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**ANALYSIS OF GALVANIC CORROSION BETWEEN A
TITANIUM CONDENSER AND A COPPER-NICKEL PIPING SYSTEM**

by
Harvey P. Hack and Wayne L. Adamson

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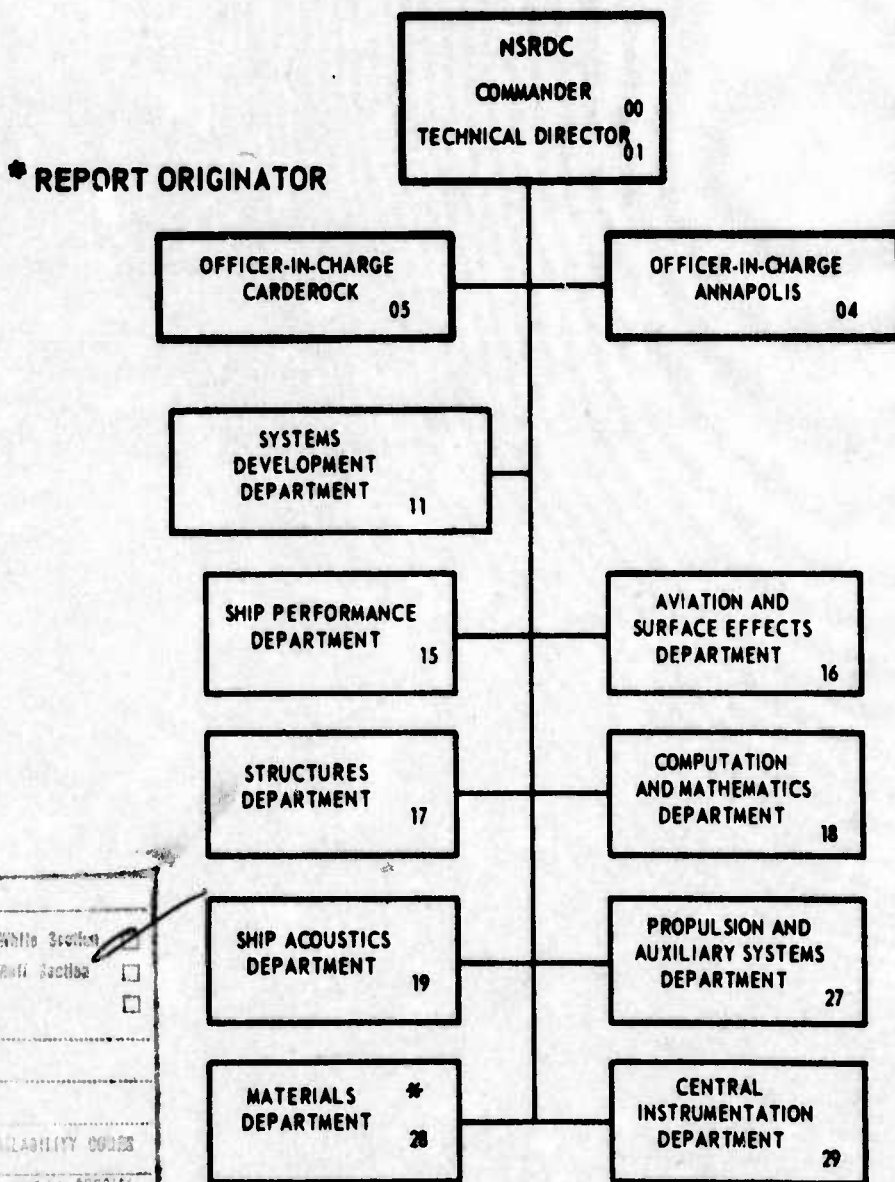
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Tests were conducted in a specially designed seawater-corrosion test loop to evaluate the extent of galvanic corrosion expected from the installation of an all-titanium steam condenser in a shipboard 70-30 copper-nickel piping system. Titanium to copper-nickel area ratios of 1:1, 2:1, and 100:1 were used in the loop. Copper-nickel specimens were exposed to seawater at a velocity of 10 feet per second and temperatures between 75° and 110° F (over)			

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20. Abstract (Cont)

(24² to 43⁸ C). Corrosion rates for uncoupled copper-nickel specimens increased from 0.5 to 2.2 mils per year (0.01 to 0.06 millimeter per year) to 5.1 to 23.5 mils per year (0.13 to 0.60 millimeter per year) upon coupling to a simulated titanium condenser. Results showed that a change in the area ratio from 1:1 to 100:1 only doubled the corrosion rate of the copper-nickel specimens. No significant difference in corrosion rate was found between seawater inlet and outlet ends of the condenser. Complete corrosion protection was established by the use of sacrificial zinc or impressed-current cathodic-protection systems. Another corrosion-protection method evaluated was the use of polyvinyl chloride or titanium pipes to maintain a physical separation of the copper-nickel pipe specimens from the condensers while ensuring electrical continuity externally. This approach did not provide adequate corrosion protection. It is concluded that galvanic corrosion of an unprotected copper-nickel piping system will exceed allowable limits when coupled to a titanium condenser, but either sacrificial zinc or impressed-current cathodic-protection systems can prevent such attack.

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ADMINISTRATIVE INFORMATION

This investigation was carried out under Element 63513N, Task Area S4632001, Task 15941, Work Unit 2761-108. The program manager is Dr. F. Ventriglio, NAVSEA (SEA 0331F).

LIST OF ABBREVIATIONS

A	- amperes
° C	- degrees Celsius
dc	- direct current
° F	- degrees Fahrenheit
ft ²	- square feet
ft/s	- feet per second
gal/min	- gallons per minute
ICCP	- impressed-current cathodic protection
in.	- inches
kg	- kilograms
kW	- kilowatts
lb	- pounds
l/s	- liters per second
m	- meters
mA	- milliamperes
mm	- millimeters
m/s	- meters per second
PVC	- polyvinyl chloride
vdc	- volts direct current
yr	- year

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The use of titanium alloys for main, auxiliary, and air ejector condensers onboard Navy ships offers several distinct advantages over present materials. These alloys provide considerable resistance to steamside corrosion and erosion attack as well as high resistance to corrosive seawater environments.¹ In addition, their higher strength-to-weight ratio could result in considerable weight saving on these condenser systems.

Unfortunately, the use of titanium in conjunction with present copper-nickel piping systems poses a problem of galvanic compatibility. The use of a titanium condenser could cause accelerated attack of the associated copper-nickel piping system due to the presence of a galvanic cell between the two metals. This attack could be aggravated by the large area ratio of titanium to copper-nickel and the elevated seawater temperatures involved.

In this study, a simulated condenser configuration was designed, constructed, and placed in a galvanic test loop. The subsequent corrosion experiments conducted with this configuration evaluated the extent of the galvanic corrosion in copper-nickel piping coupled to a titanium condenser and possible means of minimizing the attack. This report presents the results of those experiments.

INVESTIGATION

CORROSION TEST APPARATUS

To establish test conditions which closely simulate the conditions in service, it was necessary to duplicate the temperatures, seawater velocities, and galvanic area ratios of the actual system.

The apparatus, illustrated in figure 1, consisted of a seawater piping loop in which were placed the copper-nickel pipe specimens, galvanically coupled to cylindrical titanium tanks. The three tanks, which simulate the condenser galvanic area, were connected in a series-flow configuration. The remainder of the test-loop piping was nominal 1-inch PVC. A straight run of PVC pipe, 18 inches (0.46 m)* long, was installed upstream of each tank to establish uniform flow in the copper-nickel pipe test sections.

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

*Definitions of all abbreviations used are on page i.

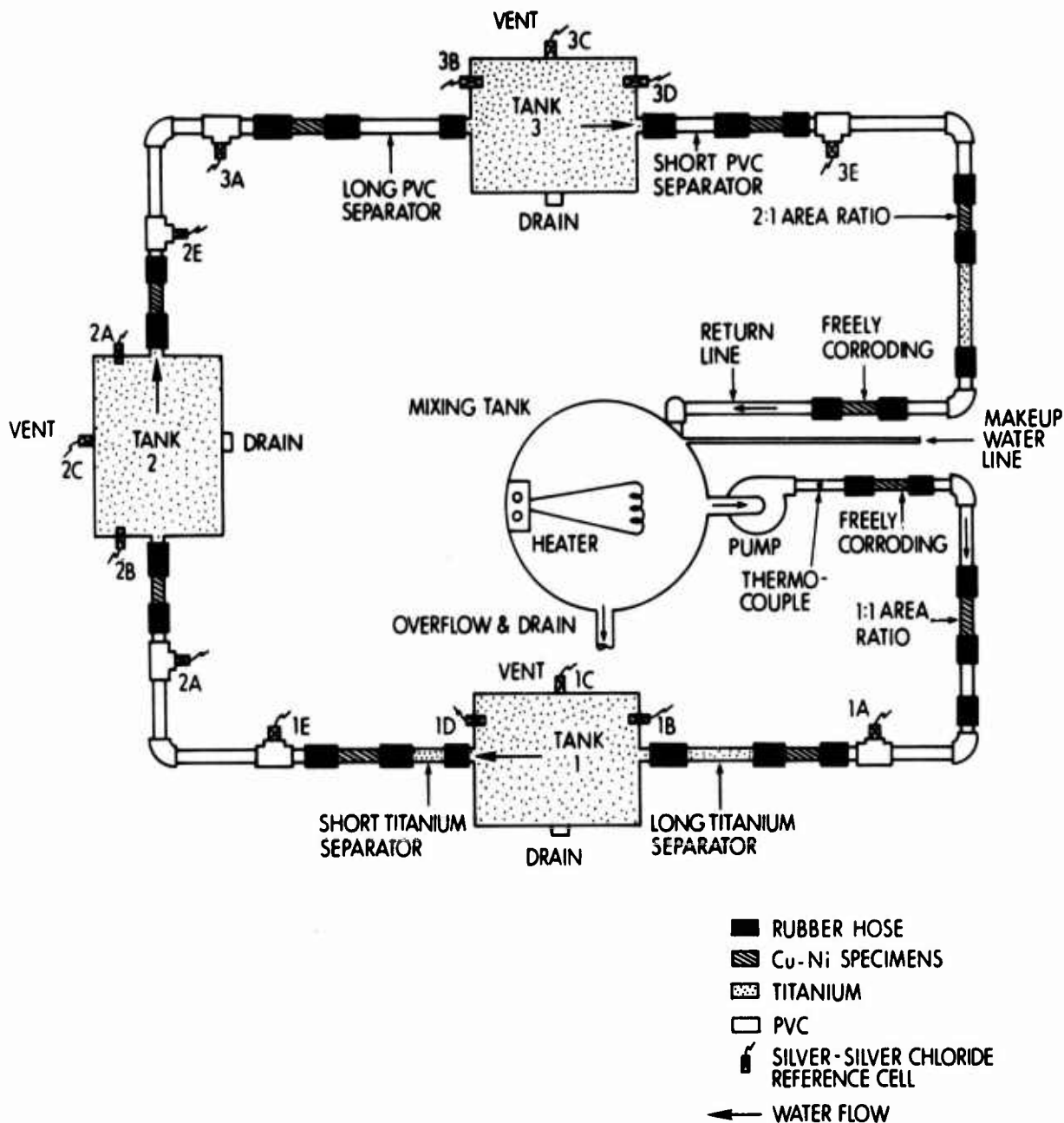


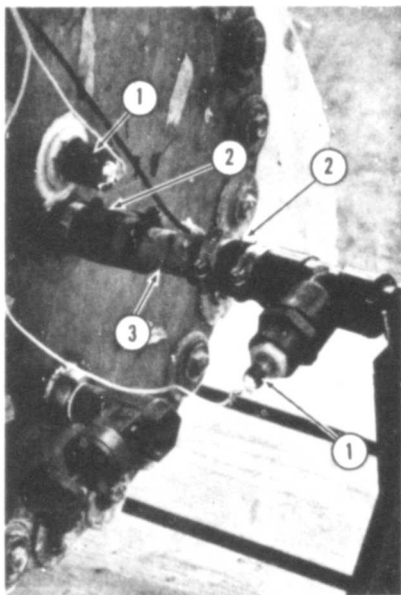
Figure 1
Piping System and Location of Components

A polypropylene tank was used to mix the water returning from the test loop with fresh, sand-filtered seawater. After first being heated in the mixing tank by a 7.5-kW immersion heating coil, this mixture was pumped back through the loop. An overflow pipe was installed at the top of the mixing tank to handle the excess water.

A typical condenser piping flow velocity of 10 ft/s (3.05 m/s) and a typical condenser seawater discharge temperature of 110° F (43.3° C) were maintained in the loop. Since it was not possible to use the 7.5-kW heater to heat the entire seawater flow of 25 to 30 gal/min (1.6 to 1.7 l/s) to the desired temperature, all but 1 gal/min (0.06 l/s) of the flow was recirculated. This provided a complete change of seawater approximately every 4 hours.

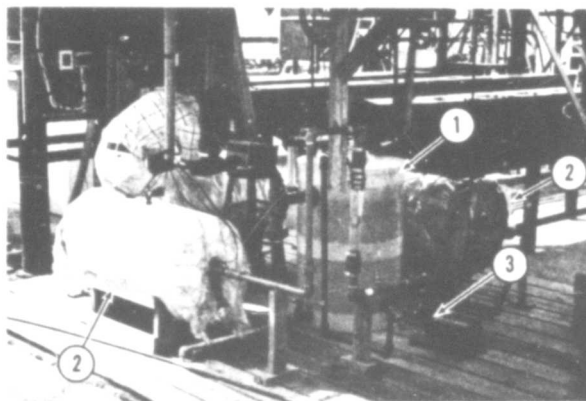
Figure 2 shows the assembled test loop at Wrightsville Beach, North Carolina. The tanks have been covered with insulation to reduce heat loss.

Close-up View of the Titanium Tank/Cu-Ni Piping Connection



- 1 - Silver/Silver Chloride Cell
- 2 - Hose
- 3 - Cu-Ni Pipe

Overall View



- 1 - Mixing Tank
- 2 - Ti Tank
- 3 - Circulating Pump

Figure 2 - Galvanic Corrosion Test Unit

CALCULATION OF THE GALVANIC AREA RATIO

To obtain galvanic corrosion rates in the test loop indicative of those that might be encountered in an actual condenser system, the same galvanic area ratio (wetted area of titanium divided by wetted area of copper-nickel) must be maintained. The area ratio of a typical condenser was calculated as follows:

The water box of a typical 2-pass condenser was geometrically approximated by a series of spheres and cylinders as shown in figure 3.

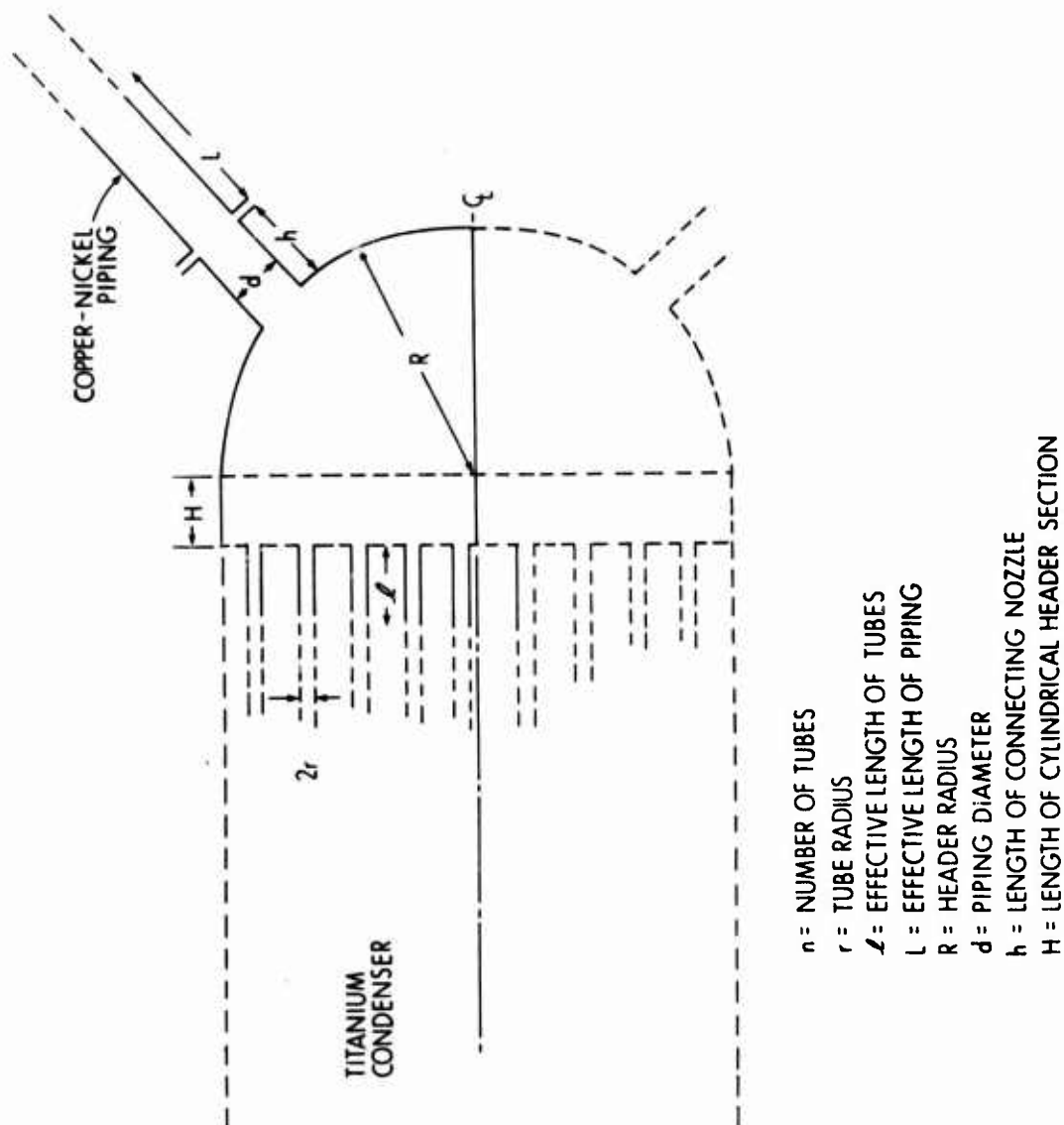


Figure 3
Geometrical Approximation of a Typical 2-Pass
Condenser with Piping

The internal area of either the inlet or the outlet side of the condenser is:

$$\pi R(2R + H) + \pi dh + n\pi r(2\ell - r).$$

For this calculation, the effective galvanic area of each condenser tube is the product of its circumference, $2\pi r$, and its effective length, ℓ . Effective galvanic area is defined as that area which contributes to the galvanic corrosion of the couple.

Substituting the dimensions of a typical condenser and piping system:

$$R = 23 \text{ in. (0.584 m)}$$

$$n = 882$$

$$r = 0.264 \text{ in. (0.006 m)}$$

$$H = 5.5 \text{ in. (0.138 m)}$$

$$d = 13.2 \text{ in. (0.335 m)}$$

$$h = 10 \text{ in. (0.254 m),}$$

the area is calculated to be:

$$3943 + 1463\ell \text{ in}^2 (2.54 + 37\ell \text{ m}^2).$$

The area of the connecting pipe, as shown in figure 1, is the product of its circumference, πd , and its effective length, or:

$$\pi dL = 41.5L \text{ in}^2 (1.05L \text{ m}^2).$$

The ratio of condenser area to connecting pipe area is therefore:

$$\frac{95}{L} + \frac{35\ell}{L}.$$

Unfortunately, the actual values of ℓ and L for these materials are not known. Generally for many common condenser materials, galvanic effects are considered to be limited to the first 2.5 pipe diameters,² although current distribution distances as high as 30 diameters have been reported.³ If 2.5 diameters is correct for titanium tubes, then ℓ and L are equal to 1.32 and 33 inches (0.034 and 0.838 m), respectively, and the area ratio is 4.3:1. If, on the other hand, a constant protected length of 3 inches (0.076 m) is assumed, then $\ell = L = 3$, and the area ratio is 67:1. However, if the constant protected length were 12 inches (0.29 m), then $\ell = L = 12$, and the area ratio is 43:1.

an actual condenser system may be anywhere from 4:1 to 67:1. To approximate the worst possible case — that is, where the maximum area of the most passive titanium is coupled to the minimum area of the more active copper-nickel — an area ratio of about 100:1 was chosen for this test. Selection of this high area ratio was intended to accelerate the corrosion rate sufficiently to allow short test durations.

The tanks were, therefore, constructed from 1/16-inch-thick (1.6 mm) Ti-6Al-4V sheet to a final length of 36 inches (0.91 m) and diameter of 20 1/2 inches (0.52 m). The 70-30 copper-nickel pipe test specimens were cut, from nominal 1-inch schedule 40 pipe to an approximate length of 5 inches (0.13 m). This gave an actual test area ratio of 96:1 based upon copper-nickel test pipes at both the inlet and outlet of each tank. The 2:1 and 1:1 area ratios were created by coupling the copper-nickel specimens to 10- (0.26 m) and 5-inch (0.13 m) titanium pipes.

DATA MEASURING PROCEDURES

TEMPERATURE AND FLOW RATE

Seawater temperature was thermostatically controlled by a thermocouple located at the circulating pump discharge. A glass thermometer was used to monitor the water temperature in the mixing tank. Water flow through the pipe specimens and tanks and the makeup water flow were both measured with rotameters.

POTENTIAL

Corrosion potentials were measured against silver/silver-chloride reference cells mounted out of the water flow path at the following points in each tank/piping unit (as shown in figure 1):

- Immediately adjacent to each pipe test specimen.
- On each end plate of each tank.
- At the top center of each tank.

The reference cells were electrically isolated from the tanks and piping by mounting them in PVC fittings. Wiring for the cells is shown in figure 4. Potentials were measured with a high-impedance digital voltmeter.

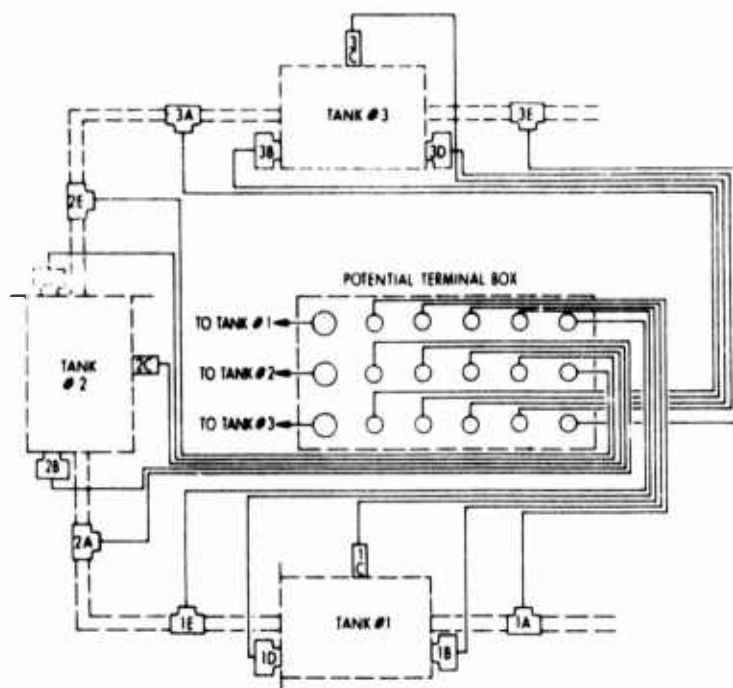


Figure 4
Reference Cell Wiring Diagram

GALVANIC CURRENT

Each specimen that was galvanically coupled was wired through a central terminal box, a schematic of which is presented in figure 5. Galvanic currents were measured by means of a zero-impedance ammeter.

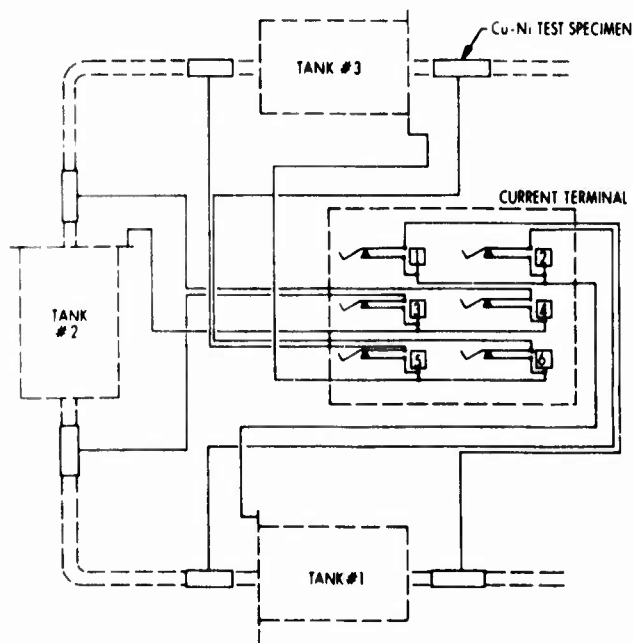


Figure 5
Galvanic Current Wiring Diagram

INTERNAL CORROSION OF PIPE SPECIMENS

After each test run, the test loop was dismantled and the specimens removed to determine the corrosion rate of the pipe sections. Profile traverses were made of the internal pipe surfaces at 30° intervals around the circumference using a Surfanalyzer model 21-1330-20, manufactured by Gould, Inc. Each profile was divided into 1/2-inch (13 mm) lengths along the pipe, and the maximum pit depth in each length determined. The average and the maximum values of the 12 profiles for each pipe in each interval of length were then calculated. In addition to the profile traverses, each specimen was also weighed before and after each run to determine total material loss.

CORROSION PROTECTION DEVICES

Several different methods were employed to try to reduce the galvanic corrosion rate of the test specimens. Each method is described below.

ZINC CATHODIC PROTECTION

One of the test tanks was equipped with four zinc anodes during several test runs. These anodes were approximately 4 x 6 x 1/4 inches (100 x 150 x 6 mm). Two were affixed to the inside of each end of the tank by means of threaded titanium studs welded to the tank. The corrosion rate of these zincs was determined by measuring their weight before and after each test run.

IMPRESSED-CURRENT CATHODIC PROTECTION

One tank was equipped with an automatic impressed current cathodic protection system. This unit, illustrated in figure 6, is capable of delivering a variable amount of current from the anode to the tank in order to hold the tank potential, relative to a silver/silver-chloride reference cell, at a constant preset protective level.

For the test run in which it was used, the ICCP system was set for a tank protection potential of -0.800 ± 0.005 volt. The anode current was monitored by using a panel meter and it never exceeded 1.5 amperes.

PVC PIPE SPACERS

To increase the electrical resistance of the seawater path, lengths of PVC pipe were inserted between the specimens and the tank, while still maintaining an external electrical connection, in an endeavor to increase the seawater resistance so that ion movement in the seawater would be sufficiently inhibited to reduce the galvanic corrosion. Lengths of PVC pipe, 5 inches (0.13 m) and 10 inches (0.25 m), were used.

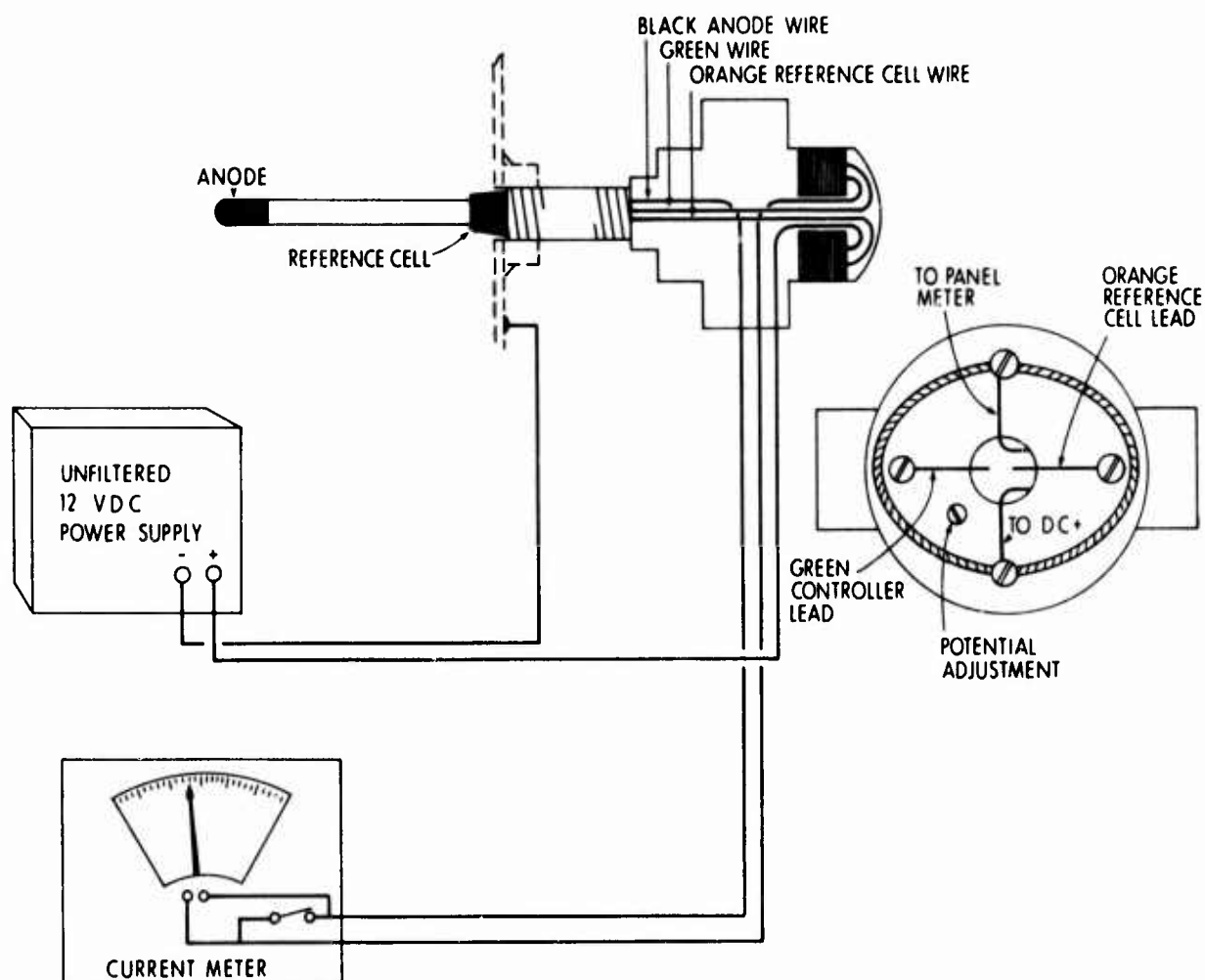


Figure 6
Automatic Cathodic-Protection Unit,
Wiring Diagram

TITANIUM PIPE SPACERS

Lengths of titanium pipe were inserted between the specimens and the tank and were electrically coupled to the tank, endeavoring to make the length of the titanium pipe sufficiently large that the galvanic current from the specimen would be absorbed entirely within the titanium pipe and never reach the tank. Thus, the specimen would not "see" the tank galvanically, and the effective area ratio would thereby be reduced from 100:1 to the simple ratio of two equal pipes, 1:1, with resultant greatly reduced galvanic corrosion. The lengths of the titanium pipes used were 5 inches (0.13 m) and 10 inches (0.25 m). For purposes of comparison, copper-nickel control specimens were coupled to titanium pipes alone, in order to create 1:1 and 2:1 area ratios.

EXPERIMENTAL PROCEDURE

Five test runs were performed, each of about 2000-hour duration. All test runs had six specimens with a 100:1 galvanic area ratio. In only the first and second runs were the tank and pipe potentials monitored on a continuous basis. The first run (2400 operating hours) was used to evaluate the extent of the galvanic corrosion problem and to determine if there was any difference in corrosion behaviour between tank inlets and outlets. One tank was fitted with sacrificial zincs, while the other two tanks were left as controls.

The second test run served to evaluate the extent of galvanic corrosion protection from zinc anodes and from an impressed-current cathodic-protection system. Uncoupled control specimens were included in this 1604-hour run.

The third and fourth runs provided data on the extent of galvanic corrosion protection afforded by PVC and titanium pipe spacers. Besides the freely corroding control specimens, these runs included copper-nickel specimens coupled to titanium pipe sections alone, in a 1:1 and a 2:1 galvanic area ratio. In the fourth run the outside of the copper-nickel pipe test specimens were coated with enamel to prevent corrosion of the exterior surface as experienced in the third run. Operating times of the third and fourth runs were 2330 and 1900 hours, respectively.

The fifth run, of 2475-hour duration, was identical to the fourth, except that the seawater was not heated but instead remained at ambient temperature. Thus, the effect of temperature on the corrosion of the specimens could be evaluated.

RESULTS AND DISCUSSION

Corrosion rates could not be determined from weight-loss data. Considerable attack had taken place on the outside of the specimens where seawater had seeped between the specimens and the rubber hoses which held them in place. Thus, weight-loss data would have given inaccurate values for the average penetration of the specimen interiors. The results of the internal pipe profile measurements were therefore used to determine corrosion rates. These measurements, for specimens in all five test runs, are presented in tables 1 through 5. Each distance interval is equivalent to 1/2 inch (13 mm) of length. Generally there was good correlation between maximum and average pit depths. Whenever localized attack occurred it was generally confined to the first three distance intervals, or about 1 1/2 pipe diameters from the noble metal, except for certain specimens in the ambient temperature run 5 where the effect extended five distance intervals, or about 2 1/2 pipe diameters. There was frequently mild attack in the most upstream distance interval. This attack was noticeable in the inlet specimens but was masked by the far greater amount of galvanic attack on the outlet specimens.

TABLE 1
DEPTH OF CORROSION PENETRATION FOR Cu-Ni SPECIMENS
IN RUN 1 (MILS)

Specimen No.	Test Condition	Entire Pipe	Distance Interval									
			1*	2	3	4	5	6	7	8	9	10**
1	100:1 inlet, no protection											
	Maximum pit depth	15	4	2	6	3	8	9	8	10	10	15
	Average pit depth	2.2	2.3	1.2	1.5	1.2	1.7	2.6	1.9	2.6	2.2	4.5
2	100:1 outlet, no protection											
	Maximum pit depth	9	9	2	2	3	5	3	3	2	2	4
	Average pit depth	1.6	2.4	1.2	1.2	1.3	2.0	1.4	1.6	1.4	1.5	1.8
3	100:1 inlet, zinc protection											
	Maximum pit depth	0	0	0	0	0	0	0	0	0	0	0
	Average pit depth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	100:1 outlet, zinc protection											
	Maximum pit depth	0	0	0	0	0	0	0	0	0	0	0
	Average pit depth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	100:1 inlet, no protection											
	Maximum pit depth	9	6	9	1	5	2	1	1	1	6	4
	Average pit depth	1.4	2.7	2.0	1.0	1.6	1.2	1.0	1.0	1.0	1.5	1.4
6	100:1 outlet, no protection											
	Maximum pit depth	20	20	2	2	2	4	2	2	5	2	1
	Average pit depth	1.6	5.2	1.2	1.1	1.2	1.4	1.0	1.0	1.5	1.2	1.0

*Closest to titanium.
**Farthest from titanium.

TABLE 2
DEPTH OF CORROSION PENETRATION FOR Cu-Ni SPECIMENS
IN RUN 2 (MILS)

Specimen No.	Test Condition	Entire Pipe	Distance Interval									
			1*	2	3	4	5	6	7	8	9	10**
1	Uncoupled control specimen											
	Maximum pit depth	5	2	2	1	1	2	5	2	2	4	1
	Average pit depth	0.4	0.7	0.5	0.3	0.1	0.2	0.6	0.2	0.3	0.6	0.4
2	100:1 inlet, no protection											
	Maximum pit depth	25	24	25	11	6	9	7	4	6	14	11
	Average pit depth	5.4	16.2	8.9	6.1	3.6	3.2	3.1	2.2	2.9	3.9	3.8
3	100:1 outlet, no protection											
	Maximum pit depth	25	25	23	8	6	5	7	3	5	3	4
	Average pit depth	4.3	14.4	9.8	3.7	2.0	2.1	3.1	1.8	1.8	2.0	2.2
4	100:1 inlet, impressed current											
	Maximum pit depth	0	0	0	0	0	0	0	0	0	0	0
	Average pit depth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	100:1 outlet, impressed current											
	Maximum pit depth	1	0	0	0	0	0	0	0	1	1	1
	Average pit depth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.1
6	100:1 inlet, zinc protection											
	Maximum pit depth	0	0	0	0	0	0	0	0	0	0	0
	Average pit depth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	100:1 outlet, zinc protection											
	Maximum pit depth	0	0	0	0	0	0	0	0	0	0	0
	Average pit depth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	Uncoupled control specimen											
	Maximum pit depth	6	3	2	0	2	3	6	2	1	2	2
	Average pit depth	0.4	2.0	0.2	0.0	0.4	0.6	0.8	0.8	0.2	0.4	1.0

*Closest to titanium.
**Farthest from titanium.

TABLE 3
DEPTH OF CORROSION PENETRATION FOR Cu-Ni SPECIMENS
IN RUN 3 (MILS)

Specimen No.	Test Condition	Entire Pipe	Distance Interval									
			1*	2	3	4	5	6	7	8	9	10**
1	1:1 area ratio											
	Maximum pit depth	17	17	6	5	4	4	4	4	4	4	4
	Average pit depth	3.5	10.7	3.6	3.2	3.4	3.1	3.2	2.3	2.3	1.6	1.9
2	100:1 inlet with long Ti Pipe											
	Maximum pit depth	17	17	14	15	17	12	13	8	6	8	5
	Average pit depth	5.3	9.1	5.0	5.8	5.9	5.2	5.3	4.3	4.6	4.2	3.7
3	100:1 outlet with short Ti pipe											
	Maximum pit depth	13	13	12	9	6	8	8	7	4	4	4
	Average pit depth	3.8	7.3	4.3	4.0	3.4	3.7	3.1	3.5	3.1	3.1	2.9
4	100:1 inlet, no protection											
	Maximum pit depth	20	20	9	5	7	9	7	7	10	5	9
	Average pit depth	3.9	12.3	4.8	2.5	2.6	3.1	2.4	2.4	3.3	2.6	3.4
5	100:1 outlet, no protection											
	Maximum pit depth	21	21	6	5	6	4	5	4	4	4	6
	Average pit depth	4.6	14.6	4.5	4.1	3.5	3.4	3.3	2.8	3.5	2.7	3.8
6	100:1 inlet with long PVC pipe											
	Maximum pit depth	7	7	2	3	4	3	3	2	3	4	4
	Average pit depth	1.7	2.7	1.6	1.7	2.1	1.3	1.0	1.1	1.6	1.7	2.2
7	100:1 outlet with short PVC pipe											
	Maximum pit depth	7	7	6	5	4	4	3	3	3	3	4
	Average pit depth	2.2	3.2	2.7	2.7	2.3	1.9	2.2	1.6	1.7	1.2	2.2
8	2:1 area ratio											
	Maximum pit depth	14	14	7	14	4	4	7	7	6	3	12
	Average pit depth	4.3	9.6	4.5	6.1	3.5	3.2	3.5	3.4	2.9	2.4	3.4
*Closest to titanium.												
**Farthest from titanium.												

TABLE 4
DEPTH OF CORROSION PENETRATION FOR Cu-Ni SPECIMENS
IN RUN 4 (MILS)

Specimen No.	Test Condition	Entire Pipe	Distance Interval									
			1*	2	3	4	5	6	7	8	9	10**
1	1:1 area ratio											
	Maximum pit depth	6	4	4	6	4	3	3	4	4	3	4
	Average pit depth	2.2	2.0	2.2	3.2	1.7	1.3	1.2	2.9	3.0	2.7	2.1
2	100:1 inlet with long Ti pipe											
	Maximum pit depth	5	4	4	5	4	4	4	4	4	4	3
	Average pit depth	3.4	3.3	3.8	3.9	3.3	3.6	3.7	3.2	3.2	3.1	2.7
3	100:1 outlet with short Ti pipe											
	Maximum pit depth	4	3	4	4	4	4	4	4	4	4	4
	Average pit depth	3.0	2.2	2.6	3.1	3.1	3.3	3.5	3.3	3.3	3.2	2.8
4	100:1 inlet, no protection											
	Maximum pit depth	5	4	5	4	4	4	4	4	4	4	4
	Average pit depth	3.2	2.9	3.5	3.3	3.2	3.0	3.4	3.2	3.0	3.2	2.9
5	100:1 outlet, no protection											
	Maximum pit depth	6	6	5	4	5	4	4	4	4	4	4
	Average pit depth	3.1	3.9	3.7	3.7	3.7	3.5	2.7	2.6	3.1	2.3	2.2
6	100:1 inlet with long PVC pipe											
	Maximum pit depth	4	4	4	4	4	4	3	3	3	3	3
	Average pit depth	1.8	2.5	2.5	2.0	1.8	1.4	1.1	1.5	1.7	1.7	2.1
7	100:1 outlet with short PVC pipe											
	Maximum pit depth	5	4	5	4	4	4	4	4	4	4	3
	Average pit depth	2.2	3.4	3.1	2.5	2.2	2.6	1.5	1.9	1.2	1.9	2.1
8	2:1 area ratio											
	Maximum pit depth	4	3	4	4	3	3	3	3	3	4	3
	Average pit depth	1.9	2.7	2.0	2.1	1.7	1.9	1.1	1.7	1.2	1.9	2.6
9	Uncoupled control specimen											
	Maximum pit depth	3	3	0	0	0	0	0	0	0	0	1
	Average pit depth	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2

*Closest to titanium.

**Farthest from titanium.

TABLE 5
DEPTH OF CORROSION PENETRATION FOR Cu-Ni SPECIMENS
IN AMBIENT TEMPERATURE RUN 5 (MILS)

Specimen No.	Test Condition	Entire Pipe	Distance Interval									
			1*	2	3	4	5	6	7	8	9	10**
1	1:1 area ratio											
	Maximum pit depth	15	15	7	8	13	11	5	7	6	12	3
	Average pit depth	3.7	6.8	3.8	4.2	5.6	3.6	2.8	3.3	2.9	3.3	2.2
2	100:1 inlet with long Ti pipe											
	Maximum pit depth	23	23	15	9	8	11	8	7	9	7	19
	Average pit depth	6.5	15.7	7.2	5.0	4.0	3.9	5.1	4.4	4.5	4.1	10.4
3	100:1 outlet with short PVC pipe											
	Maximum pit depth	20	5	3	8	11	20	16	15	14	13	11
	Average pit depth	5.8	4.2	2.3	3.2	2.7	7.5	7.9	7.5	6.6	7.4	8.3
4	100:1 inlet, no protection											
	Maximum pit depth	23	23	15	14	10	6	8	9	11	11	7
	Average pit depth	6.8	18.6	10.6	7.6	5.1	3.2	2.8	3.9	5.2	6.6	3.9
5	100:1 outlet, no protection											
	Maximum pit depth	30	30	25	19	14	15	8	9	6	9	9
	Average pit depth	8.8	20.0	18.2	11.1	7.8	7.4	5.0	4.1	3.8	4.9	5.3
6	100:1 inlet with long PVC pipe											
	Maximum pit depth	14	12	14	11	5	5	5	9	4	6	6
	Average pit depth	4.3	7.3	6.3	5.2	3.6	3.4	3.0	3.3	3.3	3.7	4.0
7	100:1 outlet with short PVC pipe											
	Maximum pit depth	28	28	8	12	10	6	4	7	5	10	19
	Average pit depth	5.0	9.9	5.4	2.2	3.0	2.2	3.0	3.8	5.7	5.7	8.6
8	2:1 area ratio											
	Maximum pit depth	27	27	19	22	14	14	6	12	12	11	11
	Average pit depth	8.0	17.9	11.3	11.1	8.2	7.3	3.5	4.5	4.5	4.7	6.5
*Closest to titanium.												
**Farthest from titanium												

A summary of the overall corrosion rates appears in table 6. These values are the average penetration depths reported in tables 1 through 5, further averaged over all distance intervals and normalized to 1 year. For freely corroding copper-nickel specimens, the corrosion rate was 0.5 to 2.2 mils/yr (0.01 to 0.06 mm/yr). The corrosion rate of galvanically coupled specimens without cathodic protection was 5.1 to 23.5 mils/yr (0.13 to 0.60 mm/yr), or an order of magnitude greater. Photographs of the internal surfaces of pipes from run 2, presented as figure 7, show this corrosion. Both the zinc and the impressed-current cathodic-protection systems afforded complete protection to test specimens, as indicated by absence of corrosion.

TABLE 6
AVERAGE PIPE CORROSION RATE (MILS/YR)

Run No.	Uncoupled	100:1 Area Ratio				Pipe Separators					
		No Protection		Cathodic Protection		PVC		Titanium		Controls	
		Inlet	Outlet	Zinc	Impressed Current	Short	Long	Short	Long	1:1 Area Ratio	2:1 Area Ratio
1		8.0 5.1	5.8 5.8	0.0 0.0							
2	2.2 2.2	21.6	23.5	0.0 0.0	0.0 0.0						
3		14.7	17.3			8.3	6.4	14.3	19.9	13.2	16.2
4	0.5	14.8	14.3			10.1	8.3	13.8	15.7	10.1	8.8
5 Unheated		24.0	31.1			17.7	15.2	18.7	22.9	13.1	28.2

The data in table 6 indicate that the specimens were protected not only from galvanic effects but also from normal freely corroding pit formation. Galvanic current data in table 7 indicate a protective current to each protected specimen of 10 to 19 mA. To provide this protection, the impressed-current system had to deliver 0.5 to 1.5 amperes to the system, or a current density of 0.024 to 0.072 A/ft² (0.26 to 0.78 A/m²) to the titanium. For a full-size condenser with $\ell = 2.5$, the total current required would be 2 to 6 amperes. The amount of zinc consumed was 1489 grams in run 1 and 995 grams in run 2, which is equivalent for both runs to 2720 grams/yr or 1409 grams/yr/m². For a full-size condenser with a protected tube length of 2.5 diameters, this would be equivalent to 10.7 kg/yr or almost 5 lb/yr. Both the current and zinc consumption rate would increase rapidly with increasing ℓ .

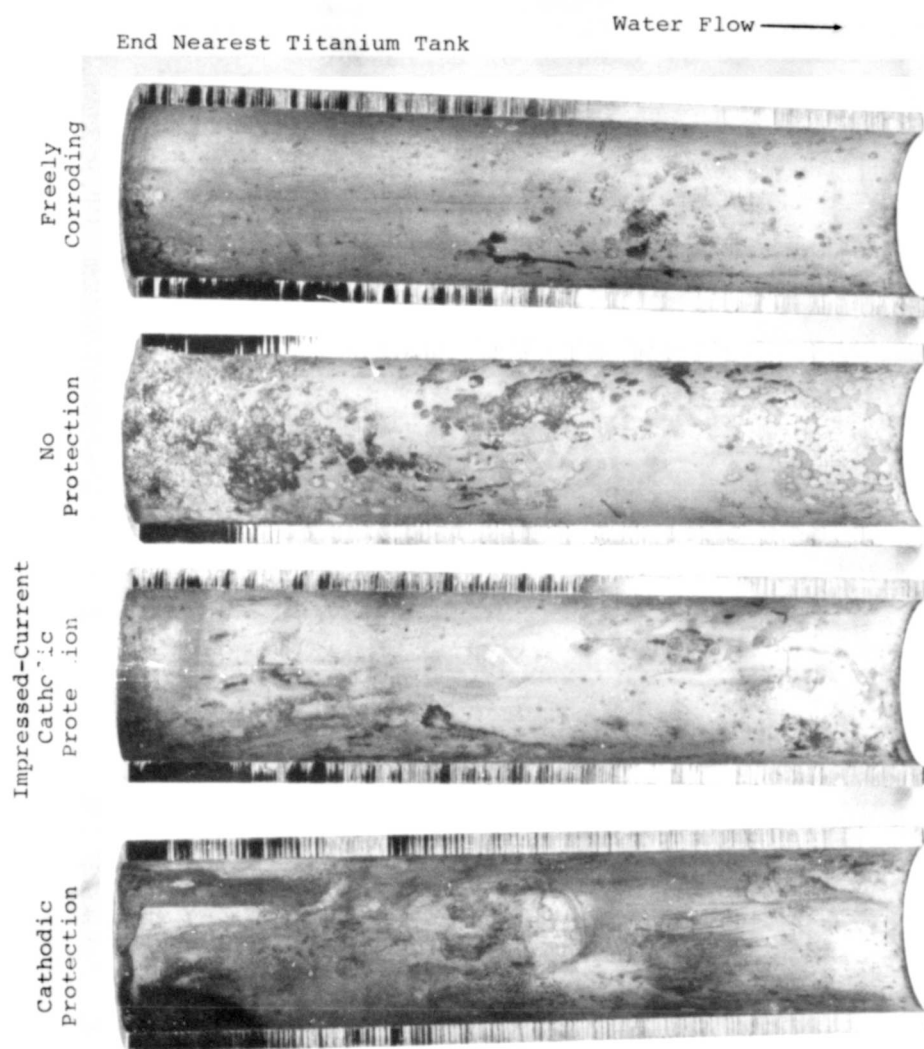


Figure 7 - Corrosion of Copper-Nickel Pipes Coupled to Titanium

TABLE 7
AVERAGE GALVANIC CURRENTS TO SPECIMENS (mA)

Run No.	100:1 Area Ratio				Pipe Separators					
	No Protection		Cathodic Protection		PVC		Titanium		Controls	
	Inlet	Outlet	Zinc	Impressed Current	Short	Long	Short	Long	1:1 Area Ratio	2:1 Area Ratio
1	0.27 0.17	0.49 0.23	-10.05 -12.77							
2	0.57	0.35	-19.00 -17.50	-13.20 -16.50						
3	1.78	1.61			0.77	0.59	2.35	1.76	1.38	1.36
4	1.18	1.41			0.82	0.43	1.55	1.10	0.58	0.72
5 Unheated	3.83	3.71			1.61	1.26	2.12	2.76	1.21	1.61

During initial testing of the automatic impressed-current cathodic protection device used in this study the reference cell shorted to the casing, causing the unit to provide its maximum output continuously. This trouble was traced to faulty factory insulation and was corrected. Near the scheduled shut-down time of test run 2 the unit again shorted out, forcing an early termination of the run to prevent the data from being affected. At this time it was discovered that the manufacturer had removed this particular unit from its product line as a result of many similar failures.

Differences in corrosion behavior between inlet and outlet specimens were found to be negligible. The corrosion rates of unprotected inlet and outlet specimens in runs 1 through 4 averaged, respectively, 16.1 and 16.7 mils/yr (0.41 and 0.42 mm/yr). The average currents for these same specimens were 0.99 and 1.02 mA, respectively. These differences are smaller than the experimental error. In addition, the corrosion potentials, as listed in table 8, are symmetrical relative to inlet and outlet ends, i.e., the values for cell A are similar to those for cell E, and those for cell B are similar to those for cell D. In summary, potential, corrosion rate, and current data all indicate that inlet and outlet sections behave identically.

TABLE 8
AVERAGE CORROSION POTENTIALS IN RUNS 1 AND 2
(Negative Millivolts Relative to Ag/AgCl)

Run No.	Cell A	Cell B	Cell C	Cell D	Cell E
<u>No Protection</u>					
1	100	92	87	92	97
1	108	112	102	111	116
2	84	110	92	104	68
<u>Impressed-Current Protection</u>					
2	374	733	764	804	366
<u>Zinc Protection</u>					
1	440	923	822	851	475
2	450	951	918	946	634

The use of PVC pipe separators did reduce the galvanic corrosion of the copper-nickel pipe specimens. The average corrosion rate (table 6) for specimens separated from the tanks by the short PVC pipe was slightly reduced to 2/3 of the value obtained when PVC was not employed. The use of the long PVC separator moderately reduced the corrosion rate to 1/2 of the unprotected value. The galvanic currents from table 7 show a moderate reduction, to 1/2 of the original value for the short separators and to 1/3 of the original value for the long pipes. Although the galvanic corrosion rate and current with PVC pipe separators were below the values for unprotected specimens, the galvanic corrosion rate was still several times higher than that of freely corroding specimens, which indicates that only partial protection was provided.

Examination of tables 6 and 7 shows that the titanium pipe separators did not provide significant protection to the specimens. Although the corrosion rates of specimens with short titanium separators were slightly less than those without any protection, galvanic currents to these specimens were greater. Thus, these slightly lower corrosion rates were apparently not a result of a lessening of the galvanic effect. Control specimens coupled to titanium separator pipes only (2:1 and 1:1 area ratios) showed significantly less corrosion and lower currents than the specimens which were coupled to the pipes and tanks combined (100:1 area ratio). The lower current values were experienced by specimens coupled to the shorter separators alone (1:1 area ratio).

Little increase in corrosion rate or current density was noted between 1:1 and 2:1 area ratios, and only a moderate increase in corrosion rate (less than 50%) and in galvanic current (less than double) was observed between the ratios of 2:1 and 100:1. This may indicate that the current-limiting process takes place on the copper-nickel surface.

The effect of seawater temperature on the corrosion of the specimens can be evaluated by referring to tables 6 and 7. Runs 3 and 4 were conducted at 100° F (43.3° C), whereas run 5 was conducted at ambient temperature, which ranged from 75° to 99° F (24° to 37° C) and averaged 85.9° F (29.9° C). Table 6 shows the corrosion rates of the specimens in the unheated seawater run to be generally about 1.5 and 2.0 times those of the specimens in the high-temperature runs. Table 7 shows the galvanic currents to be generally about 1.5 and 2.5 times higher at the lower temperature. These currents were not found to vary systematically with the seawater temperature within the low-temperature run, however.

The effects of seawater temperature in these tests can be explained by considering the amount of dissolved oxygen in the test solution. As the amount of dissolved oxygen in the seawater decreases, it becomes more difficult for the copper-nickel to combine with the remaining oxygen to form the copper oxide corrosion products. The corrosion rate (or galvanic current) will, therefore, be reduced. Since normal seawater is not completely saturated with dissolved oxygen, the amount of dissolved oxygen is not necessarily a direct function of temperature. The corrosion rate is therefore not directly related to seawater temperature. In heated seawater, dissolved oxygen reaches a state of supersaturation, and consequently some is lost to the surrounding air. The corrosion rate in heated seawater will therefore be reduced below the rate in unheated seawater.

There appeared to be no systematic variation of galvanic corrosion currents with time in test, although these currents varied widely over the test period. These data were, therefore, not presented in the report.

CONCLUSIONS

Galvanic corrosion of copper-nickel piping when coupled to a titanium condenser will exceed reasonable corrosion levels unless some method of protection is provided. The expected magnitude of the corrosion may be slightly less than the maximum values found in these tests, due to the highly unfavorable area ratio used in the tests. The magnitude of the difference will depend upon the effective area ratio in the actual system, but this area ratio effect was found to be very small. The worst attack will probably occur within the first 2 1/2 pipe diameters of distance from the condenser system.

Both impressed-current and sacrificial zinc cathodic-protection systems appear to be adequate to completely suppress the galvanic corrosion. Although the automatic impressed-current system used in these tests proved to be unsatisfactory, other impressed-current systems are available for this application which have already been proven reliable aboard ships.

The use of polyvinyl chloride piping between the condenser and the copper-nickel piping will have only limited value in reducing galvanic corrosion. The use of titanium piping as a separator piece to reduce the effective galvanic area ratio is of no value in reducing the galvanic effects.

The effect of increasing the galvanic area ratio from 1:1 to 100:1 was a doubling of the corrosion rate and almost doubling the galvanic current of the copper-nickel specimens. This increase was less than expected and may indicate that the galvanic reaction is limited by the corrosion processes taking place at the surface of the copper-nickel.

Although they would be at different temperatures, the ship-board condenser inlet and the outlet piping will contain seawater with the same oxygen content. This must be the case, even if oxygen is supersaturated in the exit water, since no accumulation of oxygen in the condenser occurs. Little difference in the corrosion behavior at the two locations should, therefore, be observed in an actual condenser system, even though a great difference in corrosion behavior with temperature was observed in these tests.

From a corrosion standpoint, the use of a titanium condenser in conjunction with copper-nickel piping appears feasible provided adequate sacrificial zinc or impressed-current cathodic protection is employed.

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