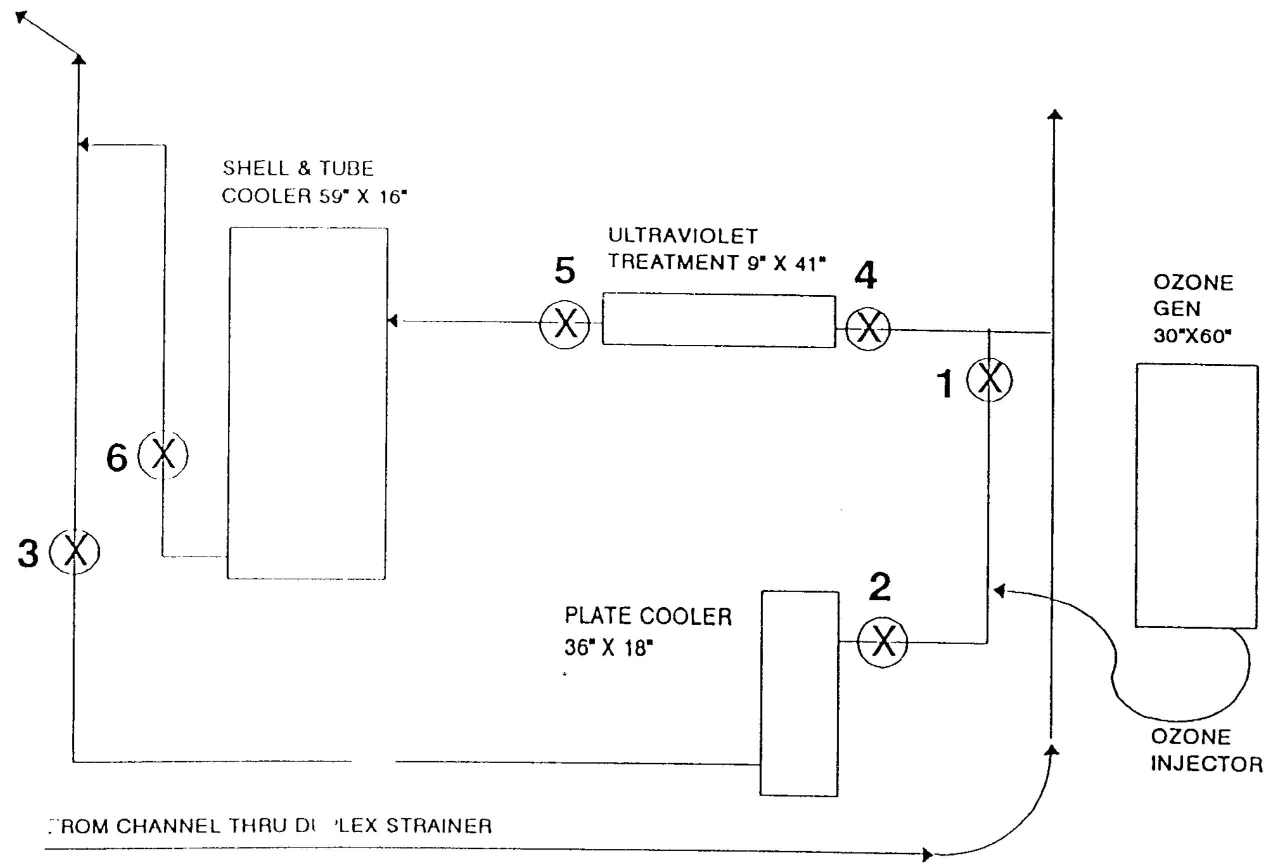
[1]Ozone generated from dry air: 82 V, 6.5-7.0 amps, 300-340 watts, 15 lb air pressure, inject 0.04. Ultraviolet total 313 hours of operation, % irradiance ranging from 50-90%.

FIGURE 1. SCHEMATIC OF TITANIUM TEST LOOP BIOFOULING CONTROL TEST, SHOWING LOCATION OF TREATMENT UNITS, HEAT EXCHANGERS, AND SAMPLING SITES.



irradiation level (using monitoring devices on the equipment). Biological and organic parameters measured included: microbial counts of water samples (aerobic heterotrophic bacteria, general anaerobes, acid-producing bacteria, sulfate-reducing bacteria, marine fungi, and total direct counts)[2], total organic carbon, total dissolved carbon, total particulate carbon, total suspended solids and total dissolved solids. Samples were collected throughout the 20-day test period at each of the six sites marked in Figure 1.

Results

Both micro- and macrofouling have been monitored throughout the test loop fo, nearly two years using counts of aerobic bacteria, sulfate-reducing bacteria (SRB) and marine fungi, examination of scrapings with environmental scanning electron microscopy (ESEM), and examination of the piping surfaces with fiber optics. Biofilm microorganisms have been present in numbers expected for flowing marine systems (10^5-10^8 cells·cm^{-2}), with higher numbers detected in the stagnant leg and blank-off. SRB have been found intermittently at several sites. Biofilm and mineral stains on the insides of the pipes are readily removed by wiping. No significant macrofouling has been detected in sections of the test loop in which flow rates exceeded 8 ft·sec^{-1}. Relatively low levels of fouling, including tunicates and tubeworms, have been observed in lower flow areas.

During the three-week biofouling control test, ozone and UV treatments were applied to separate, parallel legs of the test loop for a period of 10 days. Then both treatments were removed, and the test was run for an additional 10 days. Results of the biological analyses indicated that both treatment methods were effective in reducing microbial numbers in flowing seawater by several orders of magnitude, leading to lower fouling rates compared to controls. Typical results of microbial counts are presented in Figures 2-4. Figure 2, for example, shows an approximately three log decrease in counts of acid-producing bacteria (APB) during the first ten days of ozone treatment. Once the treatment was stopped,

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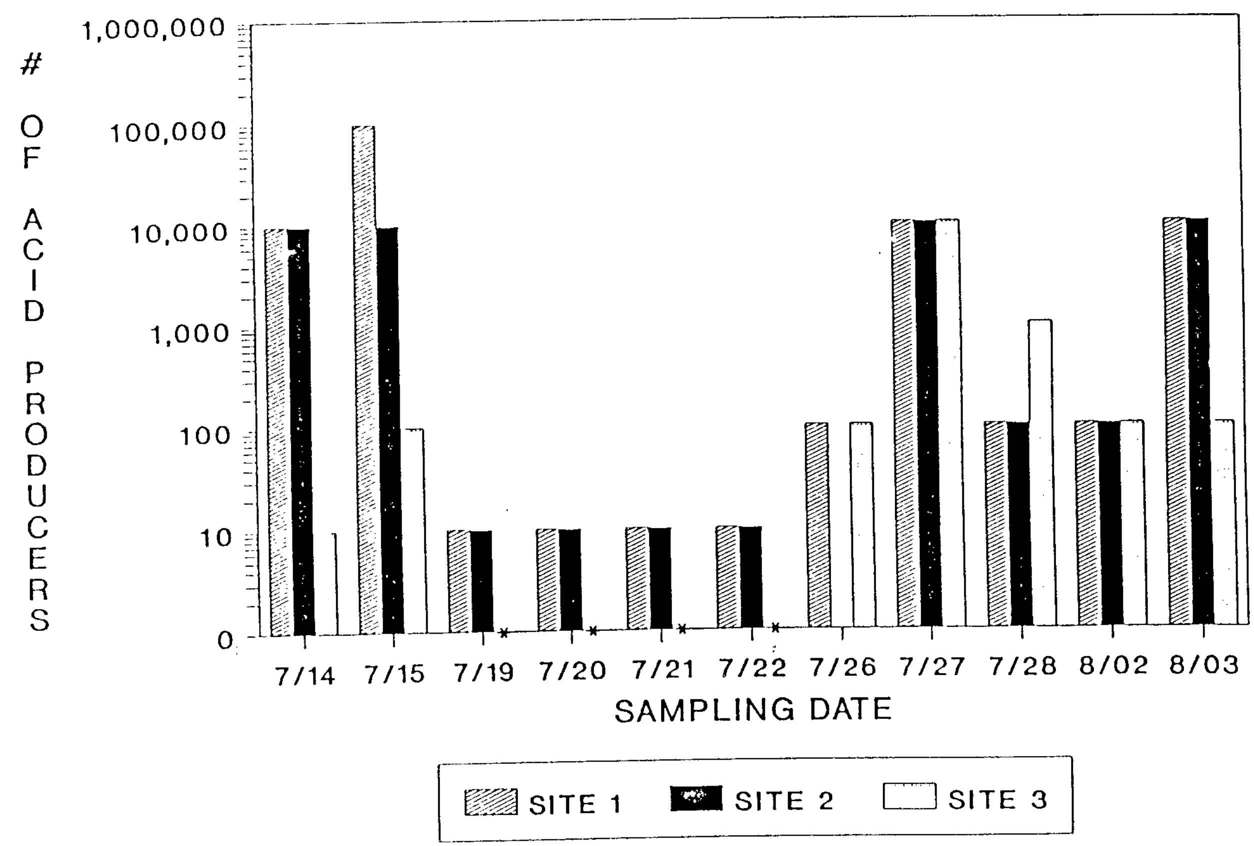
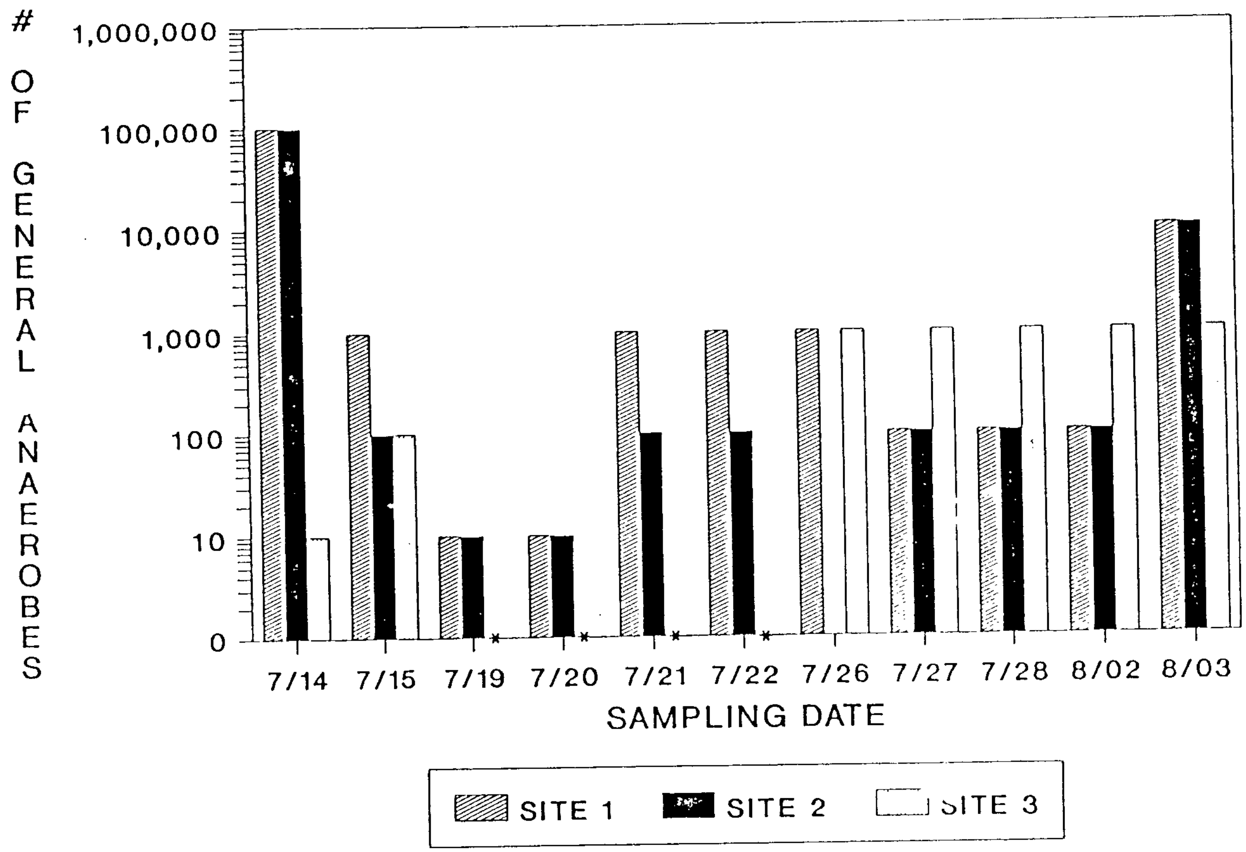
[2]Aerobic, heterotrophic bacteria counted by spread plate on Difco Marine Agar 2216. Marine fungi cultured on Difco Sabouraud Dextrose Agar amended with NaCl to seawater concentration. Sulfate-reducing bacteria , general anaerobes and acid-producing bacteria counted by serial dilution in media obtained from Bioindustrial Technologies, Inc., Georgetown, TX. Direct counts by acridine orange staining and epifluorescence microscopy.

FIGURE 2. COUNTS OF ACID-PRODUCING BACTERIA WITH (7/15-7/22) AND WITHOUT (7/26-8/03) OZONE TREATMENT. SAMPLING SITES ARE THOSE INDICATED IN FIGURE 1 OF THIS REPORT.



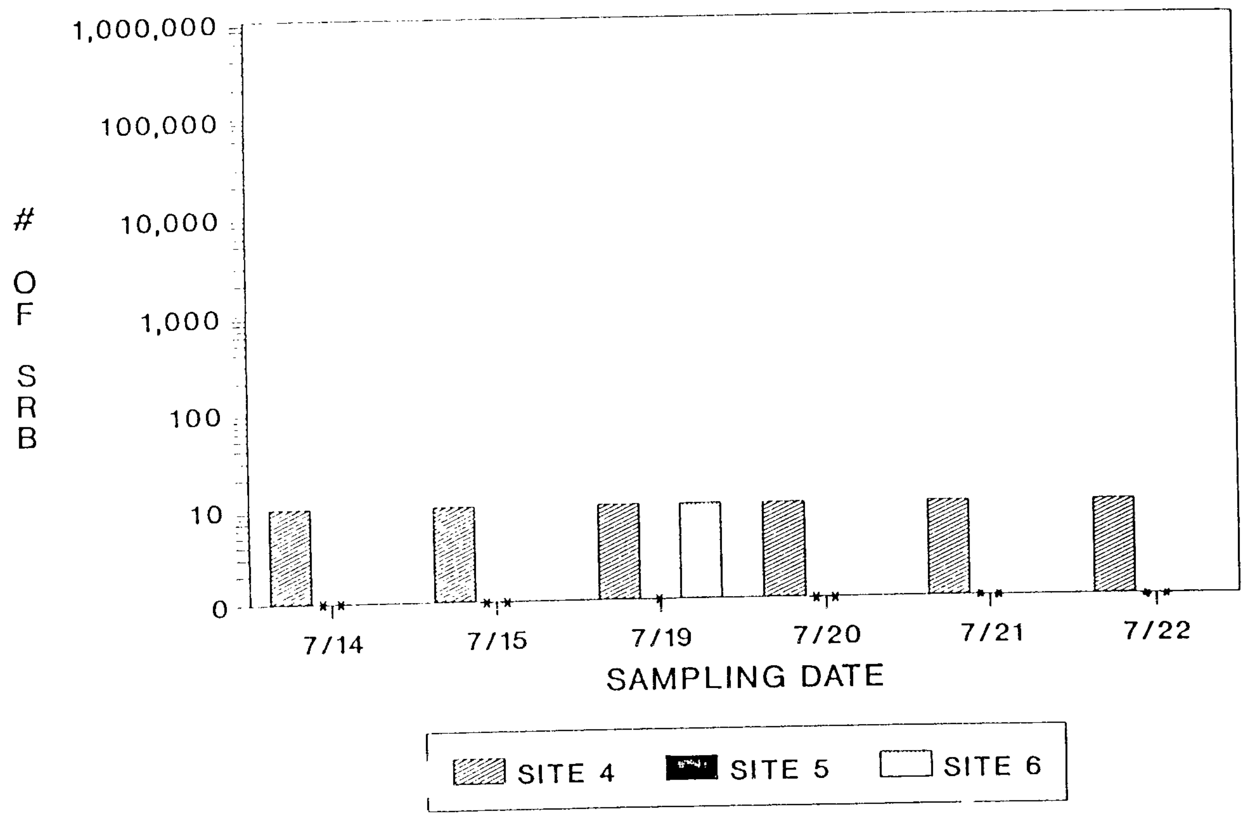
* - NO BACTERIA FOUND

FIGURE 3. COUNTS OF ANAEROBIC BACTERIA WITH (7/15-7/22) AND WITHOUT (7/26-8/03) OZONE TREATMENT. SAMPLING SITES ARE THOSE INDICATED IN FIGURE 1 OF THIS REPORT.



* = NO BACTERIA FOUND

FIGURE 4. COUNTS OF SULFATE-REDUCING BACTERIA DURING TREATMENT OF SEAWATER BY ULTRAVIOLET STERILIZATION. SAMPLING SITES ARE THOSE INDICATED IN FIGURE 1 OF THIS REPORT.



SRB = SULFATE-REDUCING BACTERIA
* = NO BACTERIA FOUND

however, counts climbed to their previous levels within a couple of days. Similarly, numbers of general anaerobes were reduced by 2-4 orders of magnitude (Figure 3). SRB counts in the UV-treated water dropped to undetectable levels (Figure 4). Visual and microscopic inspections of the piping and heat exchanger plates and tubes showed noticeably lower levels of both micro- and macrofouling during the first ten days of treatment than during the last ten days of the test when no treatment of the water was used.

These results agree with those of a previous, preliminary test on the effectiveness of UV sterilization of seawater entering the titanium test loop. In that test, seawater prior to UV irradiation contained approximately 10^1 SRB per ml, 10^3 acid-producing bacteria per ml, and 10^4 general anaerobes per ml. After treatment all of these groups of microorganisms dropped to undetectable levels.

Chemical analyses of the seawater both before and after treatment by ozonation and UV sterilization demonstrated that total organic carbon (TOC) and total dissolved organic carbon (TDOC) increased after the treatments stopped. Total suspended solids (TSS), total dissolved solids (TDS) and total particulate organic carbon (TPOC) values were similar throughout the testing, both before and after treatments.

III. Evaluation of Pulsed Power Treatment

Acoustic methods for biofouling control have been studied for many years. Recently, conventional ultrasonic sources have been field tested for possible prevention of fouling by the freshwater zebra mussel (*Dreissena polymorpha*) (Levy, 1993). Another study, using pulsed acoustics, reported prevention of algae accumulation in freshwater piping over a range of over 15 ft. (Bryden, 1993). This study, however, lacked adequate controls, so interpretation of results was difficult.

Pulsed acoustic shock wave technology differs from conventional sonic/ultrasonic technologies in several important respects. First, the cavitation threshold is much higher for short-pulse, high-frequency acoustic waves than for low-frequency, continuous-wave ultrasonics (Urick, 1983). For biofouling control, this offers two advantages: (1) more acoustic power can be delivered to the water at higher efficiency, thus allowing larger areas to be treated at greater range; and (2) based on results of our own work, biofouling control does not appear to be related to cavitation as in conventional ultrasonics, and thus the potential for materials damage is greatly reduced. Secondly, in contrast to ultrasonics, the hardware required to produce pulsed acoustic shock waves uses underwater electrical discharges formed by simple, relatively inexpensive arc-discharge equipment.

In a previous study, we demonstrated the feasibility of using pulsed acoustic waves at intensities above the cavitation threshold to remove accumulated scale and/or biofouling from the inside walls of piping (Grothaus *et al.*, 1993). An alternative that we are currently studying is to use low energy acoustic shock waves to *prevent* biofouling.

Study Design

A seawater PVC test loop was constructed in February 1994 at the NSWC/Code R33 test site in Ft. Lauderdale. The loop was built from schedule 40, 2-inch diameter clear PVC plastic piping. As in the titanium test loop experiments described above, seawater from the Port Everglades shipping channel was pumped continuously through the loop at 0.5 $ft \cdot sec^{-1}$ for a period of ten days. The acoustic pulse source consisted of a high-voltage power supply that produced an underwater electrical arc discharge. The repetition rate of the acoustic pulse was 0.5 Hz (once every two seconds). Treatment was maintained for approximately 10-12 hours per day. Biological analyses included visual inspection of fouling, bacterial counts of scrapings from pipe walls, and ESEM analyses of nylon coupons inserted into the pipes.

Results

The experiment demonstrated effective non-chemical biofouling prevention both upstream and downstream of the acoustic source. Specifically, a significant reduction in the rate of both micro- and, particularly, macrofouling was observed in the treated loop compared to an untreated control. Based on biofilm counts of aerobic heterotrophic bacteria, SRB, acid-producing bacteria, and general anaerobes, at least an order-of-magnitude reduction in the rate of microbial accumulation was observed at ranges of at least 10 feet for acoustic pulse treatments of less than 25 W average power (4 $W \cdot ft^{-2}$ treated). Direct observation of treated and untreated surfaces with ESEM revealed significant prevention of bacterial and algal fouling compared to the control. No degradation to the plastic piping of the loop was observed.

IV. Conclusions

The studies described here demonstrated that both ozone injection and UV irradiation treatments were effective in reducing microbial numbers in flowing seawater by several orders of magnitude. Although kill is not complete, the levels of microbial reduction seen in this study are sufficient to lead to significantly lowered fouling rates compared to untreated controls. Slow build-up of a microbial slime layer should not be of significant concern from a corrosion standpoint, as no cases of microbiologically-influenced corrosion of titanium have been reported (Little *et al.*, 1991; Little *et al.*, 1992). Almost complete prevention of macrofouling was observed in our system under both treatment regimes. Both treatment technologies can be adapted to the high-volume seawater requirements of the Navy. The Diablo Canyon Power Plant in San Luis Obispo, California, for example, uses prefiltration followed by UV sterilization to treat 1,000 gpm of seawater before it is transferred to reverse osmosis (RO) membranes for desalination (S. Hoover and J. Jones-Meehan, personal communication). Ozonation and UV sterilization both appear to represent potentially effective and environmentally-compatible alternatives to chemical treatments for control of biofouling in shipboard titanium piping and cooling systems.

Preliminary tests of pulsed acoustic treatments for biofouling prevention show promise, but much more work is need to optimize the effects and develop the technologies for practical use.

Acknowledgments

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