

Naval Surface Warfare Center Carderock Division

West Bethesda, MD 20817-5700

NSWCCD-TR-2000/04 February 2000

Survivability, Structures, and Materials Directorate

Technical Report

Feasibility Demonstration of a Pulsed Acoustic Device for Inhibition of Biofouling in Seawater Piping

by

Marianne Walch, Ph.D.

Naval Surface Warfare Center, Carderock Division

Michael S. Mazzola, Ph.D.

Mississippi State University

Michael G. Grothaus, Ph.D.

Southwest Research Institute



20000417 199

Approved for public release. Distribution is unlimited.

DTIC QUALITY INSPECTED 1

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
February 2000

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Feasibility Demonstration of a Pulsed Acoustic Device for Inhibition of Biofouling in Seawater Piping

5. FUNDING NUMBERS
PE 0602121N

6. AUTHOR(S)
Marianne Walch, Michael Mazzola, Michael Grothaus

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Surface Warfare Center
Carderock Division
9500 MacArthur Boulevard
West Bethesda, MD 20817-5700

8. PERFORMING ORGANIZATION
REPORT NUMBER
NSWCCD-TR-2000/04

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Surface Warfare Center,
Dahlgren Division
17320 Dahlgren Road
Dahlgren, VA 22448-5000

10. SPONSORING/MONITORING AGENCY REPORT
NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report describes a preliminary field test of a new biofouling control device designed for seawater piping and cooling systems. This technology uses a pulsed, underwater electrical discharge to generate an acoustic wave in pipes. The test was conducted during February 1994 in a seawater test loop, constructed of clear PVC piping, located at the Naval Surface Warfare Centers' Corrosion Test Facility in Dania, Florida. It included an untreated, control pipe and another identical pipe which was treated with an acoustic pulse every two seconds, ten hours per day, for 10 days. Results of visual observations, microbial counts, environmental electron microscopy (ESEM) and energy-dispersive x-ray analysis (EDS) demonstrated a significant reduction in the rate of biofouling in the pipe treated with the pulsed acoustic device compared to the control.

14. SUBJECT TERMS

pulsed power biofouling control marine biofouling
pulsed acoustics biofilm seawater piping

15. NUMBER OF PAGES
39

16. PRICE CODE

17. SECURITY CLASSIFICATION OF
REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF
THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION
OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF
ABSTRACT
SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Contents

	<i>Page</i>
Executive Summary	1
Introduction	2
Experimental Protocols	3
Test Site	3
Test Loop Design	3
Pulsed Acoustic Treatment	3
Analyses of Biofouling	5
Visual observations of pipe fouling	5
Microbial counts from pipe walls	5
Analysis of nylon coupons	5
Results	6
Discussion and Conclusions	21
Literature Cited	23
Appendix A - (Patent of acoustic device and system for biofouling control)	A-1

Figures

<i>Number</i>	<i>Title</i>	<i>Page</i>
1	Configuration of seawater test loop, consisting of parallel PVC pipes, one control ("C") and one treated with acoustic pulses ("P").....	4
2	Particularly clean region of treated pipe next to a pipe union and sampling port, where the acoustic wave was reflected back on itself.....	6
3	Photographs of biofouling accumulated in control and treated legs of the test loop on 24 February (day 6)	7
4	Photographs of biofouling accumulated in control and treated legs of the test loop on 27 February (day 9)	8
5	Photographs of biofouling accumulated in control and treated legs of the test loop on 27 February (day 9)	9
6	ESEM micrographs of coupons taken from sampling ports closest to the acoustic source on 24 February, Day 6 of the test: (a) C1 – control, 10 ft upstream; (b) P1 – treated, 10 ft upstream; (c) C2 – control, 2 ft downstream; (d) P2 – treated, 2 ft downstream. Magnification in micrographs is 300X. Size bar at bottom = 50 μ m	15
7	ESEM micrographs of coupons taken from sampling ports closest to the acoustic source on 24 February, Day 6 of the test: (a) C3 – control, 10 ft downstream; (b) P3 – treated, 10 ft downstream; (c) C4 – control, 20 ft downstream; (d) P4 – treated, 20 ft downstream. Magnification in micrographs is 300X. Size bar at bottom = 50 μ m	16
8	ESEM micrographs of coupons taken from sampling ports closest to the acoustic source on 27 February, Day 9 of the test: (a) C1 – control, 10 ft upstream; (b) P1 – treated, 10 ft upstream; (c) C2 – control, 2 ft downstream; (d) P2 – treated, 2 ft downstream. Magnification in micrographs is 150X. Size bar at bottom = 100 μ m.....	17
9	ESEM micrograph (b) and EDS spectrum (c) from coupon (a) pulled from sampling port P1 (treated pipe) on 27 February, Day 9 of the test. Magnification in micrograph is 300X. Size bar at bottom = 50 μ m	18
10	ESEM micrographs (a and b) and EDS spectrum (c) from coupon pulled from sampling port C3 (control pipe) on 27 February, Day 9 of the test. Silicon peak in spectrum correlates with diatom colonies on surface. Magnification in (a) is 150X. Size bar at bottom = 100 μ m. Magnification in (b) is 300X. Size bar = 50 μ m.....	19
11	ESEM micrograph (b) and EDS spectrum (c) from stained area of coupon (a) pulled from sampling port P2 (treated pipe) on 27 February, Day 9 of the test. Brown stains are corrosion products. Magnification in micrograph is 500X. Size bar at bottom = 20 μ m	20

Tables

<i>Number</i>	<i>Title</i>	<i>Page</i>
1	Viable plate counts of bacteria obtained from water samples and from scrapings of the pipe walls.....	11
2	Results of presence/absence tests for general anaerobic bacteria for water samples from each pipe as well as for scrapings from the pipe walls.....	12
3	Results of presence/absence tests for sulfate-reducing bacteria for water samples from each pipe as well as for scrapings from the pipe walls.....	13
4	Results of presence/absence tests for acid-producing bacteria for water samples from each pipe as well as for scrapings from the pipe walls.....	14

Administrative Information

The work described in this report was performed by the Applied Materials Sciences Department (Code 68) of the Survivability, Structures and Materials Directorate at the Naval Surface Warfare Center, Carderock Division (NSWCCD) and by the Pulsed Power Systems and Technology Group of the Systems Research and Technology Department (Code B20) at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD). The experimental work was funded by the Naval Surface Warfare Center, Dahlgren Division Seed and Venture Program. Preparation of this Technical Report was funded by the Office of Naval Research, Code 334 as part of the "Advanced Heat Removal Concepts for Handling Large Thermal Transients in Shipboard Power Systems" Task of the FY 1998 6.2 Power and Automation Systems Program (Program Element 62121N), and the Office of Naval Research, Code 331 as part of the FY 1998 6.2 Environmental Quality Applied Research Program (Program Element 62121N).

Acknowledgments

The authors wish to thank: Scott Hoover, Regis Conrad, John Braker and Ronald Simmons for their excellent engineering support during the field test; Joanne-Jones Meehan for assistance in planning analyses; Carl Mueller for managerial support and assistance; Brenda Little and Richard Ray for ESEM and EDS support; and Robert Brizzolara for assistance with manuscript editing.

Executive Summary

This report describes a preliminary field test of a new biofouling control device designed for seawater piping and cooling systems. This technology uses a pulsed, underwater electrical discharge to generate an acoustic wave in pipes. The test was conducted during February 1994 in a seawater test loop, constructed of clear PVC piping, located at the Naval Surface Warfare Centers' Corrosion Test Facility in Dania, Florida. It included an untreated, control pipe and another identical pipe which was treated with an acoustic pulse every two seconds, ten hours per day, for 10 days. Results of visual observations, microbial counts, environmental electron microscopy (ESEM) and energy-dispersive x-ray analysis (EDS) demonstrated a significant reduction in the rate of biofouling in the pipe treated with the pulsed acoustic device compared to the control.

Introduction

Virtually all surfaces exposed to seawater for any period of time are susceptible to fouling by communities of marine microorganisms, algae and invertebrates. Biofouling of marine structures and vessels has long been a concern both to the Navy and to industries and public utilities that operate vessels or engineering systems at or in the sea. The practical consequences of fouling, in terms of both economic losses and operational problems and downtime, are considerable. Biofouling increases the frictional resistance of ship hulls and propellers, leading to increased fuel consumption, loss of speed, and additional noise and engine stress [Characklis, W. G., N. Zilver, and M. Turakhia, 1984; Haderlie, E. C., 1984]. Journey times increase, and frequent dry-docking is required to remove fouling and renew antifouling coatings. In seawater cooling systems biofilms can lead to losses due to impairment of heat transfer efficiency [Afring, R. P., and B. Taylor, 1979]. Pipes, filters and strainers may become partially or completely obstructed. Corrosion due to biological activity on fouled surfaces may lead to premature failure of materials [Jones, J. M., and B. J. Little, 1990].

Modern solutions to the biofouling problem have included biocide injection, new types of fouling resistant coatings and materials, electrochemical chlorination, electromagnetic methods and mechanical removal techniques [Fischer, E. C., 1984]. These and other biofouling control methods have been reviewed and evaluated in a previous report [Walch, M., and R. A. Brizzolara., 1998].

Chlorination and mechanical approaches, until recently, have been among the methods of choice for controlling biofouling in piping and heat exchanger systems. Mechanical cleaning is labor intensive and often requires that ship systems be taken offline for a period of time. Chlorination is a relatively inexpensive and effective biofouling control strategy. Environmental concerns and increasingly stringent discharge regulations, however, are continually requiring users of chemical biocides to consider or use other methods. Even though development of dechlorination technologies [Christian, D.K., J.O. Bergh and E.D. Thomas., 1995] and new strategies for chlorine minimization [Weber, B.E. and D.A. Brown., 1997; Jenner, H.A., and H.J.G. Polman., 1993] may allow chlorine use by the Navy to continue for some period of time, discharge limits for chlorine and other chemicals continually decrease and may eventually reach zero. Hence, alternatives to chlorination for biofouling control in ship systems are being sought.

This report describes a preliminary field test of one such alternative system, which was developed at the Naval Surface Warfare System (Dahlgren and Carderock Divisions). This technology uses a pulsed, underwater electrical discharge to generate an acoustic shock wave in pipes. The field test was conducted at the Naval Surface Warfare Center's Corrosion Test Facility in Dania, Florida, using seawater pumped from the Port Everglades shipping channel through plastic piping. Results demonstrated a significant reduction in the rate of biofouling over a 10-day period compared to an untreated control pipe.

Details of the device design, experimental protocols and results are described below.

Experimental Protocols

Test Site

The field test was performed at the NSWCCD Marine Corrosion Test Facility in Dania, Florida from 19 February to 27 February 1994. The facility is located on the south side of the Port Everglades shipping channel, at its opening to the Atlantic Ocean. The test loop was constructed on a concrete pad next to the channel. Water for tests conducted at this site is drawn directly from the shipping channel into an elevated 1500-gallon holding tank using a 10-HP pump. From there it is pumped to the tests.

Test Loop Design

A diagram of the test loop configuration is shown in Figure 1. Seawater from the 1500-gallon plastic holding tank was fed to a manifold leading to two identical pumps. From here, the water was pumped through parallel lines of 2-inch diameter, schedule 40 PVC pipe. Pipes in the last 40-foot leg of the loop were made of clear PVC so that fouling could easily be seen. Ball valves on the lines controlled flow rate, which was set to 7 gpm, or 0.5 ft/sec. Flow was measured both by bucket and stopwatch and by a Controlotron flow meter.

The acoustic source (spark gap) was inserted through a port into one of the clear pipes at its center. Sampling ports were located 10 feet upstream from the source, 2 feet downstream, 10 feet downstream and 20 feet downstream. Sampling ports also were placed in the same positions on the control leg, which received no acoustic treatment. The pipes were mounted on low wooden supports and were isolated acoustically from one another by cushioning them with thick foam. Acoustic isolation was confirmed using pressure transducers coupled to an oscilloscope.

Pulsed Acoustic Treatment

The hardware used in generating pulsed underwater shock waves in this field test is described in United States Patent No. 5,636,180. A copy of the patent is included in this report as Appendix A. Acoustic shock waves were generated by applying short-duration, high-voltage electrical pulses across a spark gap inserted into and fully immersed in the pipe lumen. The electrical discharges were produced by high voltage pulses (12-15 kV) from a storage capacitor. The rise time of the current between the electrodes was less than 1 microsecond. The resulting acoustical shock waves generated at the electrodes interact with biofouling organisms to prevent attachment to adjacent surfaces.

Seawater flow through the test loop and operation of the pulsed acoustic source began on the morning of 19 February. The treatment was run for an average of 10 hours per day and was shut down at night, because the system was not designed to run unattended. Average power use was 25 W, or 4 W per square foot treated. The repetition rate of the acoustic pulse was 0.5 Hz (once every two seconds).

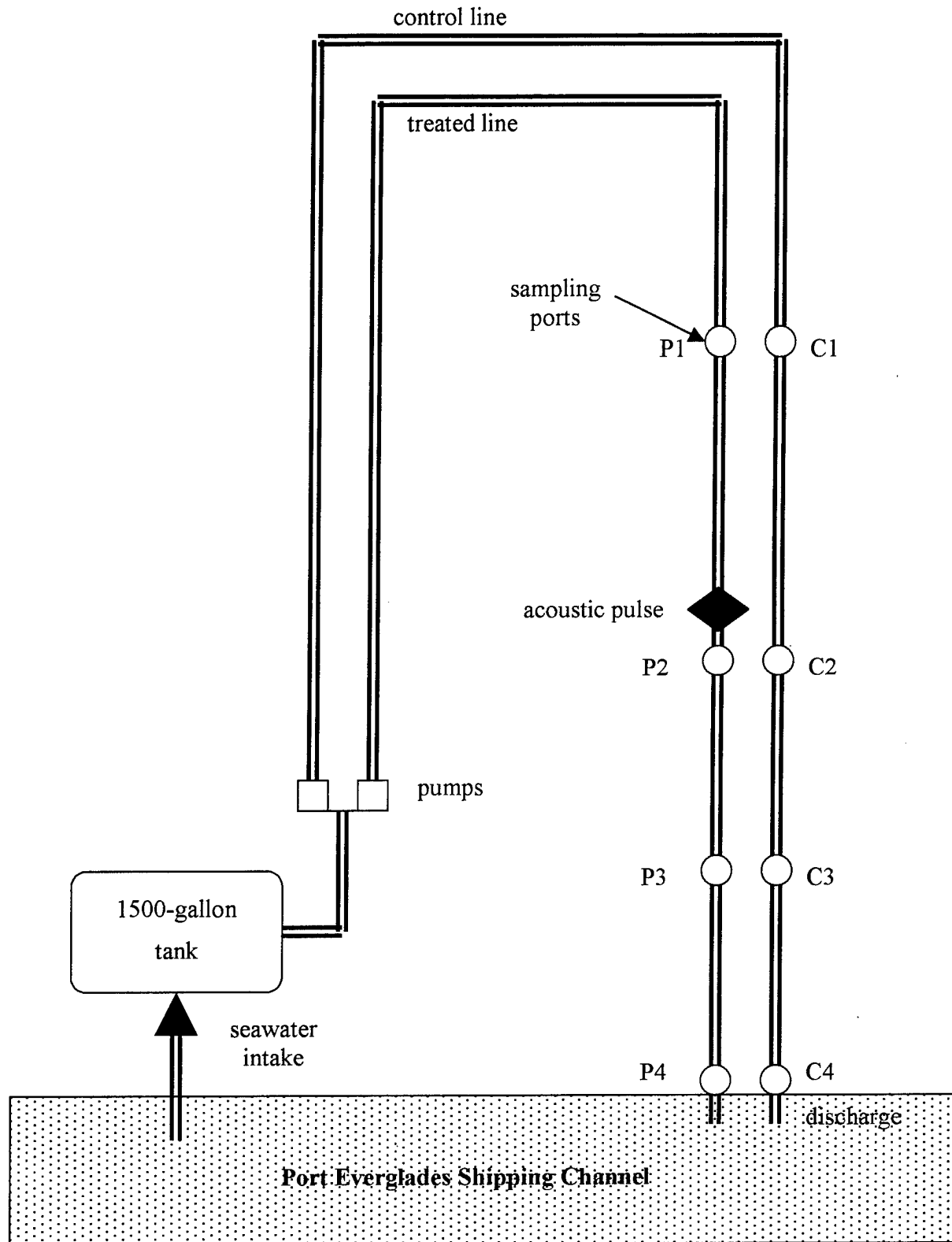


Figure 1. Configuration of seawater test loop, consisting of parallel PVC pipes, one control ("C") and one treated with acoustic pulses ("P").

Analyses of Biofouling

Visual observations of pipe fouling

The clear legs of test loop were examined visually on 24 February and 27 February, i.e., six and nine days into the test. Observations of fouling were recorded by photographing sections of the control and treated piping runs against a white background at distances 1, 5, 15 and 25 feet downstream of the location of the acoustic source, and at 5 and 15 feet upstream of it.

Microbial counts from pipe walls

Periodically during the test, the sampling ports were opened, and the pipe walls at those points were scraped with sterile cotton swabs for bacterial counts. Each sample was taken by making 15, 2-inch swipes with even pressure against the pipe wall. The intent was not to remove all cells from an area, but rather to obtain samples of the biofilm communities in a standardized way so that they could be compared. Scrapings were taken on the sides of the pipes to avoid sediment in the bottom area as well as intermittently dried areas at the top. Care was taken to avoid swabbing the same place on the pipe wall more than once.

After scraping the swabs were shaken vigorously into sterile culture tubes containing 2.0 ml filtered (0.2 μ pore size) seawater. The resulting suspension of cells was serially diluted and spread plated onto Marine Agar 2216 (Difco). Samples of seawater from the control and treated pipes also were counted. The plates were incubated at room temperature and counted 2 to 3 days later.

Presence/absence tests for general anaerobes, sulfate-reducing bacteria and acid-producing bacteria also were performed by inoculating the undiluted suspensions of bacteria into vials of broth prepared for these purposes by BioIndustrial Technologies (Arlington, Texas). 0.5 ml of the scrapings suspensions and 1.0 ml of the water samples were used as inocula. These vials were incubated at room temperature for up to one week before scoring positive or negative for growth of the corresponding type of bacteria.

Analysis of nylon coupons

One-inch diameter nylon washers were used as coupons to monitor microbial biofouling in the test loop during the test. Nylon was chosen because of its similarity to the PVC piping material. For each sampling port, four washers were mounted on a short threaded Teflon rod, separated by nylon spacers. The threaded rod was inserted into a cylindrical plastic plug machined to fit tightly into the hole at each port. When inserted into the port, the stack of coupons projected into the center of the pipe lumen, with the flat surfaces of the coupons oriented parallel to the direction of water flow.

Coupons were removed from the sampling ports on days 3, 6 and 9 of the test. They were handled with clean forceps and immediately placed into plastic tubes containing 0.18% formaldehyde in filtered seawater (0.2 μ pore size). Samples were refrigerated until analysis.

Coupons pulled on 21 and 24 February (days 3 and 6) were examined with an Electroscan E3 environmental scanning electron microscope (ESEM) located at the test site. Accelerating voltage was 14-16 kV, working distance 6-7 mm, and water vapor pressure 5-6 Torr. Coupons

pulled on 27 February (day 9) were sent to the Naval Research Laboratory Detachment, Stennis Space Center, Mississippi. There they were similarly examined by ESEM. Energy-dispersive x-ray analysis (EDS) also was performed on the samples to obtain elemental spectra of the coupon surfaces.

Results

Most of the visible fouling was due to brownish-green filamentous algae, which were exposed to sunlight in the clear pipes. No invertebrates were observed.

At the conclusion of the test, the control leg of the test loop was moderately fouled along its entire length. Fouling was heaviest on the bottoms and lower sides of the pipe. Fouling in the treated pipe was similar to the control downstream of sampling port P3 (Figures 3b, 3c, 5c, 5d) and slightly less fouled between ports P2 and P3 (Figures 3a, 5b) and upstream of port P1 (Figure 4c). The treated pipe was extremely clean for 6-8 inches between the acoustic source and P2, apparently due to reflection of the acoustic wave when it hit the dissimilar material in the port (Figures 2, 4a). The upstream leg of the treated pipe was cleaner than the control pipe all the way up to P1 (Figures 4a, 4b).

Fouling in general in the treated pipe was slower, with longer lag time than the control. The differences in extent of fouling between the treated pipe and the control became less pronounced with time. It is likely that much of the fouling in the treated leg was initiated at night when the acoustic source was turned off. Once fouling is initiated, low-energy pulsed acoustics may not remove adhered organisms from the surface.

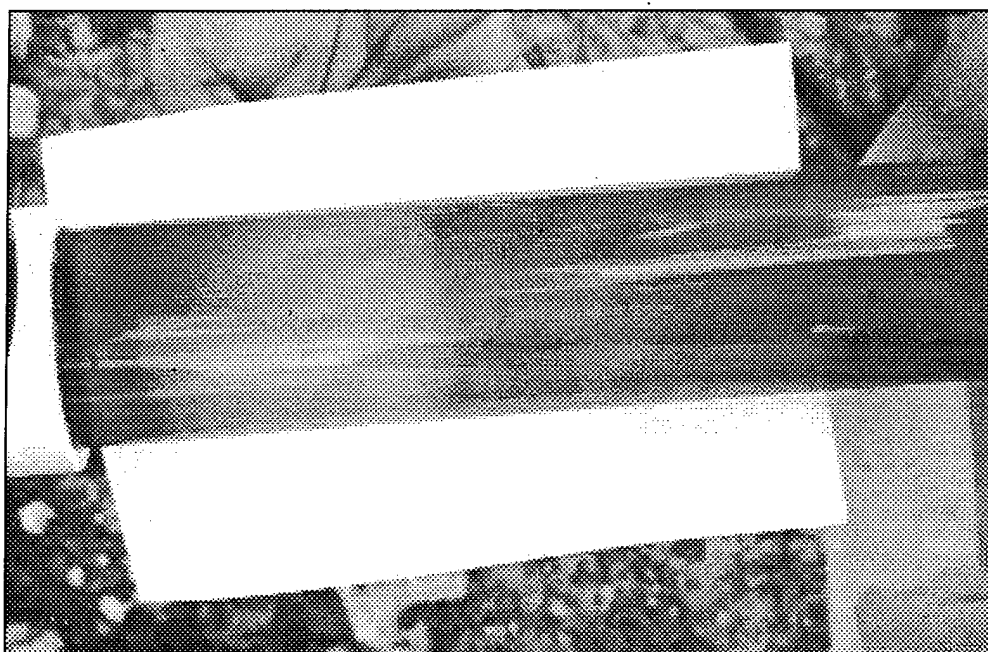
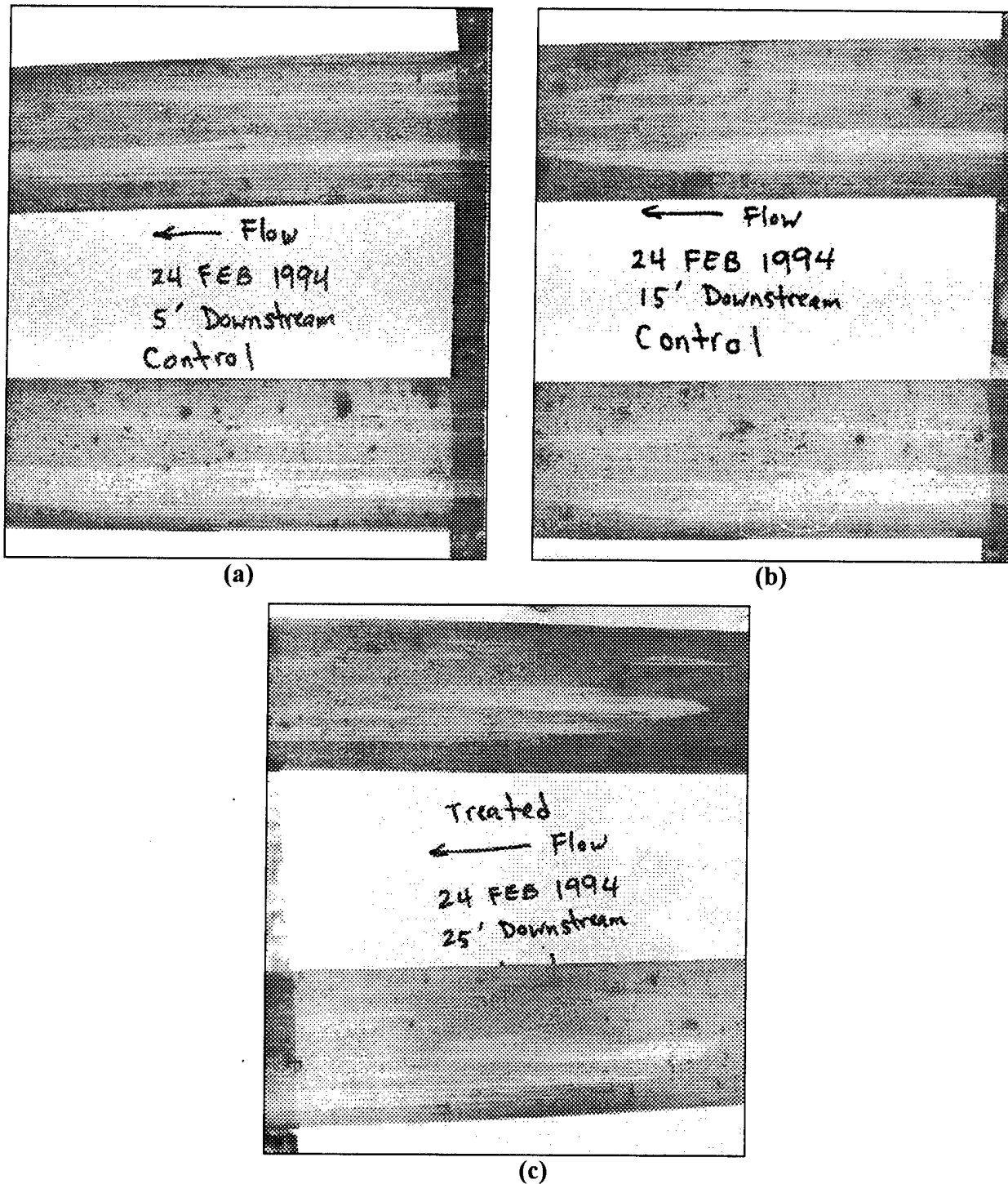
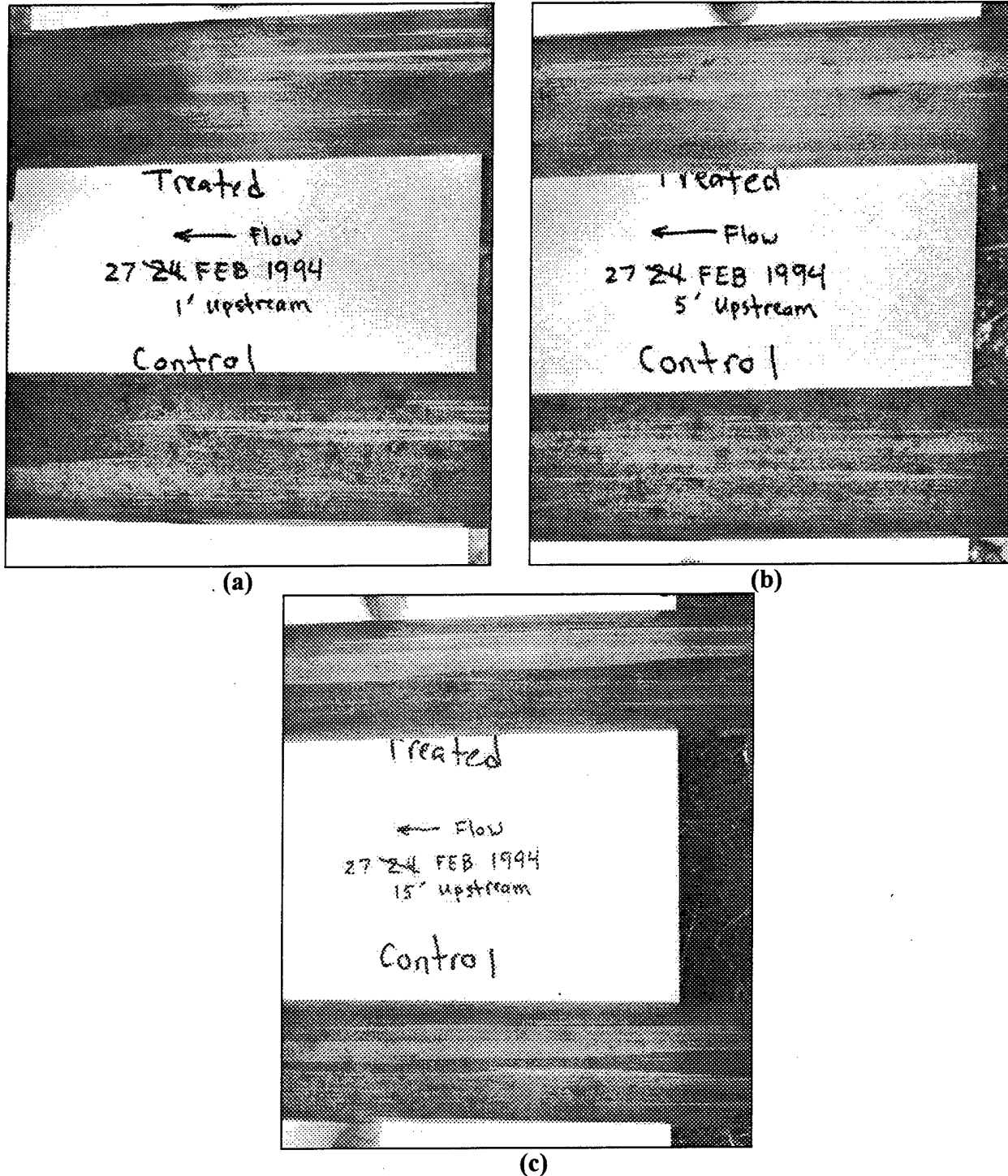


Figure 2. Particularly clean region of treated pipe next to a pipe union and sampling port, where the acoustic wave was reflected back on itself.



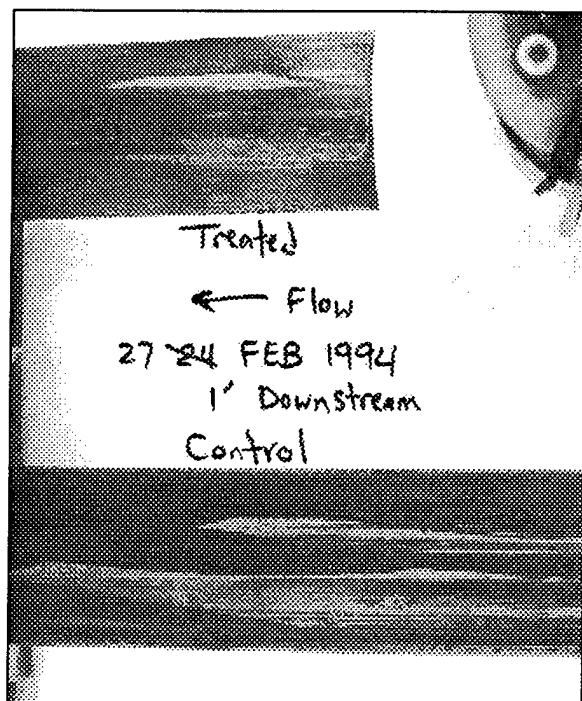
Treated pipe is at the top of each photograph, control at the bottom. Arrows indicate the direction of water flow. "Downstream" and "upstream" labels are in reference to the location of the pulsed acoustic source.

Figure 3. Photographs of biofouling accumulated in control and treated legs of the test loop on 24 February (day 6).

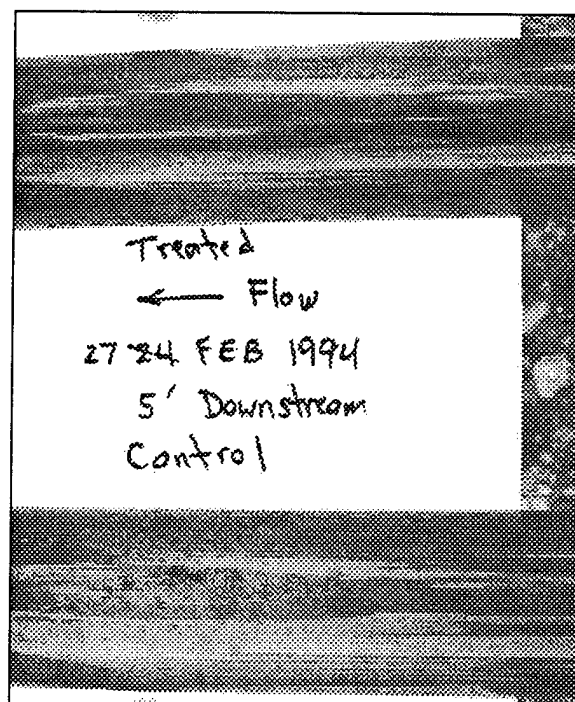


Treated pipe is at the top of each photograph, control at the bottom. Arrows indicate the direction of water flow. "Upstream" labels are in reference to the location of the pulsed acoustic source.

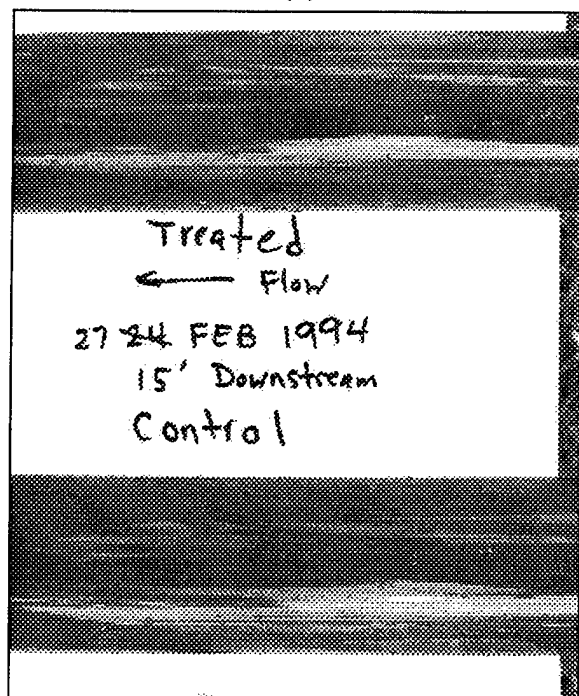
Figure 4. Photographs of biofouling accumulated in control and treated legs of the test loop on 27 February (day 9).



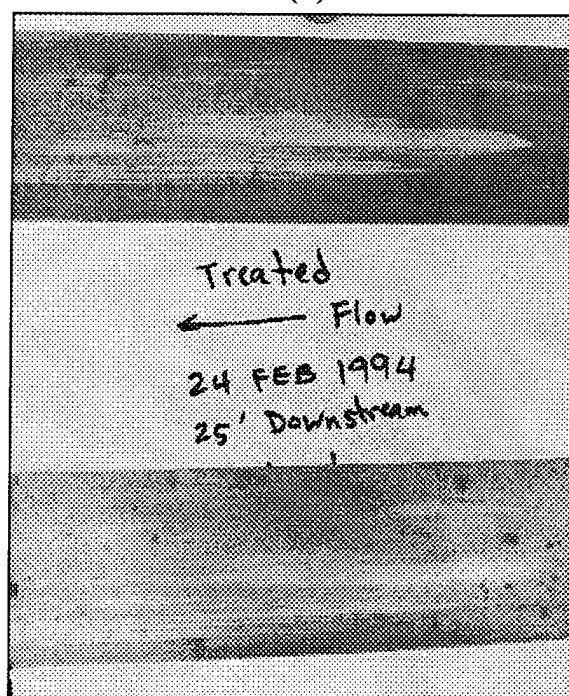
(a)



(b)



(c)



(d)

Treated pipe is at the top of each photograph, control at the bottom. Arrows indicate the direction of water flow. "Downstream" labels are in reference to the location of the pulsed acoustic source.

Figure 5. Photographs of biofouling accumulated in control and treated legs of the test loop on 27 February (day 9).

Results of viable plate counts of bacteria scraped from the walls of both pipes, in general, supported our visual observations of the fouling. Through the sixth day of the test, counts of samples taken from ports P1 and P2 of the treated pipe were up to an order of magnitude lower than those of samples from the corresponding ports in the control pipe (Table 1). These are the two ports closest to the acoustic source on the upstream and downstream sides, respectively. No replicates were done, so we do not know whether this difference is statistically significant. By the ninth day these differences had begun to disappear, again indicating that bacteria were not removed by the acoustic waves once they had adhered to the pipe surfaces. Like the visual observations, the plate counts also demonstrated that the protective effects of the acoustic device did not extend far beyond the first sampling port encountered by the shock wave.

Presence/absence tests for general anaerobic bacteria, sulfate-reducing bacteria and acid-producing bacteria were performed because these groups of microorganisms often are associated with microbiologically-influenced corrosion (MIC) in seawater piping and cooling systems [Little, B. J., P. A. Wagner, W. G. Characklis, and W. Lee, 1990]. Results of these tests (Tables 2, 3, 4) show no significant differences between the control and treated pipes after the media vials had been incubated for one week. In general, however, we observed that positive reactions in vials inoculated from the treated pipe developed more slowly than those from the control. This may be a reflection of lower numbers of these microorganisms occurring in the treated part of the test loop. A quantitative test would be required to confirm this.

In general, visual observations also were supported by ESEM analysis. At sites viewed by ESEM, there usually was less biofouling on coupons from the treated pipe than on those from the control leg of the test loop (Figures 6-8). This difference was particularly noticeable at ports C1/P1 and C2/P2, which were located closest to the acoustic source (Figures 6, 8). As distance from the source increased and, in particular, as the number of intervening pipe fittings and other potential interferences with the acoustic wave increased, less difference was observed between the extent of fouling in the two pipes. Algal attachment and growth was substantially greater on the control coupons (Figures 6, 8, 10). Algae included filamentous forms, as well as diatoms. Fouling was patchy on all of the coupons, particularly those pulled from the treated pipe. This observation again supports the conclusion that the pulsed acoustics are able only to prevent attachment of microorganisms. Once attached, the organisms can continue to grow into large colonies or patches.

EDS spectra obtained from the coupons aided in identification of the fouling material. Spectra from relatively clean coupons, such as that from port P1, basically reflected the elements in seawater salts (Na, Mg, Cl, Ca), with prominent Ca peaks which may represent CaCO_3 deposition (Figure 9). Diatoms were abundant on many of the more heavily fouled surfaces, and EDS spectra from these coupons featured large Si peaks (Figure 10). Diatoms were most numerous in samples taken at the end of the test. Bacteria and filamentous algae predominated on coupons that were pulled earlier in the experiment. Some of the coupons had areas of brown staining. Large amounts of Fe, Cr and Ni confirmed that these stains were corrosion products, perhaps derived from the test loop pumps (Figure 11).

Table 1. Viable plate counts of bacteria obtained from water samples and from scrapings of the pipe walls.

Counts are in units of colony-forming units (cfu) per ml for water samples, and cfu per cm² for wall scrapings.

Sample	Microbial Counts (cfu per ml or per cm ²)		
	2/20/94 (Day 2)	2/24/94 (Day 6)	2/27/94 (Day 9)
Water sample, port C1	1.1×10^4		
Water sample, port C4	1.7×10^3		
Water sample, port P1	3.6×10^3		
Water sample, port P4	2.1×10^3		
Pipe Wall, C1	1.6×10^4	1.7×10^5	5.8×10^3
Pipe Wall, C2	2.1×10^4	3.3×10^4	1.6×10^4
Pipe Wall, C3	1.3×10^4	4.0×10^4	4.4×10^3
Pipe Wall, C4	1.7×10^3	1.1×10^4	1.4×10^3
Pipe Wall, P1	4.5×10^3	1.5×10^4	2.1×10^4
Pipe Wall, P2	2.1×10^3	1.0×10^4	7.5×10^3
Pipe Wall, P3	1.1×10^4	1.4×10^4	6.0×10^3
Pipe Wall, P4	9.6×10^2	8.6×10^3	2.2×10^4

Table 2. Results of presence/absence tests for general anaerobic bacteria for water samples from each pipe as well as for scrapings from the pipe walls.

“C” indicates sample came from the control pipe. “P” indicates sample came from the pipe treated with pulsed acoustics. The number indicates the location of each sampling port (refer to Figure 1).

Sample	2/20/94	2/24/94	2/27/94
Water sample, port C1	+		
Water sample, port C4	+		
Water sample, port P1	+		
Water sample, port P4	+		
Pipe Wall, C1	+	+	-
Pipe Wall, C2	+	+	+
Pipe Wall, C3	+	+	-
Pipe Wall, C4	+	-	
Pipe Wall, P1	+	-	-
Pipe Wall, P2	+	+	-
Pipe Wall, P3	+	-	+
Pipe Wall, P4	+/-	-	

Table 3. Results of presence/absence tests for sulfate-reducing bacteria for water samples from each pipe as well as for scrapings from the pipe walls.

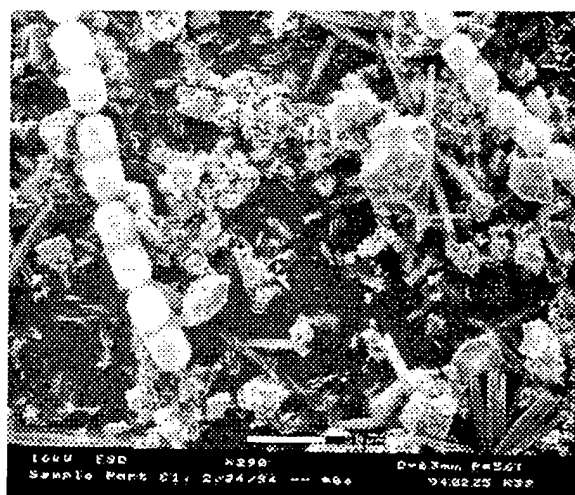
“C” indicates sample came from the control pipe. “P” indicates sample came from the pipe treated with pulsed acoustics. The number indicates the location of each sampling port (refer to Figure 1).

Sample	2/20/94	2/24/94	2/27/94
Water sample, port C1	+		
Water sample, port C4	+		
Water sample, port P1	+		
Water sample, port P4	+		
Pipe Wall, C1	-	-	-
Pipe Wall, C2	+	-	-
Pipe Wall, C3	+	-	-
Pipe Wall, C4	-	-	-
Pipe Wall, P1	-	-	-
Pipe Wall, P2	-	-	-
Pipe Wall, P3	+	-	-
Pipe Wall, P4	+	-	-

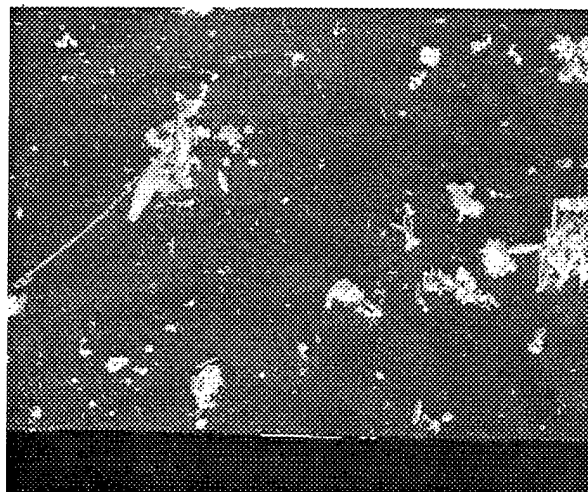
Table 4. Results of presence/absence tests for acid-producing bacteria for water samples from each pipe as well as for scrapings from the pipe walls.

“C” indicates sample came from the control pipe. “P” indicates sample came from the pipe treated with pulsed acoustics. The number indicates the location of each sampling port (refer to Figure 1).

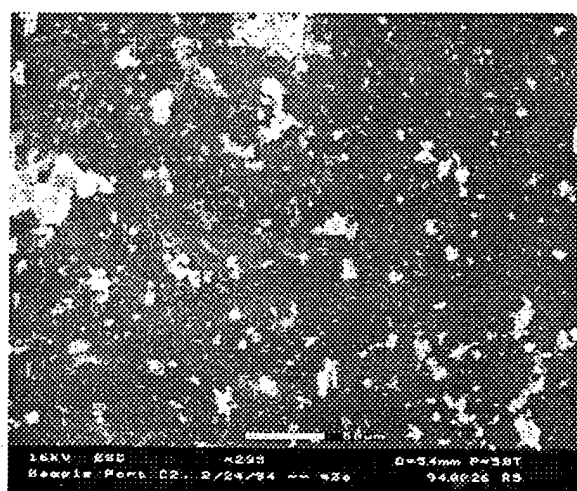
Sample	2/20/94	2/24/94	2/27/94
Water sample, port C1	+		
Water sample, port C4	+		
Water sample, port P1	+		
Water sample, port P4	+		
Pipe Wall, C1	+	-	+
Pipe Wall, C2	+	+	+
Pipe Wall, C3	+	+	+
Pipe Wall, C4	+	-	
Pipe Wall, P1	+	-	+
Pipe Wall, P2	+	+	+
Pipe Wall, P3	+	+	+
Pipe Wall, P4	+	-	



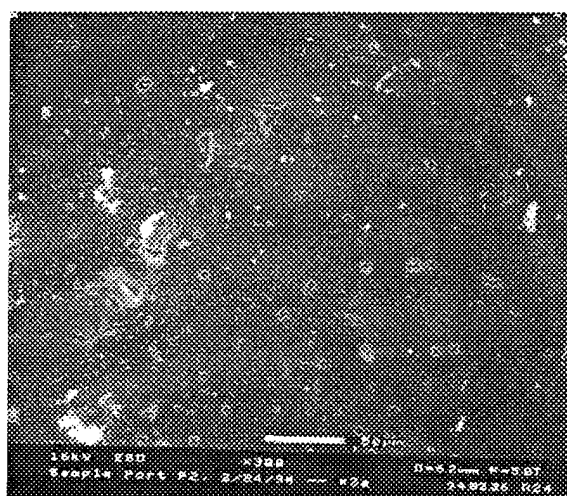
(a)



(b)

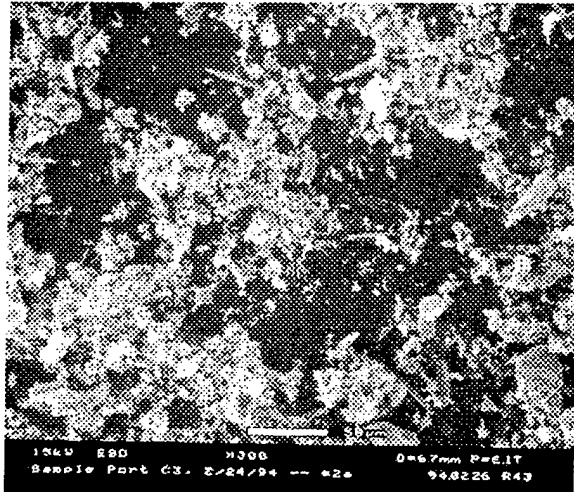


(c)

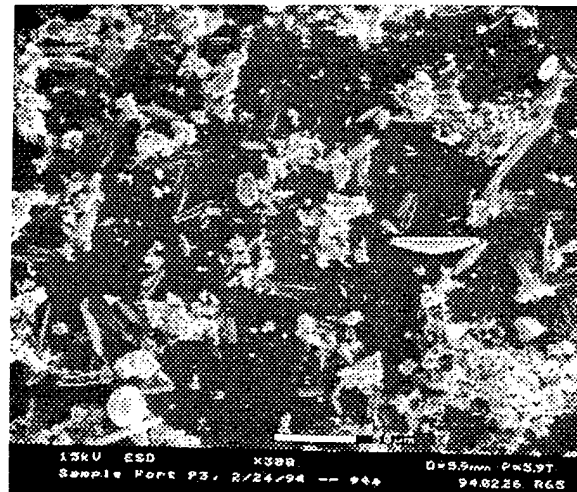


(d)

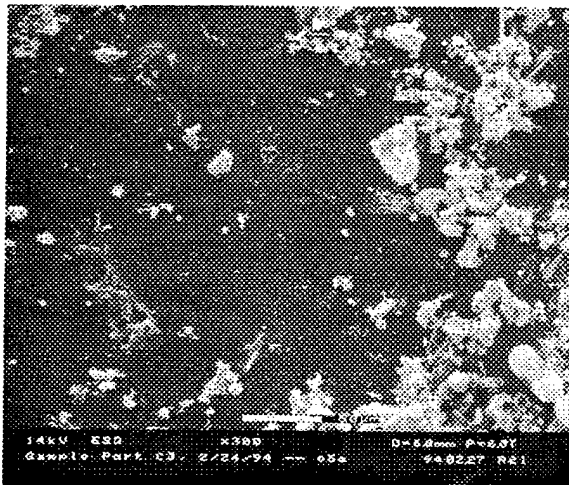
Figure 6. ESEM micrographs of coupons taken from sampling ports closest to the acoustic source on 24 February, Day 6 of the test: (a) C1 – control, 10 ft upstream; (b) P1 – treated, 10 ft upstream; (c) C2 – control, 2 ft downstream; (d) P2 – treated, 2 ft downstream. Magnification in micrographs is 300X. Size bar at bottom = 50 μ m.



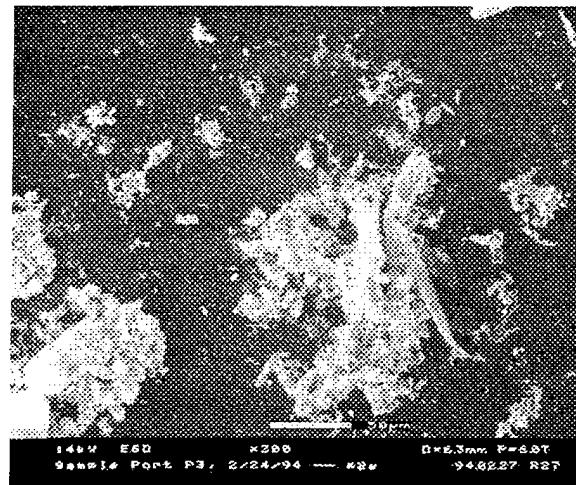
(a)



(b)

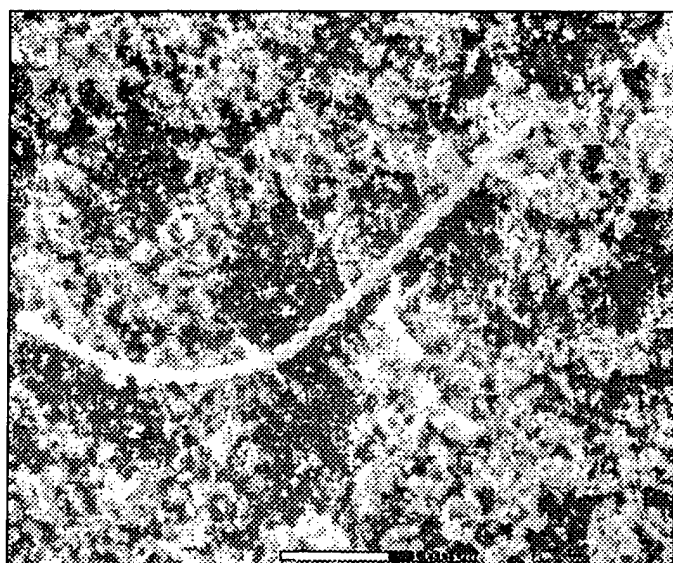


(c)

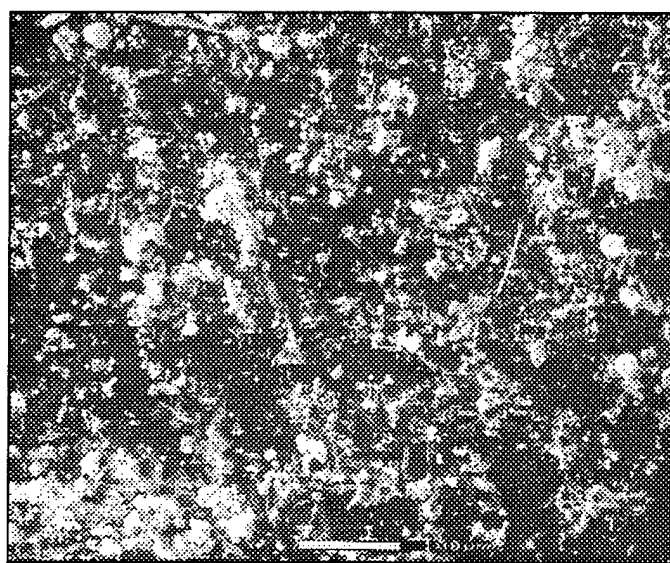


(d)

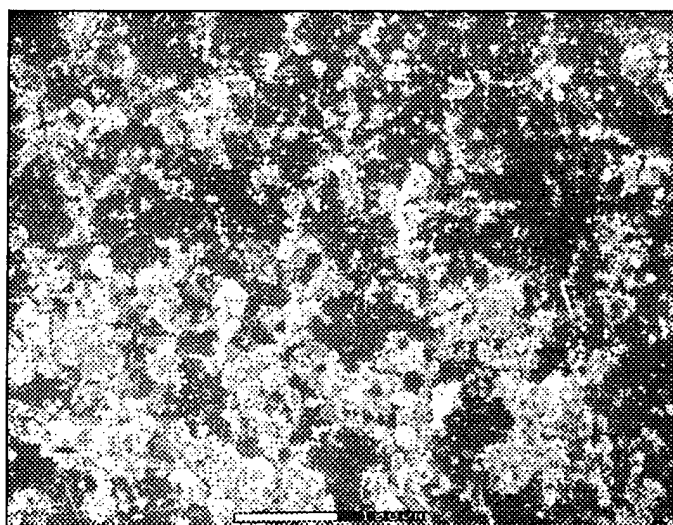
Figure 7. ESEM micrographs of coupons taken from sampling ports closest to the acoustic source on 24 February, Day 6 of the test: (a) C3 – control, 10 ft downstream; (b) P3 – treated, 10 ft downstream; (c) C4 – control, 20 ft downstream; (d) P4 – treated, 20 ft downstream. Magnification in micrographs is 300X. Size bar at bottom = 50 μ m.



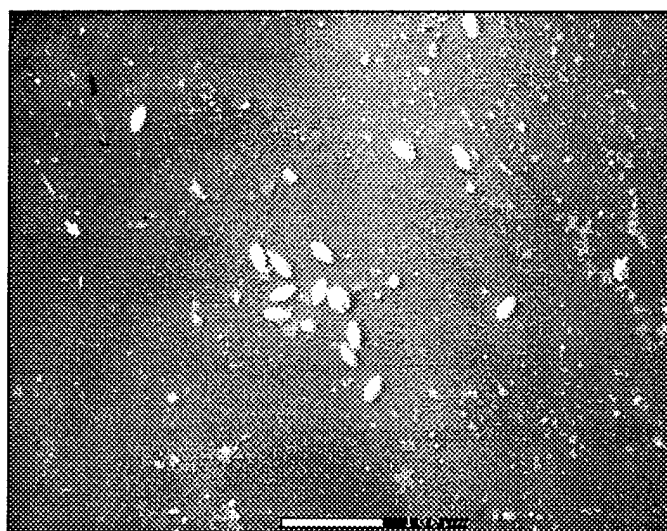
(a)



(b)

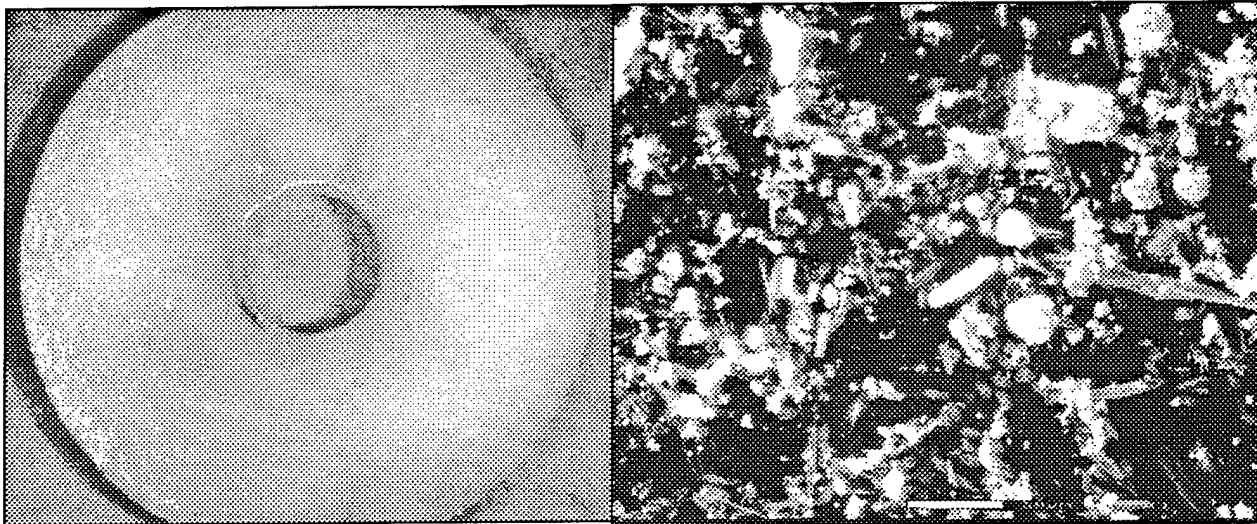


(c)



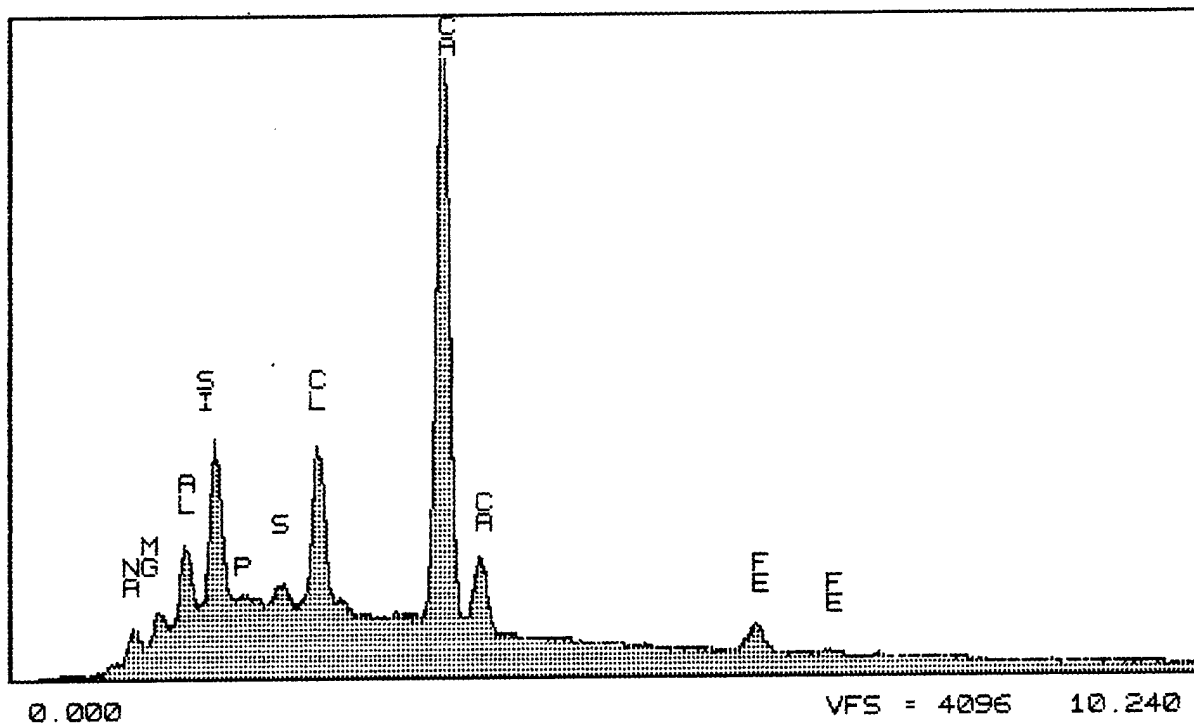
(d)

Figure 8. ESEM micrographs of coupons taken from sampling ports closest to the acoustic source on 27 February, Day 9 of the test: (a) C1 – control, 10 ft upstream; (b) P1 – treated, 10 ft upstream; (c) C2 – control, 2 ft downstream; (d) P2 – treated, 2 ft downstream. Magnification in micrographs is 150X. Size bar at bottom = 100 μ m.



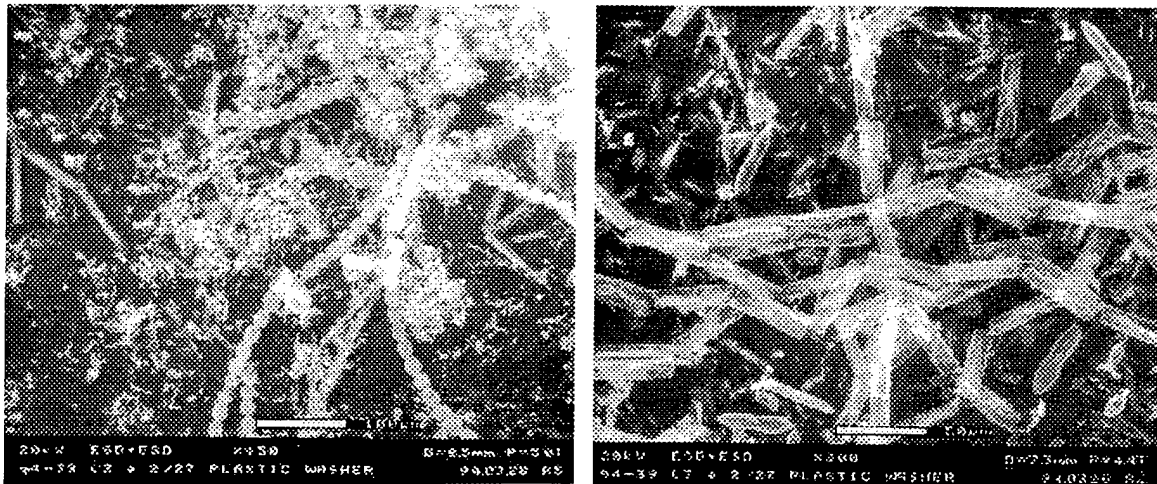
(a)

(b)



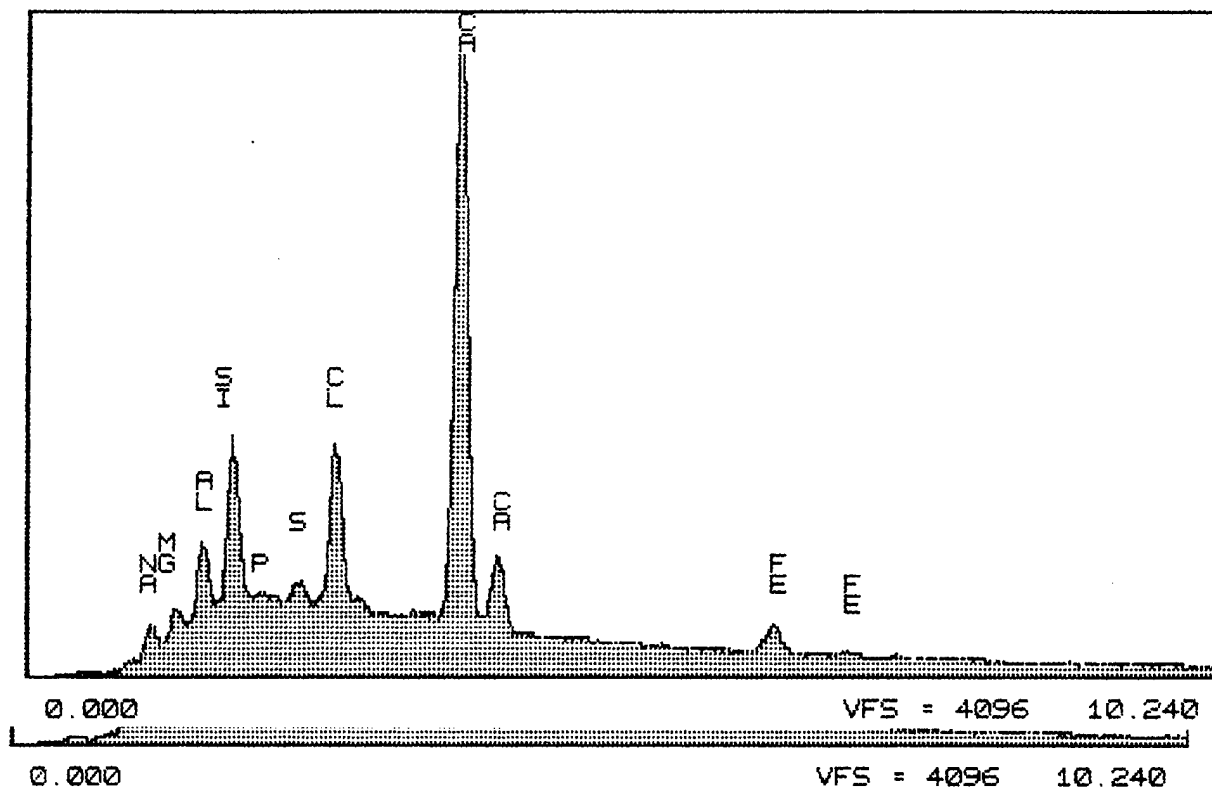
(c)

Figure 9. ESEM micrograph (b) and EDS spectrum (c) from coupon (a) pulled from sampling port P1 (treated pipe) on 27 February, Day 9 of the test. Magnification in micrograph is 300X. Size bar at bottom = 50 μm .



(a)

(b)

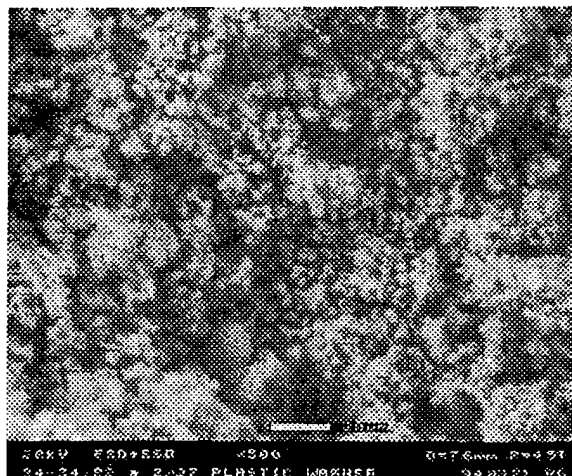


(c)

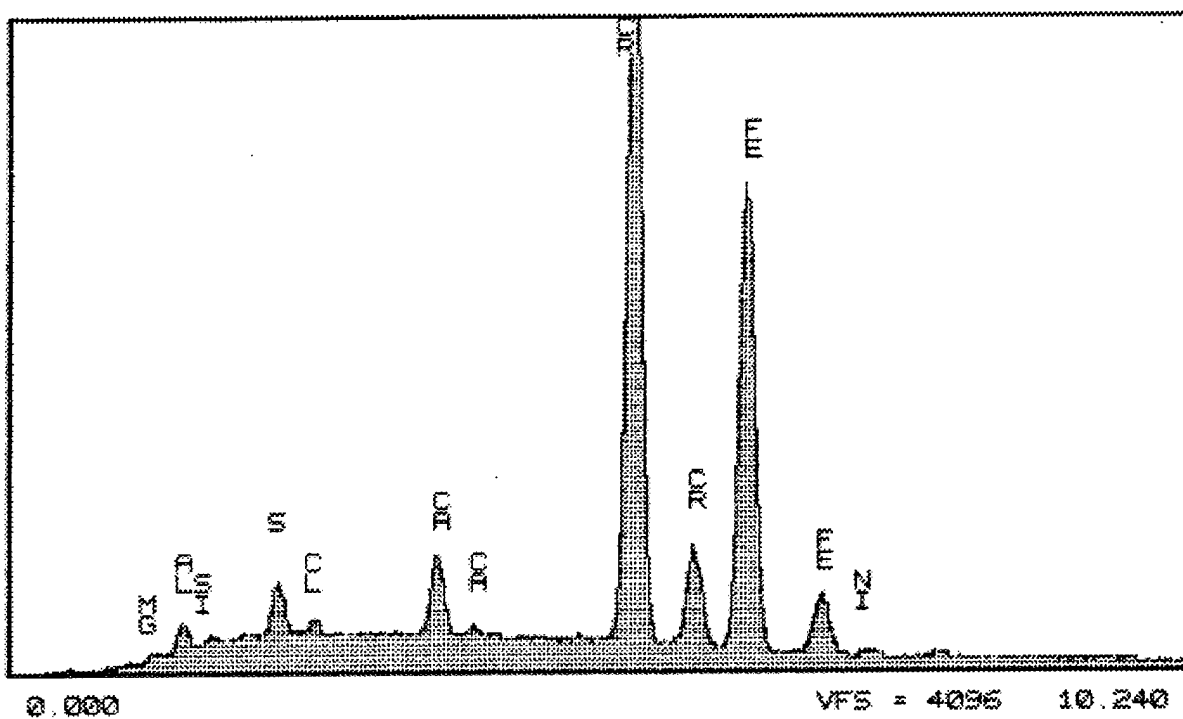
Figure 10. ESEM micrographs (a and b) and EDS spectrum (c) from coupon pulled from sampling port C3 (control pipe) on 27 February, Day 9 of the test. Silicon peak in spectrum correlates with diatom colonies on surface. Magnification in (a) is 150X. Size bar at bottom = 100 µm. Magnification in (b) is 300X. Size bar = 50 µm.



(a)



(b)



(c)

Figure 11. ESEM micrograph (b) and EDS spectrum (c) from stained area of coupon (a) pulled from sampling port P2 (treated pipe) on 27 February, Day 9 of the test. Brown stains are corrosion products. Magnification in micrograph is 500X. Size bar at bottom = 20 μm .

Discussion

The field experiment described here demonstrated effective, non-chemical biofouling prevention both upstream and downstream of the acoustic source. Specifically, we demonstrated a significant reduction in the rate of micro- and macrofouling, with respect to an untreated control, in a seawater test loop treated with pulsed acoustic waves. Based on viable plate counts, an order of magnitude reduction in bacterial attachment was observed at ranges of at least 10 feet for 0.5-Hz acoustic pulse treatments of less than 4 W/ft² for 10 hours per day. Direct observation of treated and untreated surfaces using ESEM revealed substantial reduction of bacterial and algae settlement compared to the untreated control. This effect decreased with time, as organisms that did attach were not removed by the acoustic pulse and continued to grow. Much of the original settlement of microorganisms and algae in the treated pipe presumably occurred at night, when water continued to flow even though the acoustic source was turned off. No degradation of the clear PVC plastic piping was observed.

The most pronounced effects of the acoustic pulse were observed in the segments of piping between the source and the first set of sampling ports, both upstream and downstream. The pipe unions, fittings, sample holders, etc., were not designed in this experiment to be acoustically compatible with the pipe material. Thus, it is almost certain that the acoustic impedance mismatch at these locations resulted in significant dissipation of the acoustic energy traveling through the pipe and the water. This could be confirmed using pressure transducers placed before and after the pipe fittings. On the other hand, when nothing interferes with the acoustic wave, it presumably could propagate for quite some distance. A long cylindrical pipe is an ideal waveguide for this type of energy. These findings suggest that it is the acoustic energy in the pipe that is responsible for preventing settlement of organisms on the pipe surface, rather than the acoustic energy in the water. The implication of this finding is that this technology for biofouling prevention may be best suited for heat exchanger tubes and long piping runs with few flanges, valves or other fittings.

Acoustic and electrical methods for biofouling control have been studied for some time. Conventional ultrasonic sources are the best known of these. The biofouling control mechanism of most ultrasonic devices usually is attributed to the effects of acoustic cavitation. Because of cavitation bubble implosion, extreme temperatures and pressures are generated at the center of the collapsed bubble and free radicals and other highly reactive oxidizing species may be produced [Hua, I., and M. R. Hoffman, 1997].

Our pulsed power method uses *low*-energy acoustic shock waves to prevent, rather than remove, biofouling. Pulsed acoustic shock wave technology differs from conventional sonic and ultrasonic methods in several respects. First, the cavitation threshold is much higher for short-pulse, high frequency (<1 μ s duration, >1 MHz carrier) acoustic waves than for low frequency (~10 kHz), continuous wave ultrasonics. The higher cavitation threshold allows more acoustic power to be delivered to the water, at higher efficiency, and lessens the risk of damage to materials and coatings that is associated with cavitation. Secondly, the equipment used to

produce the underwater pulsed shock wave is fundamentally different. Only relatively simple arc-discharge equipment is required.

The biofouling prevention effects that we observed in this test occurred at ranges that exclude the influence of cavitation and ultraviolet illumination. Based on observations of particle movement in the clear pipes, we hypothesize that the mechanism of fouling inhibition involves the interaction of the acoustic pulse with particles (cells) caught in the boundary layers at surfaces in contact with the flowing water column. This interaction reduces the effective "sticking coefficients" of the particles. The mechanism appears to be equally effective in preventing the accumulation of microscopic objects such as bacteria, algae and larvae, as well as macroscopic objects such as sand. Since the effect is non-chemical, but confined to the range of the acoustic wave in the system being treated, it should be more environmentally compatible than competing chemical biocides and thermal treatments alone. Alternatively, experience with other techniques that influence boundary layer diffusion [Costerton, J. W., 1993] makes it likely that biocides used in conjunction with pulsed acoustic treatment will be more effective, especially in low-flow or stagnant regions. Since the focus is on prevention of settlement at the microscopic level, a collateral waste stream essentially is avoided.

Concern is often expressed about using acoustic biofouling control methods on vessels aboard which acoustic signature is a concern. We anticipate that such methods, should they prove useful for shipboard applications, would be used primarily while vessels are in or near port. This represents, in general, the period of highest biofouling risk.

Literature Cited

- Afring, R. P., and B. Taylor. 1979. Assessment of microbial fouling in an ocean thermal energy conversion experiment. *Applied and Environmental Microbiology*. **38**:734-739.
- Characklis, W. G., N. Zelver, and M. Turakhia. 1984. Microbial films and energy losses, p. 75-81. In J. D. Costlow and R. C. Tipper (eds.), *Marine Biodeterioration: An Interdisciplinary Study*. The Naval Institute, Annapolis, Maryland.
- Christian, D.K., J.O. Bergh and E.D. Thomas. 1995. Dechlorination equipment for shipboard pollution prevention. *Sea Technology* **36**(10):51-56.
- Costerton, J. W. 1993. Control of microbial biofilm by electrically enhanced biocide treatment. Presented at the 12th International Corrosion Congress.
- Fischer, E. C. 1984. Technology for control of marine biofouling - a review, p. 261-291. In J. D. Costlow and R. C. Tipper (eds.), *Marine Biodeterioration: An Interdisciplinary Study*. U. S. Naval Institute, Annapolis, Maryland.
- Haderlie, E. C. 1984. A brief overview of the effects of macrofouling, p. 163-166. In J. D. Costlow and R. C. Tipper (eds.), *Marine Biodeterioration: An Interdisciplinary Study*. U. S. Naval Institute, Annapolis, Maryland.
- Hua, I., and M. R. Hoffman. 1997. Optimization of ultrasonic irradiation as an advanced oxidation technology. *Environmental Science and Technology*. **31**:2237-2243.
- Jenner, H.A., and H.J.G. Polman. 1993. Pulse-chlorination: a new way of reducing chlorine for mitigation of mussel fouling. Abstr. Eighth Internat. Zebra Mussel and Aquatic Nuisance Species Conf., Sacramento, California, March 16-19, 1998.
- Jones, J. M., and B. J. Little. 1990. USS PRINCETON (CG 59): Microbiologically Influenced Corrosion (MIC) and Macrofouling Status of Seawater Piping Systems. Technical Report. Naval Surface Warfare Center.
- Little, B. J., P. A. Wagner, W. G. Characklis, and W. Lee. 1990. Microbial corrosion, p. 635-670. In W. G. Characklis and K. C. Marshall (ed.), *Biofilms*. John Wiley and Sons, Inc., New York.
- Walch, M., and R. A. Brizzolara. 1998. Initiation Decision Report (IDR) on Biofouling Control in Seawater Piping and Heat Exchanger Systems. Technical Report NSWCCD-TR-1998/014. Naval Surface Warfare Center, Carderock Division.
- Weber, B.E. and D.A. Brown. 1997. Prevention of biofouling in heat exchanger tubing through use of intermittent chlorination and velocity flushing. In C.B. Panchal (ed.), *Fouling Mitigation of Industrial Heat-Exchange Equipment*. Begell House Inc., New York.

Appendix A

Patent No. 5,636,180

Inventors: Michael G. Grothaus, Michael S. Mazzola and Marianne Walch
"System for Preventing Biofouling of Surfaces Exposed to Water."

United States Patent [19]

Grothaus et al.

[11] Patent Number: **5,636,180**[45] Date of Patent: **Jun. 3, 1997**[54] **SYSTEM FOR PREVENTING BIOFOULING OF SURFACES EXPOSED TO WATER**[75] Inventors: **Michael G. Grothaus**, Boerne, Tex.;
Michael S. Mazzola, Mississippi State,
Miss.; **Marianne Walch**, Laurel, Md.[73] Assignee: **The United States of America as
represented by the Secretary of the
Navy**, Washington, D.C.[21] Appl. No.: **515,879**[22] Filed: **Aug. 16, 1995**[51] Int. Cl.⁶ **G10K 15/06**[52] U.S. Cl. **367/147; 367/139**[58] Field of Search **367/139, 147;
116/22 A**[56] **References Cited****U.S. PATENT DOCUMENTS**

3,486,062	12/1969	Schrom	367/147
4,092,858	6/1978	Edgerton	73/170 A
4,375,991	3/1983	Sachs et al.	134/1

5,208,788	5/1993	Dancer et al.	367/147
5,245,988	9/1993	Einars et al.	367/147
5,397,961	3/1995	Ayers et al.	315/111.21
5,432,756	7/1995	Bryden	367/139

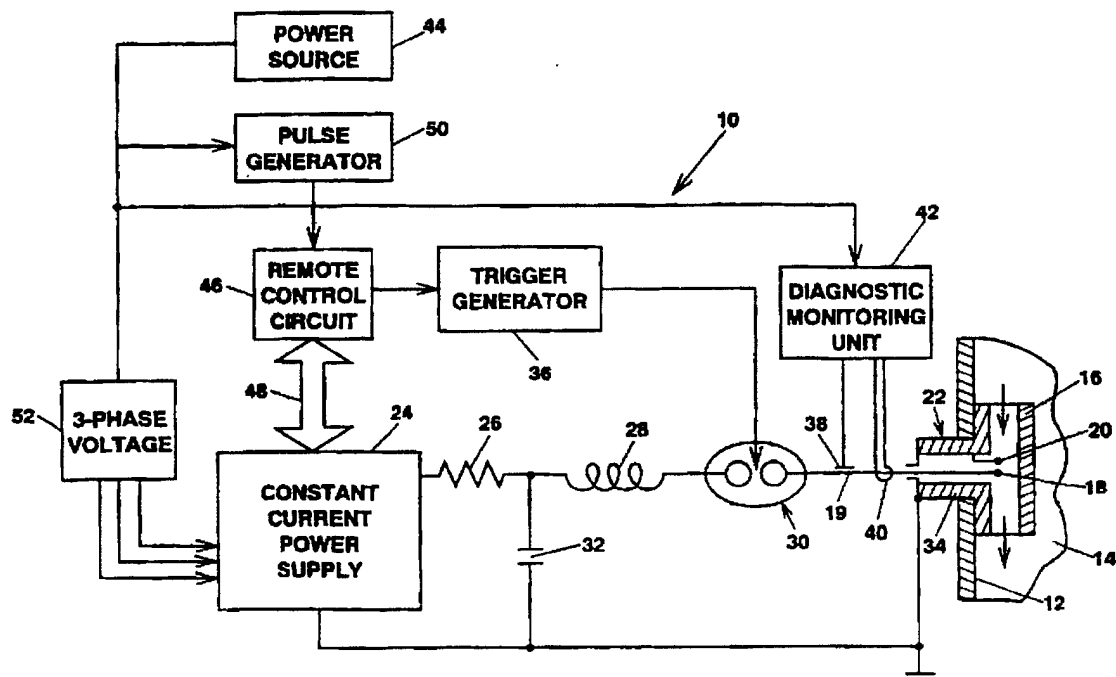
OTHER PUBLICATIONS

Taylor et al. "Ultrasonics as an alternative to Chlorine for inhibiting Biofouling". Johns Hopkins APL Tech. Dig. (USA), vol. 3, No. 3, pp. 295-297. Jul 1982.

Primary Examiner—Jan J. Lobo
Attorney, Agent, or Firm—John L. Forrest; Jacob Shuster

[57] **ABSTRACT**

Acoustical shock waves are generated by electrical sparks within a gap between electrodes adjustably positioned for exposure to water adjacent a surface immersed therein. High voltage electrical energy derived from a constant current power supply, is stored in a capacitor for rapid application to the electrodes by discharge during cyclic periods of short duration under remote control in order to render the acoustical shock waves so generated effective in preventing biofouling of the surface by organisms in the water.

7 Claims, 2 Drawing Sheets

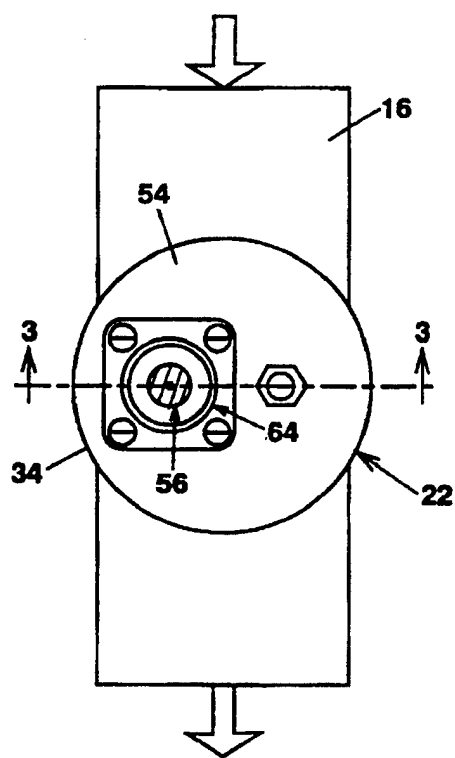


FIG. 2

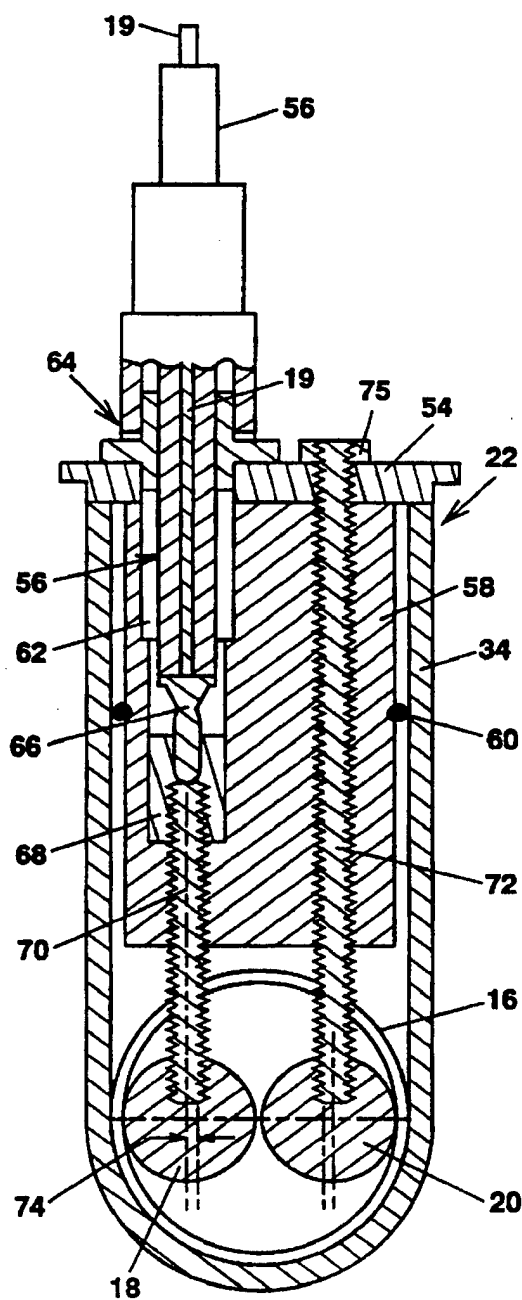


FIG. 3

5.636.180

1

SYSTEM FOR PREVENTING BIOFOULING OF SURFACES EXPOSED TO WATER

BACKGROUND OF THE INVENTION

The present invention relates in general to an electrical method and apparatus for preventing biofouling buildup on surfaces exposed to fresh water or saltwater.

The growth and accumulation of biological organisms and the by-products resulting therefrom on surfaces of structures and machinery in contact with either fresh water or salt water, represents a constant maintenance problem for such structures and machinery. For example, the hull of ships and associated seawater exposed systems become coated with both microfouling and macrofouling material such as water-borne algae, bacterial-induced biofilm, barnacles, mussels, etc., which may additionally enhance or induce corrosion.

In order to deal with the foregoing problem, a considerable amount of research activity has been undertaken in an effort to find solutions that are both economical and environmentally compatible, involving various non-chemical treatment technologies including sonics. Biofouling control by use of sonics under study for some time, is now well known and includes the use of conventional ultrasonic sources found to have mixed results for a variety of reasons, including for example a low cavitation threshold at ultrasonic frequencies associated with the use of prior biofouling treating techniques. The use of electric fields and currents in biofouling control applications are also known, but has met with varied results which are furthermore difficult to duplicate.

In connection with the foregoing referred to technologies, U.S. Pat. Nos. 3,486,062, 5,208,788 and 5,245,988 to Schrom, Dancer et al. and Einars et al., respectively, may be of interest. The Schrom patent relates to the generation of shock waves by electric spark discharge from an electrode in a surrounding liquid medium, such shock waves being directed and focused for various types of manufacturing and process operations. The Dancer et al. patent relates to circuitry for triggering sparks within gaps between electrodes for purpose of electrode position detection and correction. As to the Einars et al. patent, it relates to the production of shock waves by electrical discharge of capacitor stored energy between electrodes immersed in liquid for treatment of living tissue. However, none of the foregoing Schrom, Dancer et al. and Einars et al. patents relates to biofouling prevention, treatment or control.

Accordingly, it is an important object of the present invention to generate pulsed acoustic shock waves for continuous biofouling control purposes within a body of liquid water, with greater efficiency in the delivery of acoustic power and having a higher cavitation threshold to enlarge the water treatment region with reduced collateral damage.

SUMMARY OF THE INVENTION

In accordance with the present invention, acoustical shock waves are cyclically produced by high voltage pulses from a storage capacitor across a spark gap between bail-shaped, electrodes adjustably positioned for exposure to water adjacent to a surface immersed therein. Such high voltage pulses, stored within the capacitor during short charging cycles of less than 1 microsecond, are rapidly applied to the electrodes by capacitor discharge through a stray inductance in series with a peaking spark gap device to prevent conduction of current to the electrodes between capacitor charging cycles. Electrical energy for charging of the storage

2

capacitor during such charging cycles is derived from a constant current power supply that is protected against voltage reversals by a resistor through which the power supply is connected to the storage capacitor. The power supply is also disabled during cyclic periods of capacitor discharge to the electrodes of short duration, under control of circuitry which also controls capacitor charging voltage and charging time. The resulting acoustical shock waves generated at the electrodes, interact with biofouling organisms to prevent attachment thereof to the water immersed surface being protected.

BRIEF DESCRIPTION OF DRAWING FIGURES

A more complete appreciation of the invention and many of its attendant advantages will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawing wherein:

FIG. 1 is a circuit diagram of a biofouling treatment system in accordance with one embodiment of the invention;

FIG. 2 is a top plan view of an acoustic pulse source component of the system depicted in FIG. 1; and

FIG. 3 is a side section view taken substantially through a plane indicated by section line 3—3 in FIG. 2.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

Referring now to the drawing in detail, FIG. 1 diagrams a system 10 for preventing biofouling build-up on a wall surface 12 immersed within liquid 14, such as fresh water or seawater. The liquid in contact with surface 12 is conducted through a pipe section 16 mounted in abutment with surface 12 for exposure of such liquid to pulsed acoustic energy produced by electric sparks in a gap between high voltage electrodes 18 and 20 of an acoustic pulse source generally referred to by reference numeral 22. At the instant that each spark occurs between electrodes 18 and 20, a steep compression shock wave is generated which interacts with any bio-matter suspended in the body of liquid 14 within the region adjacent to surface 12 in order to prevent attachment thereof to surface 12. Such bio-matter includes a variety of organisms. As a result, a significant reduction in the rate of biofouling of an underwater surface by both micro and macro organisms has been achieved in accordance with the present invention.

With continued reference to FIG. 1, the electrode 18 is connected by power line 19 to a constant current power supply 24 through a resistor 26 in series with an inductance 28 and a spark gap peaking type of switch device 30. A storage capacitor 32 is connected between the power supply and its ground line electrically grounding the electrode 20 through the housing 34 of the acoustic pulse source 22. Upon closure of the spark gap peaking device 30, under control of a trigger generator 36, a high voltage is applied by power supply 24 across the electrodes 18 and 20 through stray inductance 28 and resistor 26 in series therewith. The resistor 26 protects the power supply from voltage reversals without dissipation of any significant amount of power, in view of the constant current nature of the power supply 24. The voltage and current supplied by discharge of capacitor 32 to the electrode 18 of the acoustic pulse source 22, are respectively monitored through voltage and current sensors 38 and 40 connected to a diagnostic monitoring unit 42.

Electrical energy for operation of the monitoring unit 42, the power supply 24 and the trigger generator 36 is derived

5.636.180

3

from a suitable power source 44 as diagrammed in FIG. 1. The power supply 24 is of a commercially available type capable of being externally controlled by a remote control circuit 46 through a 15-pin interface 48, for example, so as to implement high voltage cyclic charge of storage capacitor 32 through resistor 26. At the end of each charge cycle, the high voltage power supply 24 is disabled under control of the remote control circuit 46 to isolate the power supply and deliver a signal to trigger generator 36 so as to provide rapid, low energy output pulses causing rapid closure of the aforementioned spark gap peaking device 30. Rapid application of the high voltage stored in capacitor 32 to the acoustic pulse source 22 through inductance 28, is thereby achieved. The operating characteristics of the spark gap device 30 may be varied by adjustment of its gap spacing and gas operating pressure, as generally known in the art, to meet desired voltage and current conditions. The voltage and current applied to acoustic pulse source 22 from capacitor 32 are therefore monitored through the aforementioned diagnostic unit 42. The pulse width of a high voltage pulse of relatively short duration is formed when the switch device 30 discharges capacitor 32 resulting in a discharge current to the electrodes conducted through cable 19 having a rise time of less than one (1) microsecond corresponding to the charging time of capacitor 32 which is controlled by pulse generator 50. Such charging voltage applied to capacitor 32 under control of pulse generator 50 ranges from 12 to 15 kV, derived from the constant current power supply 24 to which a 208 volt, 3-phase prime power input 52 is fed, as denoted in FIG. 1. Acoustic waves having a relatively high cavitation threshold is thereby generated at source 22 in accordance with the present invention.

Referring now to FIGS. 2 and 3 in particular, the electrode geometry of the acoustic pulse source 22 is shown enclosed within the housing 34 extending perpendicular from its intersection with the pipe section 16 at which the electrodes 18 and 20 are located. A base plate 54 connected to housing 34 closes its axial end into which the power line 19 extends within a cable, 56. An insulator body 58 is enclosed within the housing 34 in abutment with the base plate 54, seating an O-ring 60 in engagement with the housing 34 to form a water-tight seal. The cable 56 extends into a stepped bore 62 formed in the insulator body 58 in alignment with a base plate opening closed by a demountable connector 64 removably anchoring the cable 56 in its illustrated position within the insulator body 58. The end of the power line 19 within the housing 34 is electrically connected by contact terminal 66 to a conductive adapter plug 68 made of brass, for example. The plug 68 seated in the insulator opening 62 at its lower end, has a threaded bore receiving one end portion of a threaded support rod 70 made of stainless steel. The other end portion of rod 70 below the insulator body 58, is threadedly connected to the electrode 18 which is in the form of a stainless steel ball bearing, as shown in FIG. 3.

The other electrode 20 is similar in construction and mounting support to that of electrode 18, as also shown in FIG. 3. Thus, a threaded support rod 72 positions the electrode 20 in spaced adjacency to electrode 18. Such mounting of the ball-shaped electrodes 18 and 20 may be somewhat offset from the axes of rods 70 and 72, as indicated by reference number 74, so that spark gap spacing adjustment may be made by either rotating the electrodes on the rods 70 and 72 or replacing them with electrodes having different ball diameters centered relative to the internal diameter of the pipe section 16. Also, the rod 72 threadedly extends completely through the insulator body 58 between its axial ends, parallel to rod 70. The upper end of rod 72

4

furthermore extends through the base plate 54 to which it is anchored by nut 75 and through which the electrode 20 is grounded by connection to the ground line as aforementioned.

From the foregoing description it will be apparent that the pulses generated between the electrodes 18 and 20 of the acoustic pulse source 22 are formed when the spark gap switch 30 causes the capacitor 32 to discharge into the cable 19 to the electrode 18. The rise time of the resulting current between electrodes 18 and 20 should be less than 1 microsecond as aforementioned corresponding to the limited discharge time of the capacitor 32. By use of the foregoing described acoustic source 22, non-chemical treatment to prevent biofouling is achieved both upstream and downstream of its location within an otherwise untreated body of water. Obviously, other modifications and variations of the present invention may be possible in light of the foregoing teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A method of treating a body of liquid within a region in contact with a surface immersed in said liquid, by means of acoustical energy, including generation of the acoustical energy by electrical discharge through a spark gap established within said region, the improvement residing in conducting constant electrical current during charging cycles for cyclic storage of the acoustical energy; preventing conduction of the current to the spark gap during said charging cycles; and limiting said electrical discharge to cyclic periods of short duration of less than a predetermined time to prevent biofouling of the surface.

2. Apparatus for treating a body of liquid adjacent to a surface immersed therein to prevent biofouling of said surface, including: a storage capacitor; an acoustic pulse source operatively connected to the storage capacitor; and means mounting the acoustic pulse source on said surface for cyclic emission of shock waves within the body of liquid in response to discharge of electrical energy from the storage capacitor, the improvement residing in: means operatively connected to the storage capacitor for supplying constant current thereto; and means for controlling storage of the electrical energy by the storage capacitor in response to said supplying of the constant current thereto for limiting said discharge therefrom resulting in current conducted through the acoustic pulse source having a rise time of less than one (1) microsecond.

3. The apparatus as defined in claim 2 wherein the means mounting the acoustic pulse source comprises: a pipe section in abutment with the surface through which the liquid is conducted; a housing extending from the pipe section through said surface in enclosing relation to the electrodes; conductive support means connected to the electrodes for electrical connection thereof to the storage capacitor; and insulator means within the housing through which the conductive support means extends for positioning the electrodes in spaced relation to each other while exposed to the liquid within the pipe section.

4. The apparatus as defined in claim 3 wherein said electrodes are ball shaped.

5. In a system for treating a body of water adjacent to a surface with acoustical shock waves preventing biofouling of the surface, a power supply from which voltage pulses are derived and means for generating said acoustical shock waves comprising: a pair of electrodes; a pipe section through which the water is conducted; a housing connected to the pipe section enclosing the electrodes therein; support

5.636.180

5

rods connected to the electrodes; insulator means through which the support rods extend within the housing for positioning the electrodes in spaced relation to each other establishing a spark gap; and means operatively connecting the support rods to the power supply for applying said voltage pulses across the spark gap between the electrodes during cyclic periods of short duration to produce said acoustical shock waves within the body of water.

6. The system as defined in claim 5 wherein the means operatively connecting the support rods to the power supply includes: a storage capacitor from which discharge occurs limited to current between the electrodes having a rise time of less than one (1) microsecond corresponding to said cyclic periods of short duration and means limiting charging of the storage capacitor by constant current from the power supply between said cyclic periods of discharge.

7. Apparatus for generating an acoustical shock wave in a liquid medium which comprises:

- (a) first and second spaced electrodes contacting the liquid medium.

6

(b) positioning means for maintaining spacing between the first and second electrodes in contact with the medium adjacent to a surface subject to biofouling;

(c) a pulse-forming network coupled between a power supply and the first and second electrodes for initiating a spark discharge current therebetween; and

(d) output switch means connected between the pulse-forming network and at least one of the electrodes for transmitting a pulse of energy to said electrodes whereby the shock wave is generated in said medium. said pulse-forming network including: at least one storage capacitor within which the pulse energy is stored in response to constant current received from the power supply; and means for limiting said spark discharge current to a rise time of less than one (1) microsecond corresponding to short duration discharge of the pulse energy from the storage capacitor.

* * * * *

Distribution

	<i>Copies</i>		<i>Copies</i>
CHIEF OF NAVAL OPERATIONS		COMMANDER	
2000 NAVY PENTAGON		NAVAL SURFACE WARFARE CENTER	
WASHINGTON DC 20350-2000	1	CRANE DIVISION	
		300 HIGHWAY 361	
ATTN		CRANE IN 47522-5001	1
33 DEMARCO	1		
332 POHANKA	1	COMMANDER	
332 SEDRICKS	1	NAVAL SURFACE WARFARE CENTER	
335 CHRISEY	1	INDIAN HEAD DIVISION	
335 GUARD	1	101 STRAUSS AVE	
335 MCELVANEY	1	INDIAN HEAD MD 20640-5035	1
335 WARD	1		
CHIEF OF NAVAL RESEARCH		ATTN BUCKY GLENN	1
BALLSTON CENTRE TOWER ONE		BILL LUCEY	1
800 NORTH QUINCY ST		COMMANDING OFFICER	
ARLINGTON VA 22217-5660		FLEET TECHNICAL SUPPORT CENTER	
		ATLANTIC	
ATTN		9727 AVIONICS LOOP	
PMS450	1	NORFOLK VA 23511-2124	
SEA 05L31 BAAS	1		
SEA 05L32 TSAO	1	ATTN	
SEA 05R1 ADEMA	1	6110 CALLAHAN	1
SEA 05U6 ARCANO	1	6110 JONES-MEEHAN	1
SEA 08E POTTS	1	6170 COLTON	1
SEA 08J ROWE	1	6930 GABER	1
SEA 92T251 KURZ	1	7303 LITTLE	1
SEA 92TE CARTWRIGHT	1	COMMANDER	
COMMANDER		NAVAL RESEARCH LABORATORY	
NAVAL SEA SYSTEMS COMMAND		4500 OVERLOOK AVE SW	
2531 JEFFERSON DAVIS HWY		WASHINGTON DC 20075	
ARLINGTON VA 22242-5160			
		DEFENSE TECHNICAL INFORMATION CENTER	
ATTN		8725 JOHN KINGMAN ROAD SUITE 0944	
B20 MORAN	1	FORT BELVOIR VA 22060-6218	1
COMMANDER			
NAVAL SURFACE WARFARE CENTER		ATTN PROFESSOR MICHAEL MAZZOLA	1
DAHLGREN DIVISION		MISSISSIPPI STATE UNIVERSITY	
17320 DAHLGREN RD		DEPARTMENT OF ELECTRICAL ENGINEERING	
DAHLGREN VA 22448-5100	1	BOX 9571	
		MISSISSIPPI STATE MS 39762	
		ATTN DR MICHAEL GROTHAUS	1
		SOUTHWEST RESEARCH INSTITUTE	
		6220 CULEBRA ROAD	
		PO DRAWER 28510	
		SAN ANTONIO TX 78228-0510	

Distribution

			<i>Copies</i>		<i>Copies</i>	
NSWC, CARDEROCK DIVISION INTERNAL DISTRIBUTION				Code Name	Copies	
				65R	Department Library	2
				652	Furio	1
				68	Sudduth	1
011	Corrado	1		681	Lee, J.	1
0112	Barkyoumb	1			Hoover	1
0119	Messick	1		682	Liu	1
3442	TIC	1			Warren	1
5200	Karafaith	1		683	Barnes	1
60	Morton	1			Brizzolara	3
603	Cavallaro	1			Walch	5
613	Conrad	1		80	Sofia	1
63	Alig	1		824	Pizzino	1
6301	Lardis	1		824	Nordham	1
640	Fischer	1				
641	Montemarano	1				
	Haslbeck	1				
	Holm	1				