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MARINE FOULING OF TITANIUM HEAT EXCHANGERS

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March 1976

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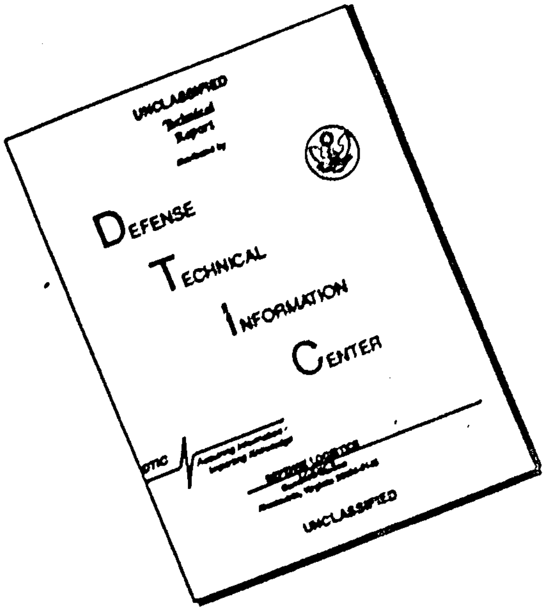

Report PAS-75-29

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MARINE FOULING OF TITANIUM HEAT EXCHANGERS

by
Wayne L. Adamson

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PROPULSION AND AUXILIARY SYSTEMS DEPARTMENT
Annapolis
RESEARCH AND DEVELOPMENT REPORT

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The Naval Ship Research and Development Center is a U. S. Navy center for laboratory effort directed at achieving improved sea and air vehicles. It was formed in March 1967 by merging the David Taylor Model Basin at Carderock, Maryland with the Marine Engineering Laboratory at Annapolis, Maryland.

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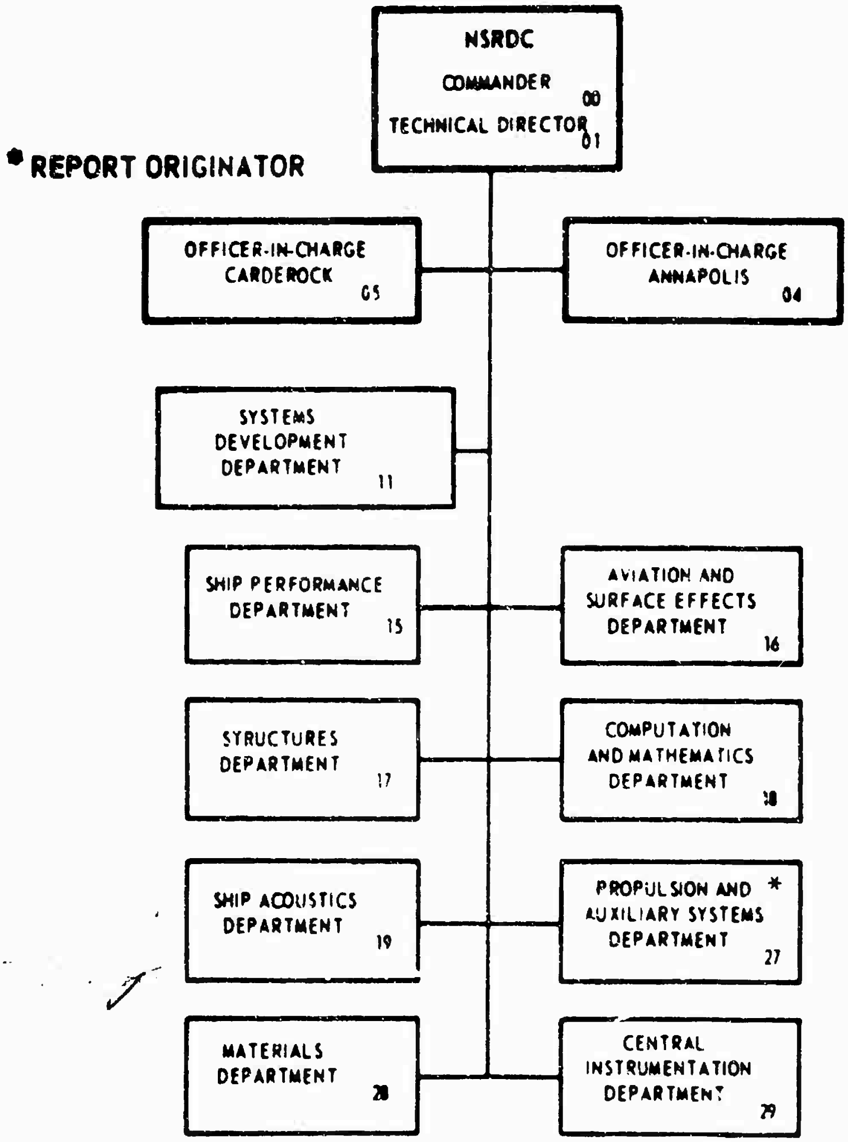

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SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER PAS-75-29 / 2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) MARINE FOULING OF TITANIUM HEAT EXCHANGERS	5. TYPE OF REPORT & PERIOD COVERED Research & Development 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(*s*) Wayne L. Adamson	8. CONTRACT OR GRANT NUMBER(*s*)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Annapolis, Maryland 21402	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Element 63513N, TA SSL 30002, Task 15941 Work Unit 2761-108
11. CONTROLLING OFFICE NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Bethesda, Maryland 20084	12. REPORT DATE March 1976 13. NUMBER OF PAGES 28
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)	15. SECURITY CLASS. (*of this report*) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Marine fouling
Titanium heat exchangers
Seawater
Chlorination
Shipboard operation

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

A series of marine fouling experiments was conducted at Freeport, Texas, on two single-pass titanium heat exchangers. The exchangers, which were constructed with commercially pure titanium tubes (5/8-inch (1.59-centimeter) outside diameter by 30-inch (76.3-centimeter length) and 6Al-4V alloy tube sheets and headers, were operated on natural seawater. One of the

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20. Abstract (cont)

exchangers was fed electrolytically chlorinated seawater, while the other was run with untreated seawater feed. Velocity and chlorination levels were varied to determine the effect of these two variables on fouling of the titanium surfaces. Operating conditions similar to those that might be expected in shipboard heat exchanger/condenser usage were modeled. The tests revealed that fouling of titanium heat exchanger surfaces can occur at velocities less than 4 feet per second (1.2 meters per second) unless preventive techniques such as chlorination are applied. Intermittent chlorination for as short as 4 hours per day at concentrations of 1 part per million total chlorine was sufficient to prevent barnacle attachment. High velocity water (9 feet per second (2.7 meters per second) killed small (1- to 2-millimeter) barnacles in a previously established colony but had no apparent effect on larger ones. It is recommended that titanium heat exchangers intended for shipboard operation at seawater tube velocities less than 4 feet per second (1.2 meters per second) be provided with chlorinated seawater. Chlorination of heat exchangers operating at higher velocities may be warranted, depending upon their other operating conditions.

(Author)

ADMINISTRATIVE INFORMATION

This investigation was carried out under Element 63513N, Task Area SSL 30002, Task 15941, Work Unit 2761-108. The program manager was NAVSEA (SEA 0331F), Dr. F. Ventriglio.

ACKNOWLEDGMENTS

The author wishes to acknowledge the contribution of Mr. M. W. Titus, who assisted in the design, fabrication, and shakedown of the test apparatus used in this investigation. Also, the contribution of Dr. D. C. Mangum of Dow Chemical Company, who conducted the actual fouling tests and the subsequent biological analyses, is acknowledged.

LIST OF ABBREVIATIONS

a-c - alternating-current
cm - centimeters
d-c - direct-current
ft/sec - feet per second
gpm - gallons per minute
g/sec - grams per second
lb/hr - pounds per hour
mA - milliamperes
mm - millimeters
m/sec - meters per second
mg/ℓ - milligrams per liter
o.d. - outside diameter
ppm - parts per million
ppt - parts per thousand
PVC - polyvinyl chloride
vdc - volts direct current

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INTRODUCTION

The David W. Taylor Naval Ship Research and Development Center, as authorized by the Naval Sea Systems Command, is investigating the use of titanium for condenser and heat exchanger applications aboard Navy ships. The purpose of this investigation has been to develop the technology necessary for successful fabrication, installation, and maintenance of shipboard titanium condensers and heat exchangers, to provide improved reliability, maintainability, and performance of these systems as compared to existing copper-nickel systems. A previous DTNSRDC study identified several areas where further investigations were required prior to application of titanium condensers aboard ship. Among these were: marine fouling of titanium, galvanic corrosion between titanium and other metals in a seawater environment, and fabrication of titanium tubes in a double tube-sheet heat exchanger or condenser. This report presents the findings on marine fouling of titanium heat exchangers.

BACKGROUND

The detrimental effects of marine fouling on ship performance have long been recognized by the Navy. These effects range from ship speed reduction due to the increased resistance on the hull to actual plugging of pipes, condensers, and other related equipment used to distribute seawater aboard ship. Under peacetime conditions, these effects are greatly increased because naval vessels spend a larger part of their time in port where fouling is most severe.

For purposes of this report, marine fouling refers to the growth of plant and animal organisms in a seawater environment and attachment of these organisms on submerged surfaces. Universally in the oceans, marine fouling increases in intensity as a ship approaches land masses or enters the warmer waters of the Tropics. Of the many species classified as fouling organisms, the mussels and barnacles are considered to be the most troublesome because of their hardiness and widespread distribution. Consequently, extensive studies have been conducted on these organisms; methods for their effective control have generally been found adequate for controlling other fouling organisms.

Prior to the use of any new material for seawater application, examination of the effects of marine organisms on that material in a marine environment is desirable. Previous studies of titanium have demonstrated that it has no inherent antifouling characteristics or toxicity that will deter or prevent attachment by animal or plant life in seawater. One such study[1] showed that titanium panels were completely covered by marine growth after 8 months in quiet seawater. Work by others[2] observed marine fouling of titanium specimens immersed in flowing seawater for 4 to 5 years at 3 ft/sec*(0.9 m/sec) velocity.

INVESTIGATION

To explore the marine fouling of titanium, a series of tests was conducted at Freeport, Texas, to simulate typical shipboard heat exchanger/condenser operating conditions and to determine typical growth characteristics of marine organisms under those conditions. Methods for fouling control and prevention were also evaluated.

FOULING CONTROL TECHNIQUES

Based upon previous studies, it appeared likely that any titanium equipment (such as condensers) in a shipboard seawater system would require some means of fouling protection. There are several techniques that have proved to be at least partially effective for controlling marine growths in noncopper-based seawater systems: mechanical cleaning, heating the seawater or the surface to be protected, maintaining high seawater velocities in the system, or adding chlorine or similar toxic substances to the water. The first two methods are undesirable over the long run for shipboard heat exchanger or condenser use. Mechanical cleaning is very time consuming and difficult to accomplish in a large heat exchanger or condenser where several hundred tubes must be cleaned. Seawater heating is impractical from the standpoint of energy consumption, alone, since the water temperature or the metal surface temperature must be raised to 125° F (51.6° C) to ensure complete protection. Even the third method, high velocity operation, can be uncertain because of the existence of points of stagnation or low velocity that can normally develop at changes in the flow cross-sectional area.

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[1] Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

*Definitions of abbreviations are on page i.

The application of chlorine gas to seawater has been previously shown to be an effective method for controlling fouling in land-based seawater-cooled power plants and desalination plants. However, the effectiveness of chlorination in a shipboard titanium condenser or heat exchanger system under a variety of operating conditions (including periods of shutdown) was unknown; therefore, it was felt that additional investigation of fouling was necessary. Furthermore, it was desired to investigate the application of an electrolytic type chlorinator for fouling control as opposed to chlorine gas injection, which is not considered suitable for ship installation for reasons of safety and logistics.

Chemically, there is no real difference between chlorine gas injection and electrolytic generation of chlorine. In the electrolytic process, chlorine collects at the anode as a result of the flow of current between two electrodes. This chlorine then rapidly reacts with water according to the equation:

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- .$$

The hypochlorous acid, HOCl, formed is a weak acid which tends to undergo partial dissociation as follows:

$$HOCl \rightleftharpoons OCl^- + H^+$$

to produce a hypochlorite ion and hydrogen ion. At a pH level of 6 or less dissociation is negligible. At higher pH levels (6.0 to 8.5), a sharp change in dissociation occurs, until at a pH of 8.5 to 9.0 very little HOCl remains in solution. The significance of this dissociation is the fact that there is a marked difference in the killing capability of the two substances, HOCl and OCl^-, on various organisms. Since the OCl^- ion is a rather poor disinfectant by comparison with HOCl, it is desirable to have the resulting chlorine solution as high in HOCl concentration as possible. This, of course, is dependent upon the pH level and the resulting dissociation. As the pH increases, then an increasingly greater volume of chlorine gas must be generated to maintain a constant weight of HOCl and, thereby, to offset the effects of dissociation. A secondary reaction that can occur when HOCl is produced in seawater is the formation of toxic bromine residuals. Further details on these topics may be obtained from White.[3]

DESCRIPTION OF FOULING TEST APPARATUS

An overall view of the system used for the fouling studies is shown in figure 1. In the actual piping layout, figure 2, two identical single-pass titanium heat exchangers were operated in parallel seawater circuits. One heat exchanger (designated No. 1) was used as the control heat exchanger with no chlorine protection; the other, No. 2, was placed downstream from an electrolytic chlorinator. The heat exchanger, figure 3, consisted of six commercially pure ASTM grade 2 seamless titanium tubes 5/8-inch (1.59-cm) o.d., 0.035-inch (0.089-cm) wall, 30-inch (76.3-cm) length rolled into 6 aluminum - 4 vanadium (6Al-4V) titanium alloy tube sheets. The headers were also constructed of 6Al-4V alloy. Neither exchanger had a shell since it was desired to conduct tests without tube heating. Details of the construction are given in figure 4.

The chlorinator, figure 5, which was designed for 0.5 lb/hr (0.063 g/sec) of chlorine generation, was operated with a 0 to 14 vdc power supply. A variable a-c transformer provided regulation of the voltage to the d-c power supply and, hence, control of the chlorine output.

A bronze centrifugal pump supplied the seawater for the test system. The entire system was set up adjacent to a seawater distribution canal. This canal, which normally furnishes cooling water for chemical processing facilities owned by Dow Chemical Company, has often been used as a test site for fouling investigations by Dow and is known to be abundant in fouling organisms. The properties for the seawater, which is taken directly from the Gulf of Mexico, are given in table 1. Details on the types and abundance of fouling organisms at that location are available.[4]

METHOD OF TEST

A summary of the fouling test schedule is provided in figure 6. All test runs were conducted by Dow Chemical Company personnel as part of Navy contract N00600-74-C-0287. The initial runs (0 to 12 weeks) were conducted at low velocities with continuous chlorination of the No 2 exchanger. These were followed by: a series of high velocity experiments (12 to 20 weeks), a run with a period of complete shutdown (20 to 24 weeks), some low velocity runs with intermittent chlorination (26 to 32 weeks), and a final run at intermediate velocity with no chlorination (32 to 38 weeks).

TABLE 1
GULF OF MEXICO SEAWATER COMPOSITION
Annual Average at Freeport, Texas

Measured Parameters	Range, mg/l	Typical Value Annual Average mg/l
Alkalinity as $CaCO_3$	75 - 125	100
Aluminum as Al	-	0.5
Ammonium ion as NH_4^+	0.01 - 0.1	0.05
Calcium as Ca	240 - 400	340
Carbon dioxide (free) as CO_2	2 - 5	3
Chloride as Cl	11,700 - 19,400	16,500
Copper as Cu (total)	0.01 - 0.1*	0.01
Hydrogen-sulfide as H_2S	-	<0.01
Iron as Fe (total)	0.5 - 5.0*	2
Magnesium as Mg	780 - 1,300	1,100
Mercury as Hg	-	<0.0001
Oxygen, dissolved as O_2	1.5 - 6.0	5
pH	7.5 - 8.6	8.4
Potassium as K	230 - 380	325
Salinity, "normal"	50% - 100%	85%
Sodium as Na	6,340 - 10,560	9,000
Sulfate as SO_4	1,800 - 3,000	2,600
Suspended solids	5 - 50	20
Temperature	60° - 80° F (15.5° - 27° C)	70° - 75° F (21° - 24° C)

*Varies with suspended solids present.

The test schedule was set up on a 2-week operating basis. Initially, both heat exchangers were completely clean with no fouling. At the end of each 2-week period, the heat exchanger headers were removed for inspection, and photographs were taken of the tubes, tube sheets, and headers. In some cases, the tubes, tube sheets, and headers were cleaned prior to reassembly by mechanically removing (scraping) any biological growths or nonbiological deposits. Cleaning of the tubing was accomplished with a brass or stainless steel wire brush run through each tube. As shown in the test schedule, the exchangers were sometimes put back on line without cleaning.

The seawater velocity in the two sets of heat exchanger tubes was controlled by bypassing a portion of the pumped seawater directly overboard. The flow rate of water to the chlorinator had to be maintained at 20 to 25 gpm (0.0126 to 0.0158 m^3/sec) in order to prevent the formation of calcareous deposits on the chlorinator electrodes.

The level of total chlorine (combined plus free) was measured by the standard orthotolidine method. Chlorine samples were taken at the discharge of the electrolytic generator and at the discharge of the heat exchanger. The chlorinator current was adjusted until the desired residual was achieved. It was necessary to readjust the voltage setting occasionally to maintain this residual.

RESULTS

INITIAL LOW VELOCITY TESTS

The initial runs, which were conducted at 1 and 2 ft/sec (0.3 and 0.6 m/sec) tube velocity in both heat exchangers, established the fact that marine fouling will occur in titanium heat exchangers, both inside the tubes and on the tube sheets and headers, figures 7 and 8. The species of fouling organisms were principally barnacles with some colonial hydroids. Fouling occurred on the control (No. 1) heat exchanger, whereas the No. 2 chlorinated exchanger remained void of any marine growth, figure 9. In spite of the fairly extensive buildup of marine life in the tubes, no problems were encountered in mechanical cleaning with the wire brush. Attachment did not appear to be as tenacious as might often be found with other tube materials.

During this first 12 weeks of fouling runs, the chlorinated heat exchanger was initially run at 1.0 ppm and was then reduced to a range of 0.5 to 1.0 ppm of chlorine. A summary of the results of this run and all subsequent runs, evaluating chlorine as a method of fouling control, is given in table 2. The chlorinated heat exchanger surfaces became covered with a thin brown residue. Principal constituents of this residue, which has been previously described,[4] are silica, manganese, and iron. When it was wet, the residue could be easily removed by hand-wiping it with a cloth. It was also found in the experiments that the action of flowing seawater gradually removed the residue from covered surfaces. Previous studies of this precipitate[4] seemed to indicate that it helps to deter attachment of barnacles.

TABLE 2
SUMMARY OF HEAT EXCHANGER FOULING CONTROL WITH CHLORINATION

Inspection Date	Heat Exchanger 1			Heat Exchanger 2			Average Chlorine Residual and Chlorinator Operating Time	Exchangers Mechanically Cleaned Prior to Run?
	Headers	Tube Sheets	Tubes	Headers	Tube Sheets	Tubes		
12-5-73	None	Light fouling - 10 barnacles and a colonial hydroid	Light fouling - few barnalces	None	None	None	1.2 ppm continuous	Initial run
12-20-73	None	Light fouling - 10 barnacles and remains of a colonial hydroid	None	None	None	None	0.9 ppm continuous	No
1-4-74	None	None	None	None	None	None	1.5 ppm continuous	Yes
1-18-74	None	None	5 or 6 barnacles per tube	None	None	None	0.6 ppm continuous	No
1-31-74	25-30 barnacles inlet; 30-50 barnacles outlet	2 or 3 barnacles inlet; 5-10 barnacles outlet	5-10 barnacles per tube	None	None	None	0.5 ppm continuous	No
2-14-74	150-200 barnacles inlet; 100-150 barnacles outlet	20-25 barnacles inlet; 15-20 barnacles outlet	25-50 barnacles per tube	None	None	None	0.7 ppm continuous	No
4-26-74	Barnacles, serpulids, & encrusting bryozoans	Barnacles	Barnacles & serpulids	None	None	None	0.6 ppm continuous	No
6-7-74	Barnacles & amphipods	Barnacles & amphipods	Barnacles	None	None	None	0.6 ppm for 8 hours per day (5 out of 7 days)	Yes
6-21-74	Barnacles & amphipods	Barnacles & mussels	Barnacles & amphipods	None	None	None	0.6 ppm for 8 hours per day (5 out of 7 days)	No
7-5-74	Barnacles & amphipods	Barnacles & mussels	Barnacles & amphipods	None	None	None	1.0 ppm for 4 hours per day (5 out of 7 days)	No

Note: Water velocity through both sets of heat exchanger tubes was maintained at 1 ft/sec (0.3 m/sec) for all runs except for the first two 12-5 and 12-20 inspection dates, which were at 2 ft/sec (0.6 m/sec).

The electrolytic chlorinator performed satisfactorily during the low velocity runs with water temperatures that ranged from 49° to 74° F (9.5° to 23.4° C) and salinities from 12.5 to 30.85 ppt. Chlorine concentration was measured only once each day and therefore was not maintained precisely, as is evident from table 3. Since chlorine demand can change appreciably with changes in dissolved and suspended solids, temperature, hydrogen ion concentration, and biological activity, monitoring chlorine concentration once daily is insufficient to maintain precise control. During the first 2 weeks the average concentration leaving the electrolytic generator was 1.1 ppm with a range of 0.8 to 1.5 ppm. During the next several weeks the concentration was reduced to try to maintain a residual of 0.5 to 1.0 ppm from the generator. Actual average concentration from the generator was 0.8 ppm with a range of 0.1 to 3.0 ppm. Similar results were obtained later in the test program when the chlorine was injected on a part-time basis (4 to 8 hours per day).

TABLE 3
MEASURED CHLORINE CONCENTRATION
FOR VARIOUS TEST RUNS

Week No.	Chlorinator Discharge Concentration, ppm				Heat Exchanger Discharge Concentration, ppm				Desired Chlorine Level ppm
	Average	Median	High	Low	Average	Median	High	Low	
0-2	1.1	1.0	1.5	0.8	1.2	1.0	3.0	0.8	1.0
2-12	0.8	0.6	3.0	0.1	0.9	0.6	3.0	0.2	0.5-1.0
20-22	0.5	0.5	0.7	0.3	0.6	0.6	1.3	0.3	0.5
26-30	0.8	0.3	3.0	0.2	0.6	0.3	3.0	0.1	0.5
30-32	1.1	0.5	5.0	0.2	1.0	0.3	5.0	0.2	0.5

Note: Chlorinator was not operated for 12- to 20-week period, 22- to 26-week period, and 32- to 36-week period.

With regard to the suitability of the chlorinator for ship application, it was found that the unit had one characteristic that might at first glance appear undesirable. A check of the resistance between the end flanges and the cathode and anode electrical connectors to the unit showed a value of only 20,000 ohms. Based on a 28 vdc supply, this resistance could result in a stray current of 1.4 mA at full load. According to the manufacturer, larger chlorinator units 2 lb/hr (0.25 g/sec) and greater do not have a problem with stray current because of the way they are wired. If it is assumed that the chlorinator was connected directly to a copper-nickel piping system at the inlet flange, then the current would be in a direction that would actually reduce galvanic current effects between the external copper-nickel piping and the titanium piping within the chlorinator. In this respect the current could be considered beneficial.

HIGH VELOCITY TESTS

During the high velocity runs no chlorine was generated. Prior to the run a fouling colony was purposely established on the surfaces of the control heat exchanger. A colony of several hundred live 1- to 2-mm-diameter barnacles was also established on a separate plastic insert strip 1/2 inch (1.27 cm) wide by 12 inches (30.5 cm) long , figure 10. The strip was placed at the inlet end of one of the control heat exchanger tubes at the beginning of the run. The No. 2 heat exchanger was free of fouling at the start of the run, but the brown residue accumulated from previous periods of chlorination was purposely left on the tubes. An objective of the run was to determine whether an attached colony of marine organisms could be killed by seawater flowing continuously at typical shipboard condenser tube velocities 9 ft/sec (2.7 m/sec) maximum . Also, it was desired to evaluate high velocity fouling of the previously chlorinated exchanger. Table 4 provides a summary of the results from this run and all subsequent runs that evaluated water velocity as a means of fouling control. The results indicated that approximately 50% kill occurred on the tubes and tube sheets of the control exchanger. The smaller (1- to 2-mm) barnacles were killed by the high velocity; larger barnacles tended to survive. By comparison, the barnacles on the plastic strip all survived and grew slightly during the 2-week period. The plastic strip apparently affected flow characteristics sufficiently to reduce the velocity at the strip boundary layer by comparison with velocity in the other tubes. In no case was there evidence that water velocity was sufficient to actually sweep attached live or dead barnacles from the tube or tube-sheet surfaces. Heat exchanger No. 2 experienced no fouling attachment, although the brown residue film was gradually washed from the exchanger with operating time.

TABLE 4
SUMMARY OF HEAT EXCHANGER FOULING CONTROL WITH WATER VELOCITY

Inspection Date	Tube Water Velocity		Heat Exchanger 1			Chlorine Residual ppm	Heat Exchanger 2			Condition of Heat Exchangers Prior to the Run
	ft/sec	m/sec	Headers	Tube Sheets	Tubes		Headers	Tube Sheets	Tubes	
2-28-74*	No. 1: 8.2-9.4 No. 2: 5.8-7.0	No 1: 2.5-2.9 No. 2: 1.8-2.1	50% of barnacles killed	50% of barnacles killed	50% of barnacles killed	0.0	None	None	None	No. 1 fouled No. 2 clean
3-15-74	No. 1: 7.8-8.2 No. 2: 5.2-6.6	No. 1: 2.4-2.5 No. 2: 1.6-2.0	None	None	None	0.0	None	2 barnacles	None	Both cleaned
3-28-74	No. 1: 9.2 No. 2: 4.6	No. 1: 2.8 No. 2: 1.4	None	None	None	0.0	None	2 barnacles	None	Neither exchanger cleaned
4-11 74	No. 1: 9.2-10.5 No. 2: 4.0-5.0	No. 1: 2.8-3.2 No. 2: 1.2-1.5	None	None	None	0.0	None	2 barnacles	None	Neither exchanger cleaned
8-5-74	No. 1: 4.0 No. 2: 2.0	No. 1: 1.2 No. 2: 0.6	None	None	None	0.0	Barnacles	Barnacles	Barnacles	Neither exchanger cleaned
[illegible]-10-74*	No. 1: 0.0 No. 2: 0.0 (shutdown)	No. 1: 0.0 No. 2: 0.0	Dead barnacles, serpulids, bryozoans	Dead barnacles, serpulids	Dead barnacles, serpulids	0.0	None	None	None	No. 1 fouled No. 2 clean

*Prior to the run, a fouling colony was allowed to develop on the natural seawater side of exchanger 1, while heat exchanger 2 was chlorinated to prevent any fouling growth.

During the final 6 weeks (weeks 4-20) of the high velocity tests, the control heat exchanger was cleaned, and both heat exchangers were run with high velocity seawater to observe whether any barnacle attachment might occur. The chlorinator was turned off during the run. Attachment of two barnacles was noted on the outlet end of the tubes of exchanger 2 which was operated at 4.0 to 6.6 ft/sec (1.22 to 2.02 m/sec) water velocity. The control exchanger was operating at 7.8 to 10.5 ft/sec (2.4 to 3.1 m/sec). The point of attachment was at the tube/tube-sheet joint, an area of relatively low velocity. As is apparent from figures 7 and 8, the tube ends were not machined flush with the tube sheet as would normally be done in a shipboard condenser or heat exchanger. Flush machining might have prevented such attachment. During the same operating period, a 3-inch (7.6-cm) PVC pipe in the test loop, which had much lower velocity water 1 ft/sec (0.3 m/sec) , suffered considerable fouling, figure 11.

EXTENDED SHUTDOWN

The next run was designed to evaluate the effect of shutdown of a condenser or heat exchanger system (zero water flow) on marine life growing in the system. A fouling colony was, therefore, established on the control heat exchanger by running at low velocity for 2 weeks (weeks 20-22). The other exchanger was chlorinated at 0.5 ppm. The system was then shut down but was purposely kept filled with seawater. When the heat exchangers were opened 2 weeks later, all marine organisms (barnacles, serpulids, and encrusting bryozoans) were dead. There was a noticeable sulfur smell, and a black film covered the surfaces of the controlled heat exchanger. The black silt layer was apparently a result of sulfur-reducing bacteria that are abundant in the Freeport area. The chlorinated exchanger remained free of fouling growth.

INTERMITTENT CHLORINATION TESTS

Two runs were conducted to determine the effectiveness of intermittent chlorine on the control of fouling in the titanium heat exchanger. The first run (26-30 weeks) was carried out at an average total chlorine level of 0.6 ppm for a period of 8 hours per day. For the second run (30-32 weeks), the chlorine concentration averaged 1.0 ppm with the chlorinator running for a period of 4 hours per day. Both intermittent injection procedures were successful in preventing fouling. It should also be noted that chlorine was not added over the weekend period of Friday evening to Monday morning. The control heat exchanger, by comparison, experienced barnacle, mussel, and amphipod attachment during these two runs.

INTERMEDIATE VELOCITY TEST

During the last 4 weeks of the experiment (32-36 weeks), the effect of intermediate velocity on heat exchanger fouling was investigated. The control heat exchanger was run at 4 ft/sec (1.2 m/sec) velocity, while heat exchanger 2 was run at 2 ft/sec (0.6 m/sec) without chlorination. The heat exchanger running at 2 ft/sec (1.2 m/sec) had light barnacle, amphipod, and serpulid fouling, while the other exchanger showed no evidence of marine growth.

CONCLUSIONS AND RECOMMENDATIONS

Under the conditions conductive to marine fouling encountered in this investigation, chlorine effectively controlled fouling of titanium heat exchanger tubes, tube sheets, and water boxes at levels of 0.5 to 1.0 ppm of total chlorine. Intermittent chlorination also was effective for preventing marine growth on titanium. A more infrequent dosage schedule than the 4 hours per day investigated might be possible, especially since the exchanger was able to be left unchlorinated over each weekend without suffering fouling. This must be tempered, however, by the fact that the intermittent chlorination tests were conducted during a time of year when fouling is relatively light.

A more sophisticated method of chlorine dosage monitoring and control than was used in the experiments is a definite requirement. The large variance in chlorine level is an indication that either the rapidly changing water characteristics created large shifts in chlorine consumption and/or the chlorine analysis technique was extremely inaccurate. In fact, the orthotolidine method is recognized as having considerable inaccuracy, depending upon the water being tested and the procedure used for the test. It is, however, the most commonly used method of chlorine measurement today. Some new commercially available chlorine monitoring and control equipment look promising as a substitute method to obtain more accurate control of chlorine levels.

Chlorination had no detrimental effect on the titanium heat exchanger surfaces other than the deposition of the brown residue. It is possible that this residue might reduce the waterside heat transfer coefficient if allowed to accumulate over a length of time. Therefore, heat transfer tests need to be performed to verify that no appreciable reduction in heat transfer will occur with continuous or intermediate chlorination.

Marine fouling problems can be minimized in titanium condensers or heat exchangers by always operating at water velocities in excess of 4 ft/sec (1.2 m/sec) throughout the exchanger. High velocity 9 ft/sec (2.7 m/sec) water can kill small barnacles (1- to 2-mm size) already attached to a heat exchanger surface. The ability of higher velocity water to prevent attachment or actually kill barnacles already attached is very dependent upon whether uniform velocity conditions exist throughout the condenser. Tube obstructions, dead end areas, and similar configurations are points where marine life can establish colonies even when there is high velocity flow through the tubes. Condenser or heat exchanger design of waterside passages can, therefore, significantly increase or decrease the fouling characteristics of the system.

Complete shutdown of the heat exchanger for an extended time period appears to be 100% effective for killing fouling organisms such as barnacles and for preventing initial attachment. How long animal organisms can live under stagnation conditions in a condenser would have to be established by further study. The time period is probably a function of the oxygen content and the nutrient characteristics of the particular water.

In view of the findings, it is recommended that chlorination be considered for fouling protection in any titanium heat exchanger where seawater velocities of less than 4 ft/sec (1.2 m/sec) are anticipated in the tubes. For higher operating velocities, chlorination might also be considered as a possible deterrent to the gradual long-term buildup of fouling organisms in low velocity areas of the water boxes and tube sheets. Based upon the results obtained, Dr. D. C. Mangum, marine biologist of Dow Chemical, recommended the schedule given in table 5 as a guideline for 100% fouling protection.

TABLE 5
PROPOSED SCHEDULE FOR SHIPBOARD
USE OF CHLORINE AS AN ANTIFOULANT

Chlorination Schedule (1 ppm residual)	First 2 Weeks of Operation	Fouling Conditions		
		Heavy Coastal or Bay Waters	Moderate Gulf or Temperate	Light Tropical
Continuous	X			
Intermittent				
8 hr/day		X		
4 hr/day			X	
1 hr/day				X

For any proposed application of titanium heat exchangers, it would appear to be advisable to review the operating characteristics of the exchanger and of the ship thoroughly before making a decision whether chlorination would be required. Every effort should be made to assure that the design of the heat exchanger and the inlet piping does not create possible stagnation areas where marine organisms can attach.

Actual installation of prototype titanium heat exchangers aboard ship is probably the best means of establishing firm shipboard fouling guidelines and expected fouling patterns.

TECHNICAL REFERENCES

1 - Williams, W. L., "The Corrosion and Mechanical Properties of Titanium and Zirconium at Normal Temperatures," (text is unclassified) USNEES Rept C-3395, C-3501B (9 Feb 1950)

2 - Bomberger, H. B., et al, "Corrosion Properties of Titanium in Marine Environments," Journal of the Electrochemical Society, p. 443-447 (Sep 1954)

3 - White, G. C., Handbook of Chlorination, New York, N. Y., Van Nostrand Rheinhold Co. (1972)

4 - "Methods of Controlling Marine Fouling in Seawater Desalination Plants," Dow Chemical Co., Office of Saline Water Contract 14-30-2829 (Apr 1973)

1 - Seawater Feed
2 - Pump and Motor
3 - Electrolytic Chlorinator
4 - Chlorinated Heat Exchanger
5 - Control (Unchlorinated) Heat Exchanger

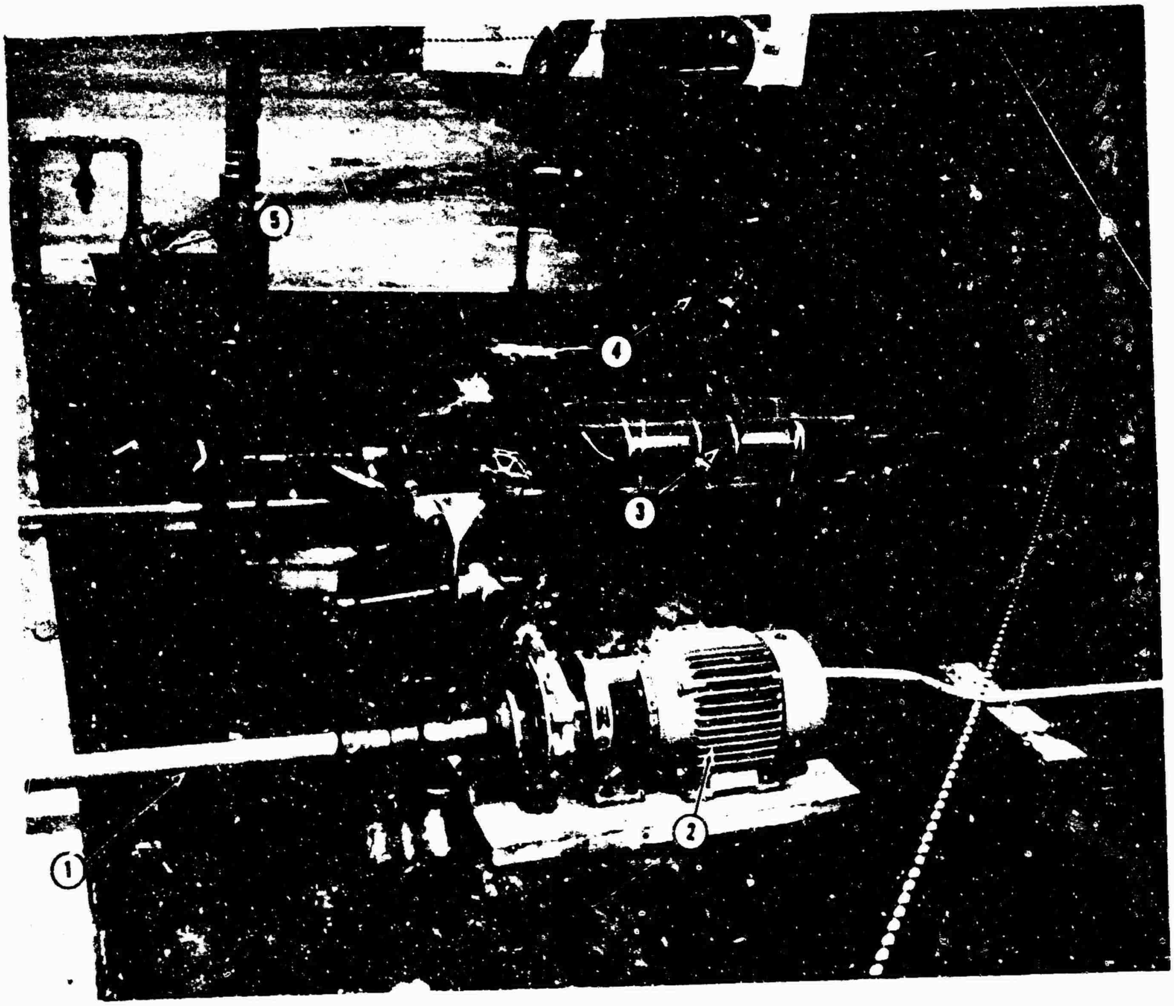


Figure 1
Overall View of Fouling Test System

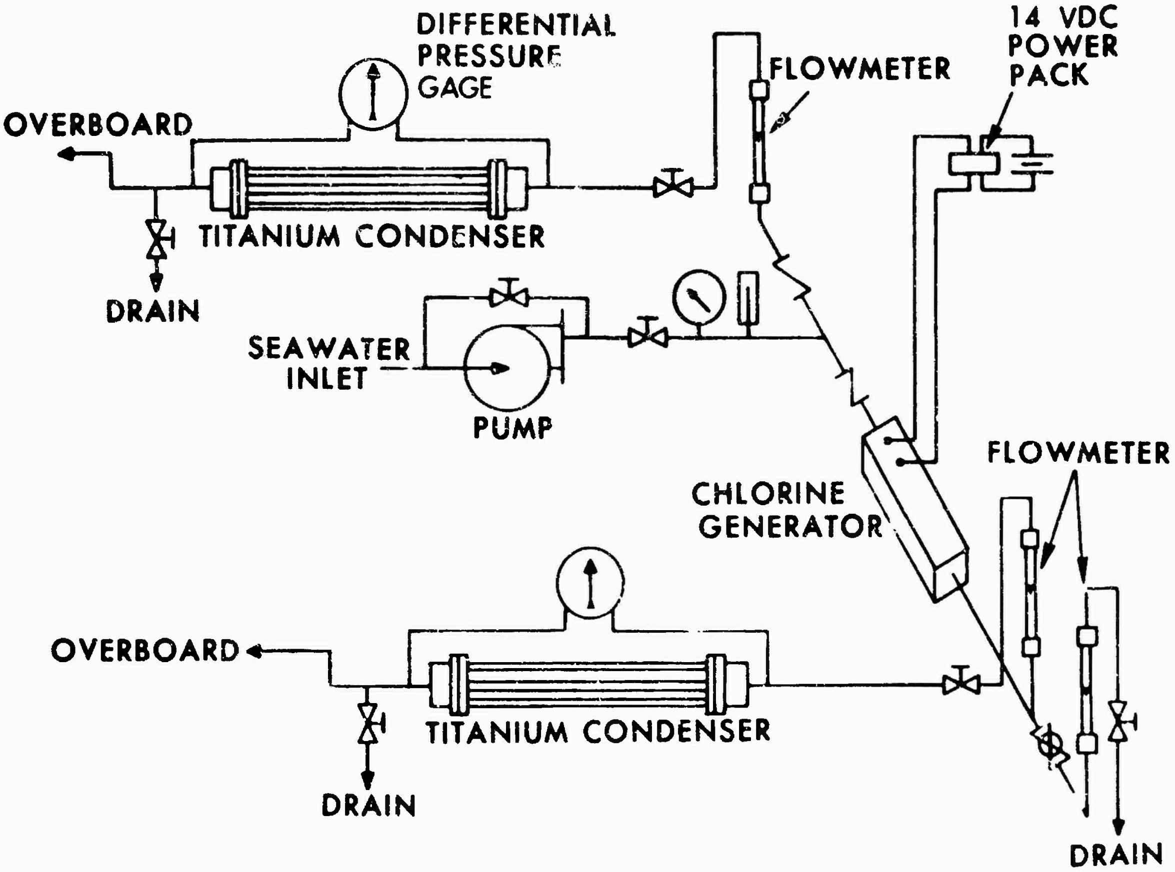


Figure 2
Piping Layout for Fouling Test

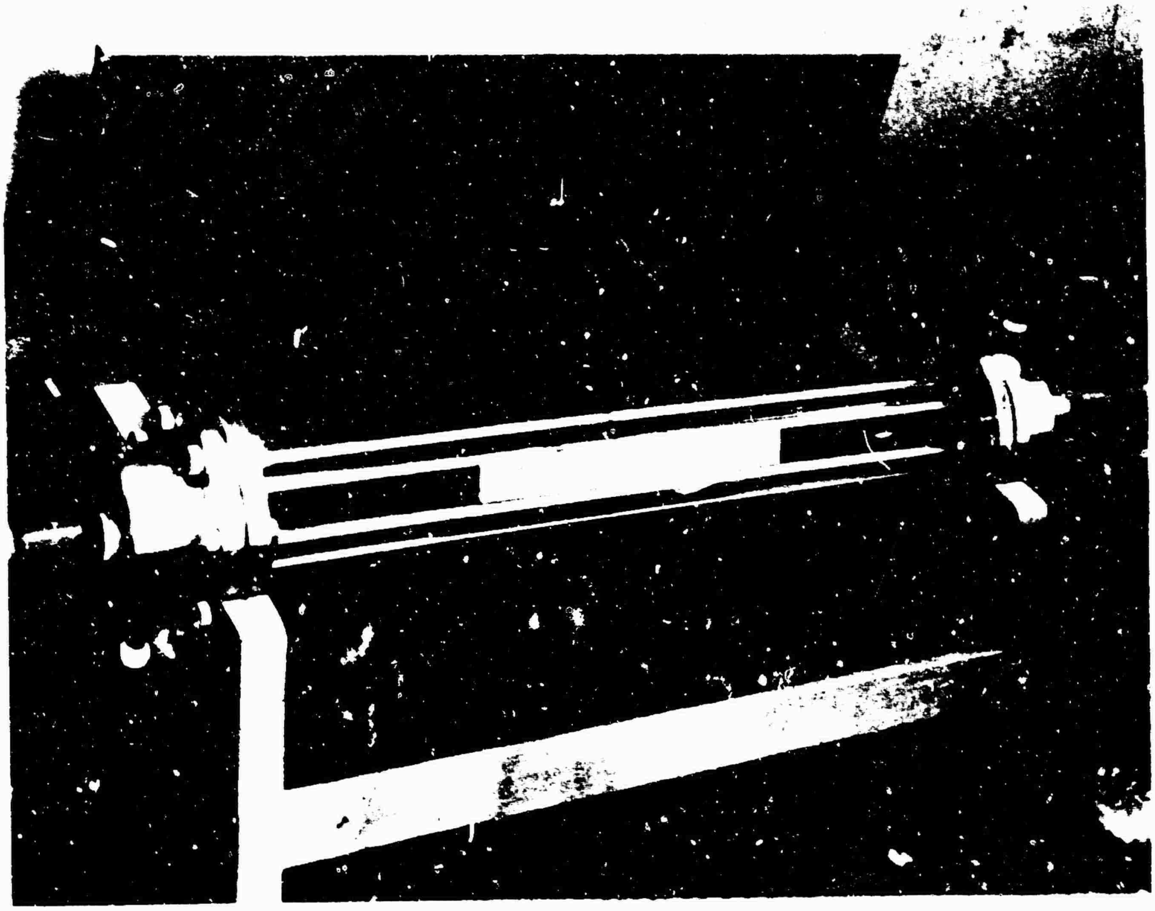
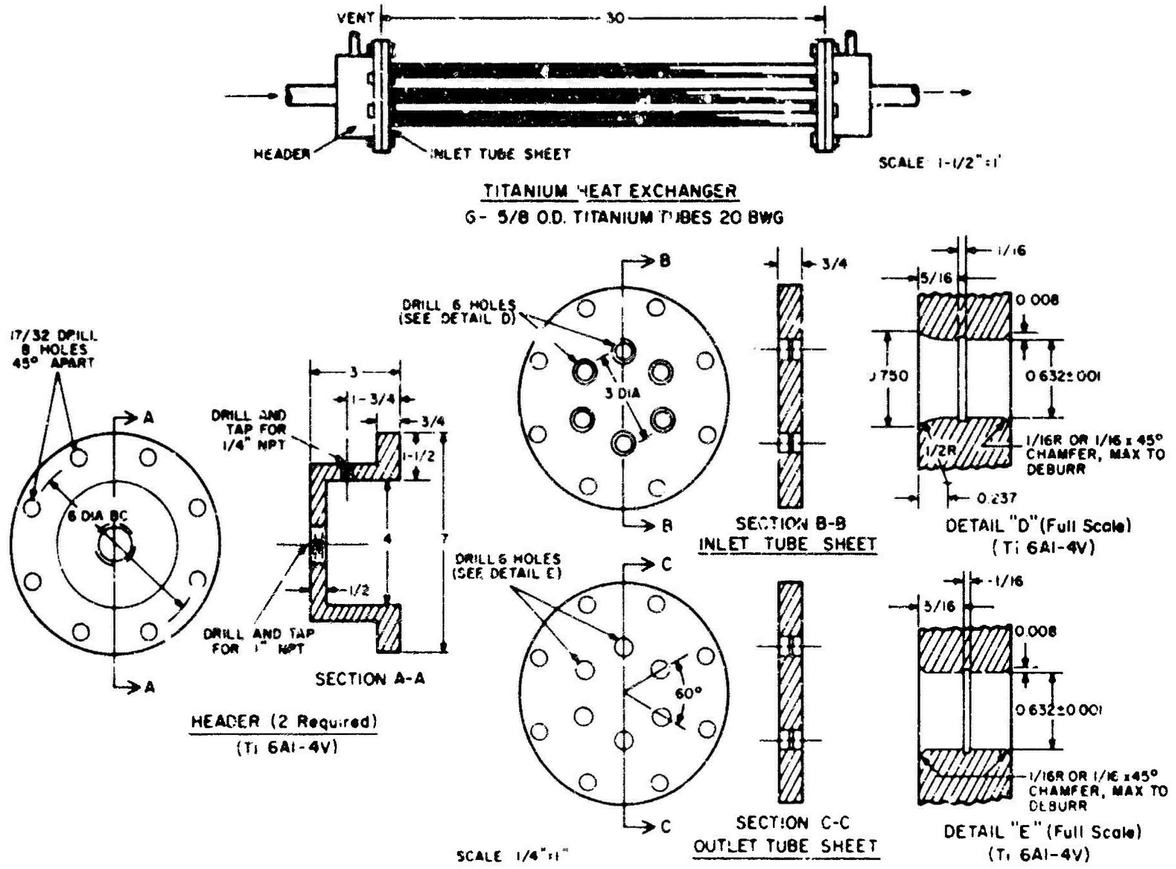


Figure 3
Titanium Heat Exchanger



NOTE ALL DIMENSIONS ARE GIVEN IN INCHES

Figure 4
Titanium Heat Exchanger Detail Drawings

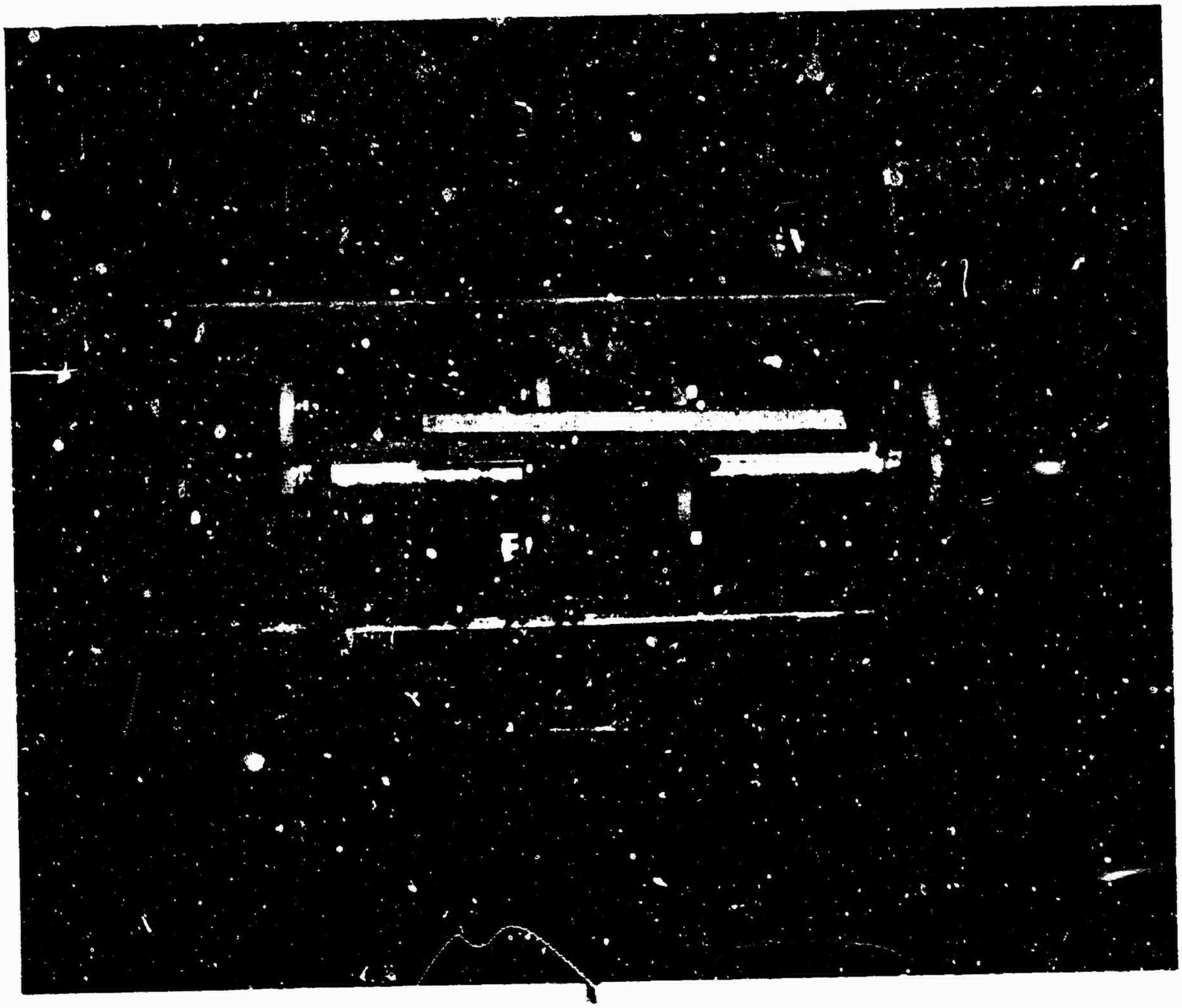


Figure 5
Electrolytic Chlorinator

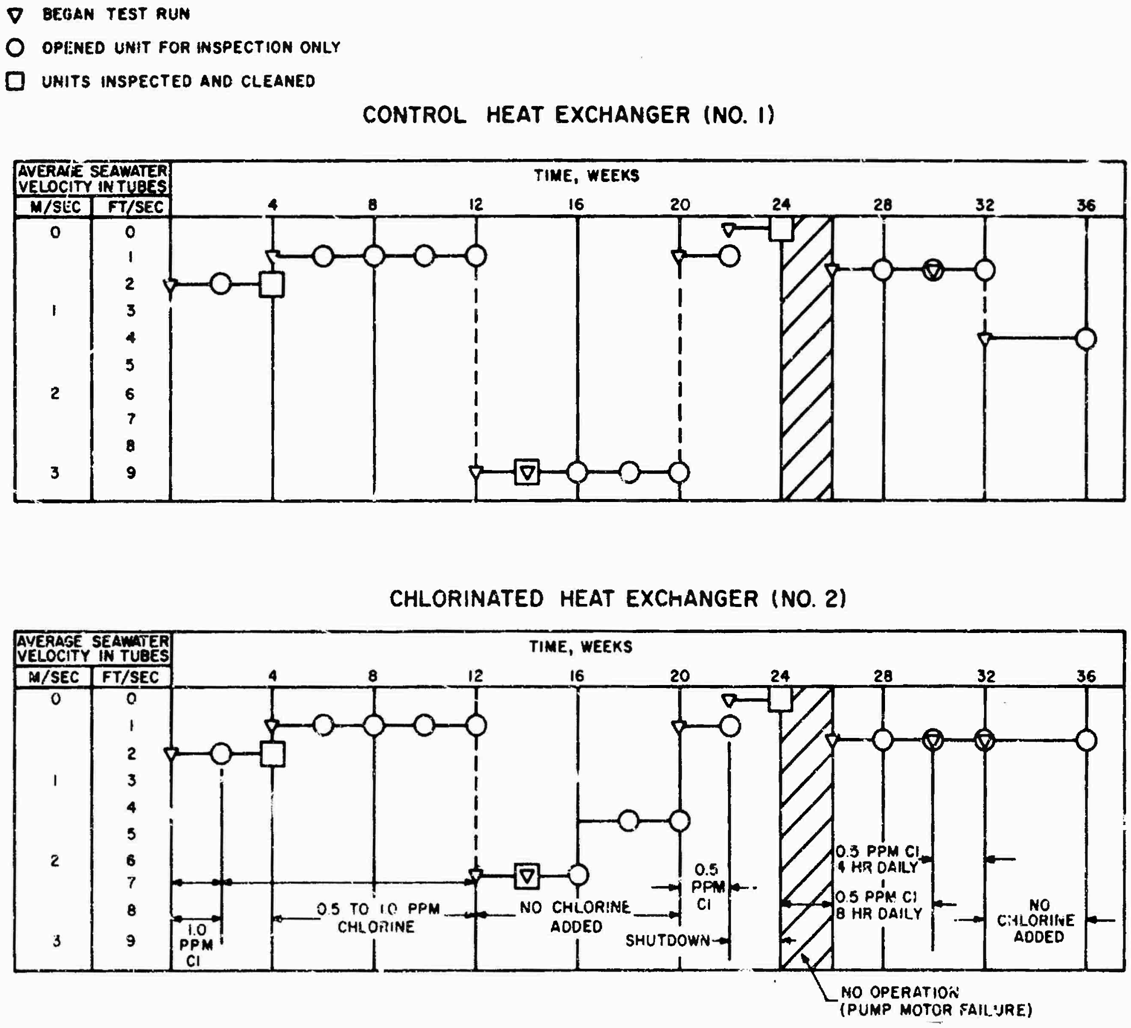


Figure 6
Heat Exchanger Operating Schedule

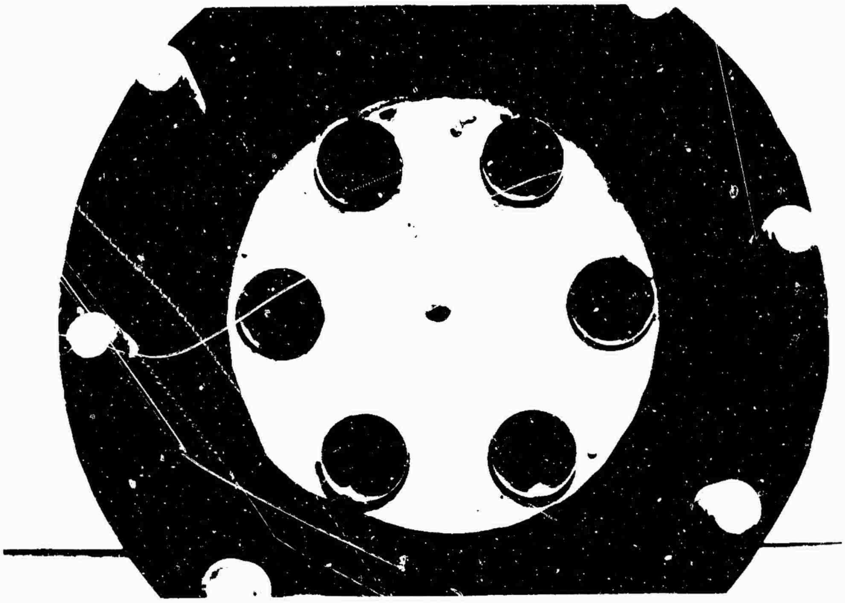


Figure 7 - Barnacle Fouling of Titanium Heat Exchanger after 2 Weeks at 1 ft/sec (0.3 m/sec) Seawater Velocity

Figure - Close-up of Barnacle Fouling in Titanium Tubes after 2 Weeks at 1 ft/sec (0.3 m/sec) Seawater Velocity

Figure 9 - Typical Unfouled Tube and Tube-Sheet Surfaces Experienced with Chlorinated Seawater

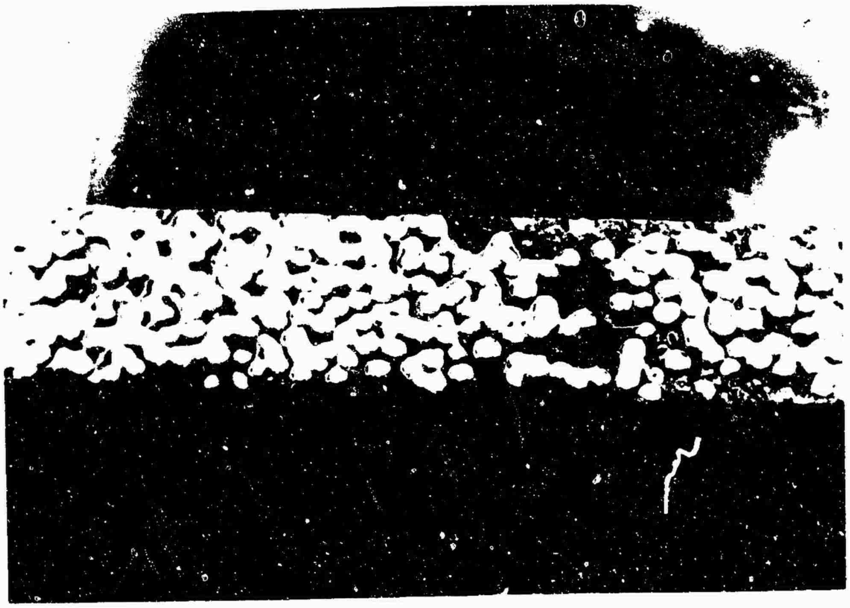


Figure 10 - Barnacle Growth on Heat Exchanger Plastic Insert

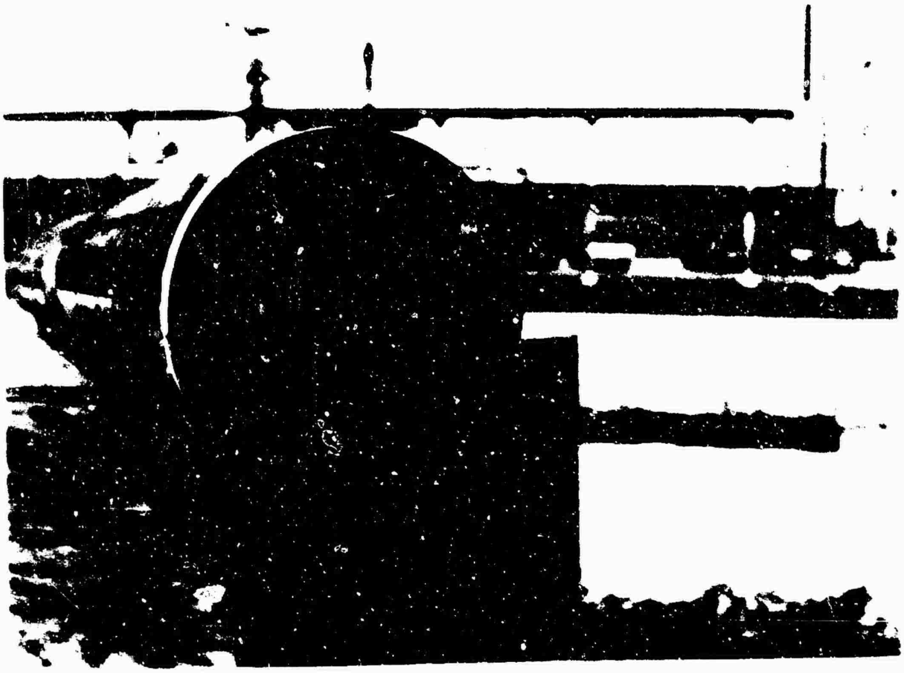


Figure 11 - Barnacle Growth Inside PVC Piping at 1 ft/sec 0.3 m/sec Seawater Velocity