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PAPER NUMBER

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Corrosion 86

The International Corrosion Forum Devoted Exclusively to
The Protection and Performance of Materials

March 17-21, 1986
Albert Thomas Convention Center
Houston, Texas

EFFECTS OF TEMPERATURE AND SALINITY ON THE CATHODIC PROTECTION CURRENT DEMAND FOR SHIPS' HULLS

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ABSTRACT

The current demand of coated steel hulls has been monitored to determine the influence of temperature, salinity, oxygen level, alkalinity and calcium carbonate concentrations. It was found that current demand of ships could be reduced as much as 70% if a vessel was operating in tropical waters rather than temperate. This reduction in current demand was maintained when the vessels returned to temperate water but was lost after passing through fresh or polluted water.

INTRODUCTION

Over the years differing opinions have been expressed concerning expected current requirements of ships moving from temperate to tropical waters. Morgan[1], Greenblatt[2], Carter and Crennel[3], Vossnack and Visscher[4] all report increased current demand with increasing temperature. Carson and Peterson[5], on the other hand, have both stated that in their experience current requirements are reduced in warmer waters. Peterson related the effect to a laying down of calcareous deposit.

We have monitored current demand as a function of location and oceanographic data and have found that when Canadian Naval vessels travel from the temperate waters of the northeast Pacific to the tropical waters of the mid Pacific, current requirements are reduced by 60-70%. The pattern of current reduction is repeated by all of our ships each time they pass through the waters near Hawaii.

EXPERIMENTAL

The data for this study was obtained from the monthly cathodic protection reports of Canadian Naval frigates based at CFB Esquimalt. These ships are approximately 110 metres in length and have an underwater wetted area of 1500 m^2. The underwater paint system consists of an aluminum pigmented vinyl anti-corrosive (CGSB Standard 1-GP-122) topcoated with a cuprous oxide pigmented vinyl anti-fouling paint (CGSB Standard 1-GP-123), each applied at a thickness of 125 μm.

The cathodic protection system for these ships consists of two lead-silver anodes mounted in the stern and four lead-silver anodes mounted forward and aft, port and starboard on the bilge rail. The anode shield around each anode is approximately three metres square and is a 4-mm thick high dielectric trowel-on epoxy.

Each ship's hull is ideally maintained at -850 mV versus two hull-mounted Ag/AgCl reference electrodes using a manually controlled impressed current system. Silver sliprings and silver-graphite brushes are also fitted for shaft grounding.

Each ship is responsible for keeping a daily log of current requirements and potential of the hull. It is from these records and the daily ship position that the data for this report is taken.

RESULTS

Under normal operating conditions of the northeast Pacific, ships require between 40 and 60 mA/m^2 to ensure total corrosion protection while underway. After a few days of operation in the warm waters of the mid Pacific, current requirements drop to between 10 and 25 mA/m^2 (Figure 1 and Table 1). This is in contradiction to what others have predicted.

The factors that can influence these changes in current requirements in sea water are salinity, temperature, oxygen concentration and the chemical constituents of sea water. The influence of each of these factors on current requirements for ships's hulls will be discussed in the following section.

DISCUSSION

Influences of Temperature and Salinity

Morgan[1], and Vossnack and Visscher[4] state that the current required to protect a hull should increase with a rise in temperature. Their reasoning, using simple electric circuit theory, is that with increasing salinity and temperature there will be a corresponding reduction in circuit resistance and hence greater current flow.

Seasonal salinity and temperature profiles of the Pacific Ocean are shown in Figures 2 and 3.[6] From these profiles one can estimate that the sea water of the northeast Pacific has an average annual temperature of about 10°C with a salinity of 31% (parts per thousand) and that the mid Pacific has an average annual temperature of 25°C and a salinity of 35%. A plot of conductivity of sea water versus temperature and salinity is shown in Figure 4. It can be calculated from this plot that the resistance of mid Pacific sea water is 60% lower than northeast Pacific sea water.

If salinity and temperature are major influences in controlling current demand then indeed one would predict, using Ohm's Law, an increase in current requirement when travelling from the northeast Pacific to the mid Pacific. In fact the opposite is observed for Canadian Naval vessels; current requirements decrease when travelling into tropical sea water from temperate. Therefore temperature and salinity are not major factors in determining current requirement changes when travelling into tropical sea water.

Influence of Oxygen Concentration

During a study of the long term current demand of mild steel[7] it was found that there is a daily cycle of oxygen centration and current demand (Figure 5) corresponding to daytime and nighttime. This is a small change (10%) but nevertheless shows the direct relationship between current demand and oxygen concentration.

The concentration of oxygen in sea water decreases with increasing sea water temperature. Oceanographic data[8] (Figure 6) shown a lowering of oxygen concentration from 0.60 milliequivalents/litre in temperate waters to 0.40 milliequivalents/litre in tropical waters. Since complete cathodic protection is only obtained when all of the oxygen reaching a metal surface is reduced by electrons supplied by the external source (Equation 1), one might expect a reduction in the cathodic current demand in tropical waters that was proportional to the drop in oxygen concentration.

$$H_2O + 1/2O_2 + 2e^- \rightarrow 2OH^- \qquad (1)$$

This effect should be immediate, but ship records show that reduction in current demand takes place after the ship enters tropical waters. Very little change is experienced as the ships approach Pearl Harbour, Hawaii, but after a few days alongside, the reduction in the at-sea current demand becomes apparent (Figure 1).

Influence of Chemical Constituents - Cathodic Films

As demonstrated by Humble[9] a film of cathodic deposit can greatly reduce current requirements by restricting the rate of oxygen diffusion to the hull. Similarly Hartt and Wolfson[10] have shown that formation of the cathodic film is dependent on the velocity of the sea water and the potential, with thicker films formed at low velocities and more negative potentials. The formation of these calcareous films is dependent on the current density and the chemical composition of the sea water.

When cathodic protection is applied, the pH of the water film adjacent to the bare areas of the hull increases, resulting in precipitation of calcium carbonate and magnesium hydroxide. Surface water in the tropics has been shown to be 300-700% supersaturated with calcium carbonate due to increased temperature and alkalinity (Figure 6).[6] Calcium carbonate films are, therefore, formed much more readily in tropical than in temperate waters. Once formed, this film is relatively permanent due to the negligible solubility of the calcareous deposit in sea water. Observations by divers confirm that after operating in tropical waters a noticeable, continuous white film is formed on the blades of bronze propellors. The conclusion that a calcium carbonate film is the cause of cathodic protection current reduction is supported by the fact that the ships continue to experience low current demand after returning to temperate waters (Figure 1). None of the other circumstances described account for the observed hysteresis.

One of the reasons for the time lag in the formation of this film until the ship has been tied up alongside for several days is that, while still underway, the alkali (OH^-) generated at the surface is not allowed to accumulate. Under these conditions the pH at the surface while a ship is underway is similar to the bulk pH of the sea water. When the ship is alongside, the pH at the surface, generated through reaction (1), will increase substantially. Calcium carbonate is even less soluble as the pH increases due to a shift in the equilibrium in reaction (2) to the left, driving reaction (3) more to the right, thus precipitating more calcium carbonate.

$$CO_3^{2-} + H_2O \rightarrow HCO_3^- + OH^- \qquad (2)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \qquad (3)$$

In temperate waters this cathodic film is still laid down but due to the lower concentrations of calcium carbonate in the sea water it is at a much slower rate. Since the films form only on the bare metal the effects of this slowly generated film are negated by factors such as age of the paint and damage to the paint, such that the effect of this film is not easily recognized.

Although this film is tenacious it is not indestructable. Even though the solubility of calcium carbonate in fresh water (K_{sp}=4.8 x 10^{-9}) is considerably less than in sea water (K_{sp}=1.2 x 10^{-6}) [8] the calcium carbonate film dissolves in fresh water. There are three factors that shift the equilibrium in equation 3 to the left:

1. calcium concentration in fresh water is much lower that in sea water,
2. the pH of fresh water is less than sea water, and
3. impressed current cathodic protection system is turned off in fresh water, reducing the alkalinity at

the surface.

As can be seen in Figure 8, (Table 2) current reduction is experienced in the waters near Hawaii, but each time a ship enters fresh water of a polluted harbour such as Tokyo Harbour, the film is partially destroyed and current requirements increase. A similar phenomenon is observed after ships have entered the fresh water estuaries of the Columbia and Fraser Rivers.

CONCLUSIONS

Experience of the Canadian Navy has shown that cathodic protection current requirements is reduced when moving from temperate to tropical waters. Current demand fails by 60-70% during the passage from the cool waters of the northeast Pacific to the warm waters of the mid Pacific and remains at these low values on their return.

The cause of this effect is the formation of calcareous cathodic films that cover areas of bare metal. These films are laid down much more quickly and at lower current densities in tropical waters that are supersaturated with calcium carbonate.

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TABLE 1
Page i

HMCS MACKENZIE

Date	Ship's Speed	Current	Lat.	Long.	Remarks
24 Aug			48° N	124° W	
25 "	11.5	78	47	128	
26 "	12	80	45	132	
27 "	5.5	83	42	137	
28 "	13	88	35	141	
29 "	13	86	35	145	
30 "	13	72	31	150	
31 "	13	72	28	153	
1Sep	12.5	76	25	156	
2 "	18.5	73	22	157	
3 "	12.5	72	22	158	
4 "	Pearl	Harbour			
5 "					
6 "					
7 "			20	159	
8 "	12	48	20	158	
9 "	15	52	16	160	
10 "	12.5	38	11	162	
11 "	13	32	8	163	
12 "	11.5	33	3	164	
13 "	14.5	31	1 S	166	
14 "	13	31	6	168	
15 "	13	29	10	169	
16 "	10	20	14	171	
17 "			14	170	
18 "	15	24	14	173	

TABLE 1
Page ii

HMCS MACKENZIE

Date	Ship's Speed	Current	Lat.	Long.	Remarks
19 Sep	12	20	15	174	
20 "	13	18	18	176	
21 "	Lautoko	Fiji			
22 "					
23 "			22	179° W	Time change + 1 day
24 "	10	17	25	177° E	
25 "	12	12	25	177	
26 "	12	12	29	169	
27 "	14	12	29	167	
28 "	14	12	32	159	
29 "	15	13	38	152	
30 "	8	13	38	152	
1 Oct	Sydney				
2 "					
3 "					
4 "					
5 "			32	153	
6 "	10	12	27	154	
7 "	15	11	27	153	
9 "	Brisbane				
10 "					Fresh water
11 "			28	155	
12 "	15	20	32	160	
13 "	15	16	35	165	
14 "	27	16	38	169	
15 "	16	23	40	173	

TABLE 1
Page iii

HMCS MACKENZIE

Date	Ship's Speed	Current	Lat.	Long.	Remarks
16 Oct	18	21	41	175	
17 "	Wellington	New	Zealand		
18 "					
19 "			41	175	
20 "	11	10	41	174	
21 "	10	11	41	176	
22 "	10	16	39	178	
23 "	Nelson				
24 "					
25 "			38	177	
26 "	12	17	35	174	
27 "	12	17	37	175	
28 "	10	13	37	175	
29 "	Auckland				
30 "					
31 "					
1 Nov					
2 "			34° S	176° E	
3 "	8	20	30	179	
4 "	13	22	29	179° W	Date Line
3 "			30	179° E	
4 "			25	178	
5 "	13	20	21	176	
6 "	10	20	17	174	
7 "	10	22	15	172	
8 "			14	172	

TABLE 1
Page iv

HMCS MACKENZIE

Date	Ship's Speed	Current	Lat.	Long.	Remarks
9 Nov	Pago Pago		13	170	
10 "	21	21	12	170	
11 "	12	18	7	168	
12 "	12	17	3° S	167	
					Equator
13 "	14	15	2° N	165	
14 "	12	16	5	163	
15 "	8	18	11	163	
16 "	14	14	14	162	
17 "	10	15	18	160	
18 "	13	15	21	158	
19 "	Pearl	Harbour			
20 "					
21 "					
22 "			21	158	
23 "	10	15	21	157	
24 "	10	17	21	157	
25 "	13	15	23	156	
26 "	10	16	27	152	
27 "	10	13	31	148	
28 "	15	14	35	145	
29 "	15	18.5	39	140	
30 "	13	15	42	136	
1 Dec	13.5	14	45	131	
2 "	15	13	48	126	
3 "	10	14	48	123	
4 "	ESQUIMALT				

TABLE 2
Page i

HMCS TERRA NOVA

Date	Ship's Speed	Current	Lat.	Long.	Remarks
15 Mar	12	92	46° N	126° W	
16 "	16	90	40	126	
17 "	15	85	35	122	
18 "	14	85	33	118	
19 "	14	90	33	118	
20 "	San	Diego			
21 "	10	95			
22 "	15	85	32	121	
23 "	8	80	31	126	
24 "	10	83	29	137	
25 "	20	88	28	137	
26 "	18	100	25	142	
27 "	10	87	23	149	
28 "	7	90	22	156	
29 "	10	90	22	160	
30 "	14	90	21	158	
31 "	Pearl	Harbour			
1 Apr					
2 "					
3 "	10	68	22	159	
4 "	12	68	24	161	
5 "	10	56	27	166	
6 "	12	56	31	170	
7 "	14	53	35	175	
8 "	14	50	39	179	
9 "	10	45	41	177	

TABLE 2
Page ii

HMCS TERRA NOVA

Date	Ship's Speed	Current	Lat.	Long.	Remarks
10 Apr	12	45	43	179	
11 "	18	45	45	179	
12 "	20	41	49° N	180° E	
13 "	14	46	50	176	
14 "	13	41	51	171	Advance one day
16 "	15	48	47	162	
17 "	16	45	47	162	
18 "	20	47	39	146	
19 "	15	51	40	147	
	Yokosuka	Japan			
20 "	10	62			Tokyo Harbour fed by 2 rivers
21 "					
22 "					
23 "	6	90	34	140	
24 "	12	96	31	135	
25 "	15	84	33	132	
26 "	Kure	Japan			
27 "					
28 "					
29 "					
30 "	10	37	34	131	
1 May	13	39	34	130	
2 "	20	49	34	125	
3 "	12	42	35	125	
4 "	22	42	33	126	
5 "	10	49	32	123	

TABLE 2
Page iii

HMCS TERRA NOVA

Date	Ship's Speed	Current	Lat.	Long.	Remarks
6 May	Shanghai	PRC			Fresh water
7 "					
8 "					
9 "	14	61	32	124	Current too low
10 "	8	58	33	128	
	Pusan /	Chinhae			
11 "	10	85			
12 "					
13 "	8	85			
14 "					
15 "	15	35 + 47	33	127	
17 "	12	72	29	123	
18 "	10	77	25	120	
19 "	10	75	23	116	
20 "	Hong Kong				
21 "					
22 "					
23 "	10	85	21	115	
	12	85			Current too high
24 "	14	47	18	119	
	10				
25 "	Manila	41			
26 "					
29 "					
28 "	12	50	14	120	
29 "	15	44	13	126	
30 "	18	28	15	131	
31 "	20	26	16	134	

TABLE 2
Page iv

HMCS TERRA NOVA

Date	Ship's Speed	Current	Lat.	Long.	Remarks
1 Jun	16	25	17	141	
2 "	8	23	18	145	
3 "	14	24	19	150	
4 "	15	24	20	155	
5 "	10	21	21	160	
6 "	16	22	21	166	
7 "	15	22	22	171	
No Day	22	23	22	171	
8 "	20	22	25	179	
9 "	15	24	26	175	
10 "	18	28	24	169° W	
11 "	11	26	22	164	
12 "	6	25	21	159	
13 "	Pearl	Harbour			
14 "					
15 "	14				
16 "	18	33	23	154	
17 "	18	29	27	148	
18 "	20	24	31	141	
19 Jun	10	24	33	134	
20 "	15	24	36	129	
21 "	10	24	38	125	
22 "	18	27	40	126	
23 "	13	24	45	126	
24 "	ESQUIMALT				

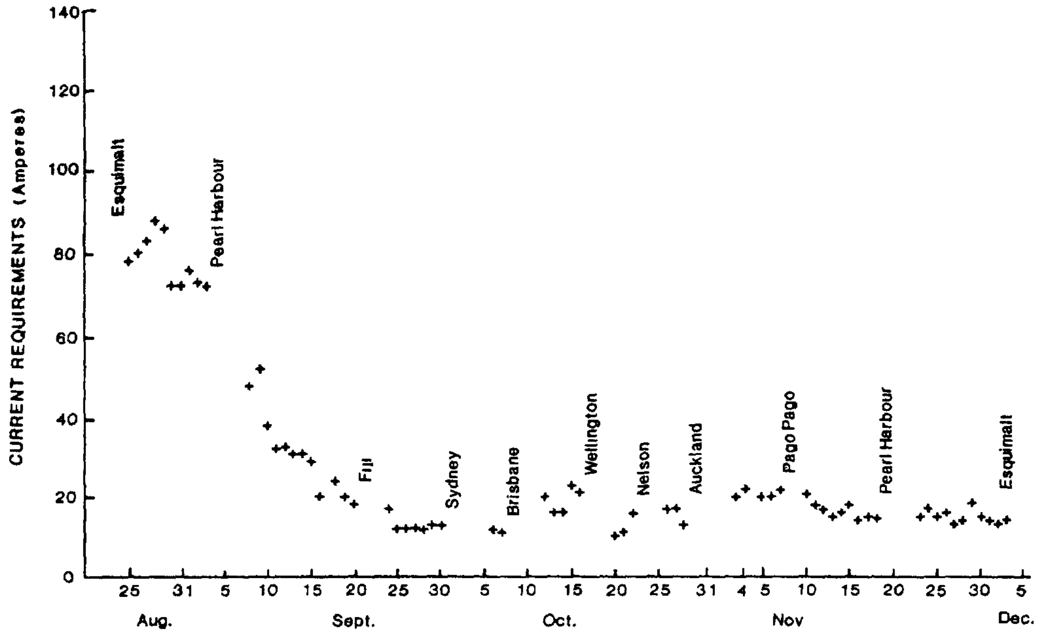
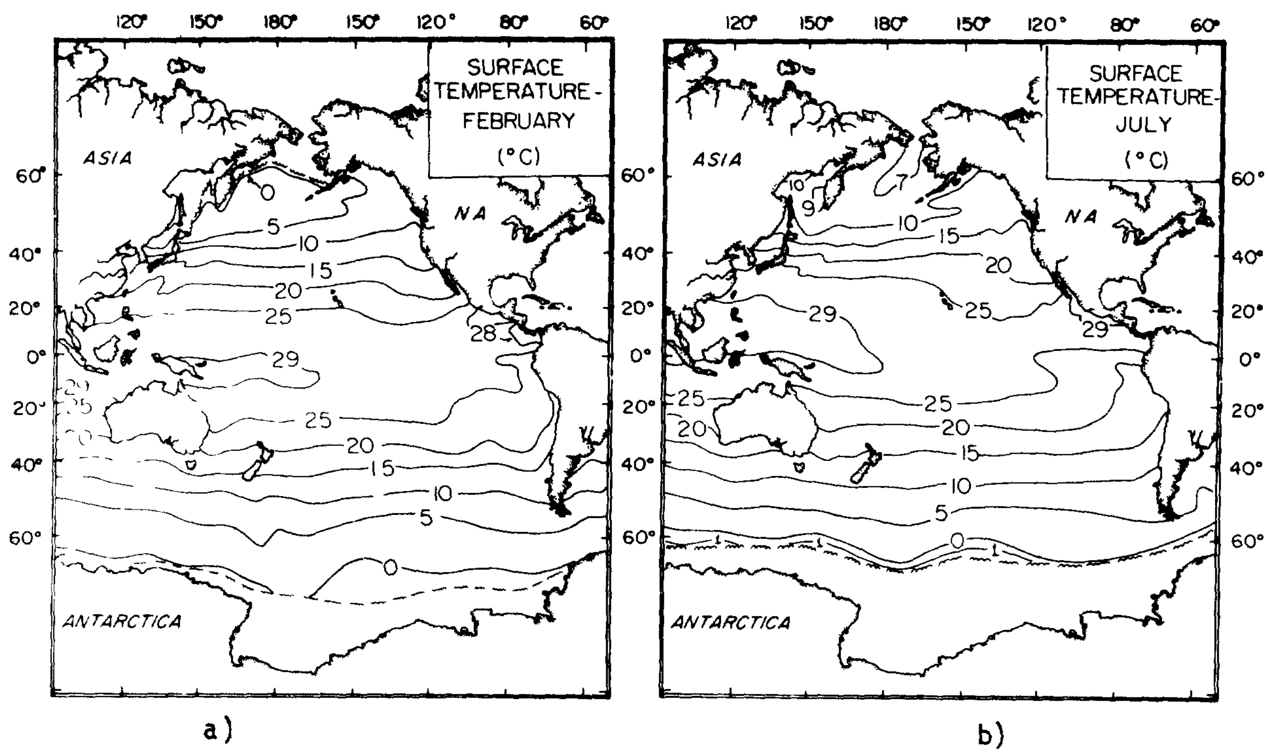


Figure 1. Current Requirements for HMCS MACKENZIE (Table 1).



a) b)

Figure 2. Pacific Ocean Temperature Profiles for a) February, and b) July.

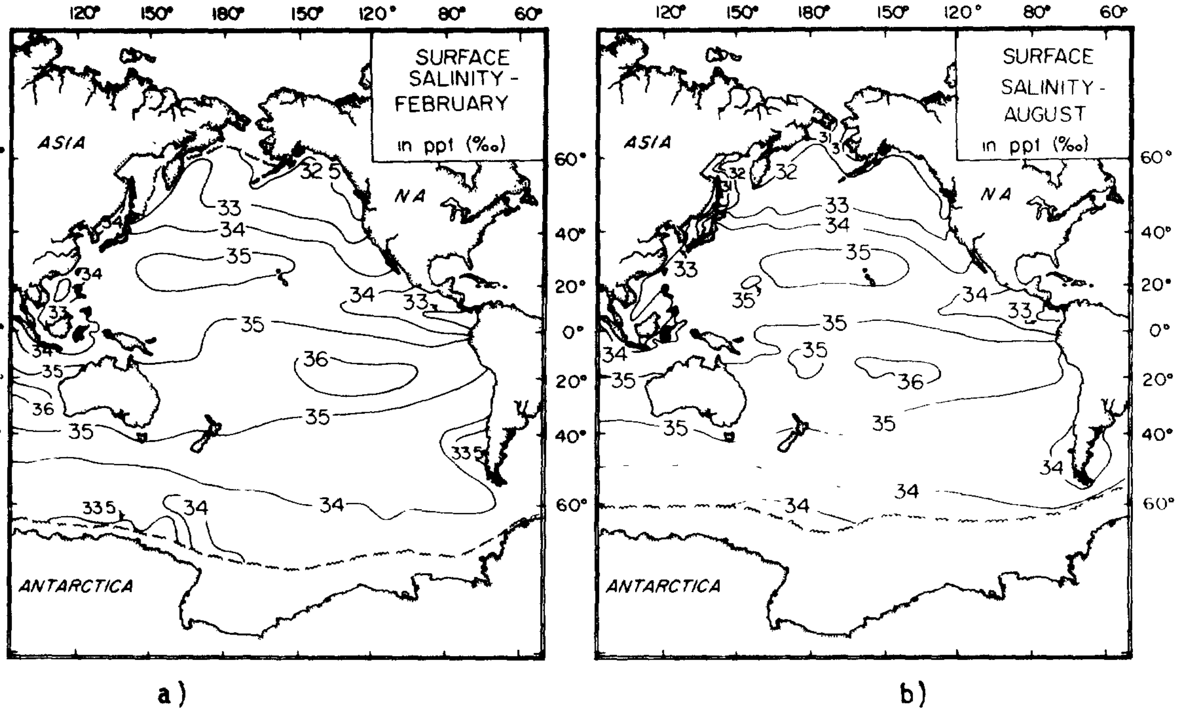


Figure 3. Pacific Ocean Surface Salinities (0/00) Distribution for a) February, and b) August.

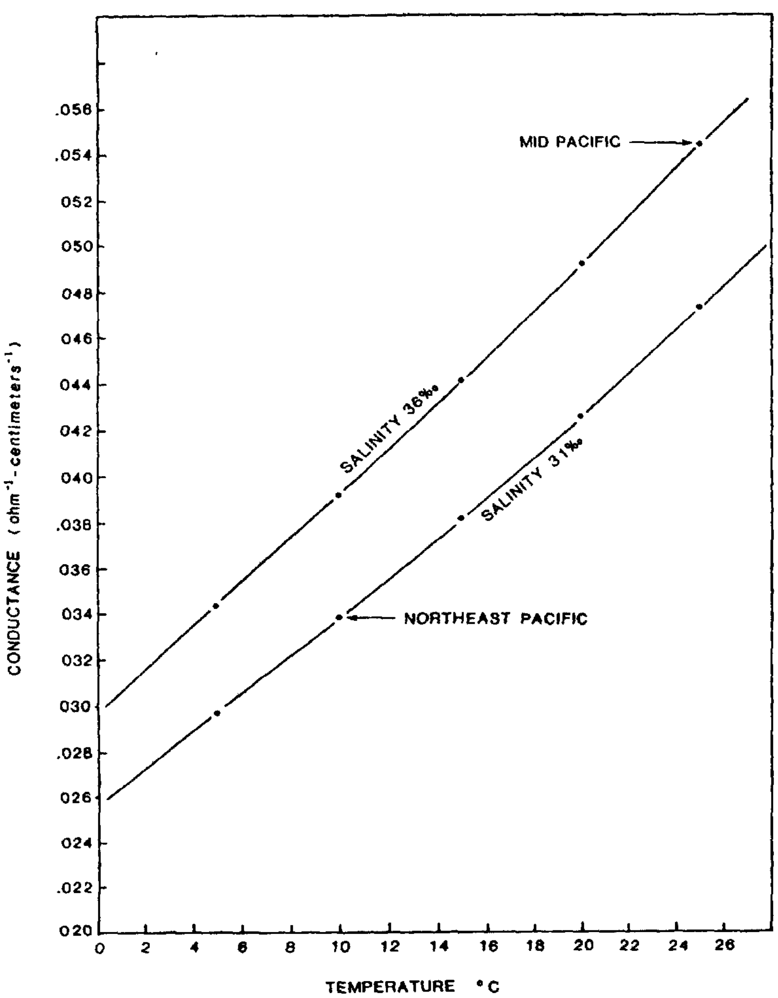


Figure 4. Conductivity of Sea Water vs. Temperature and Salinity.

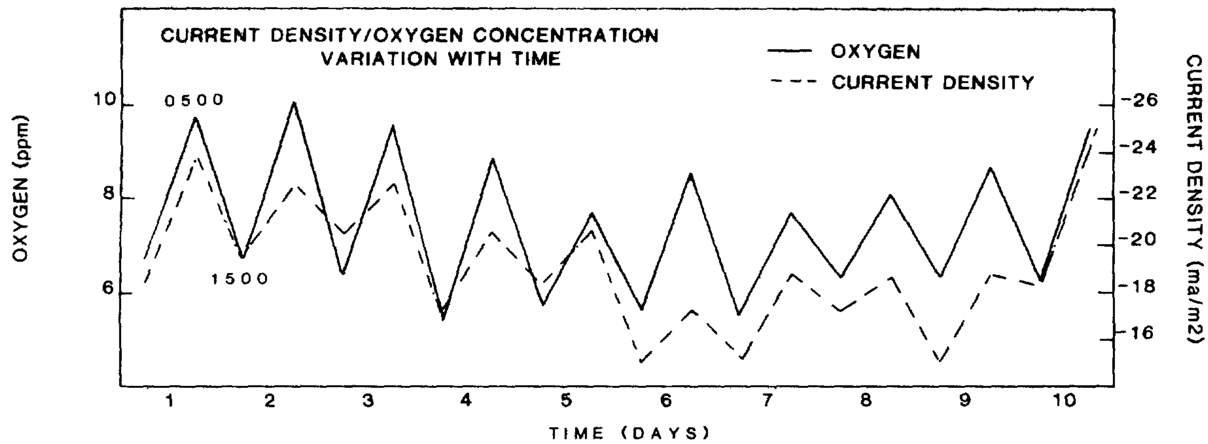


Figure 5. Variation of Current Density and Oxygen Concentration with Time.

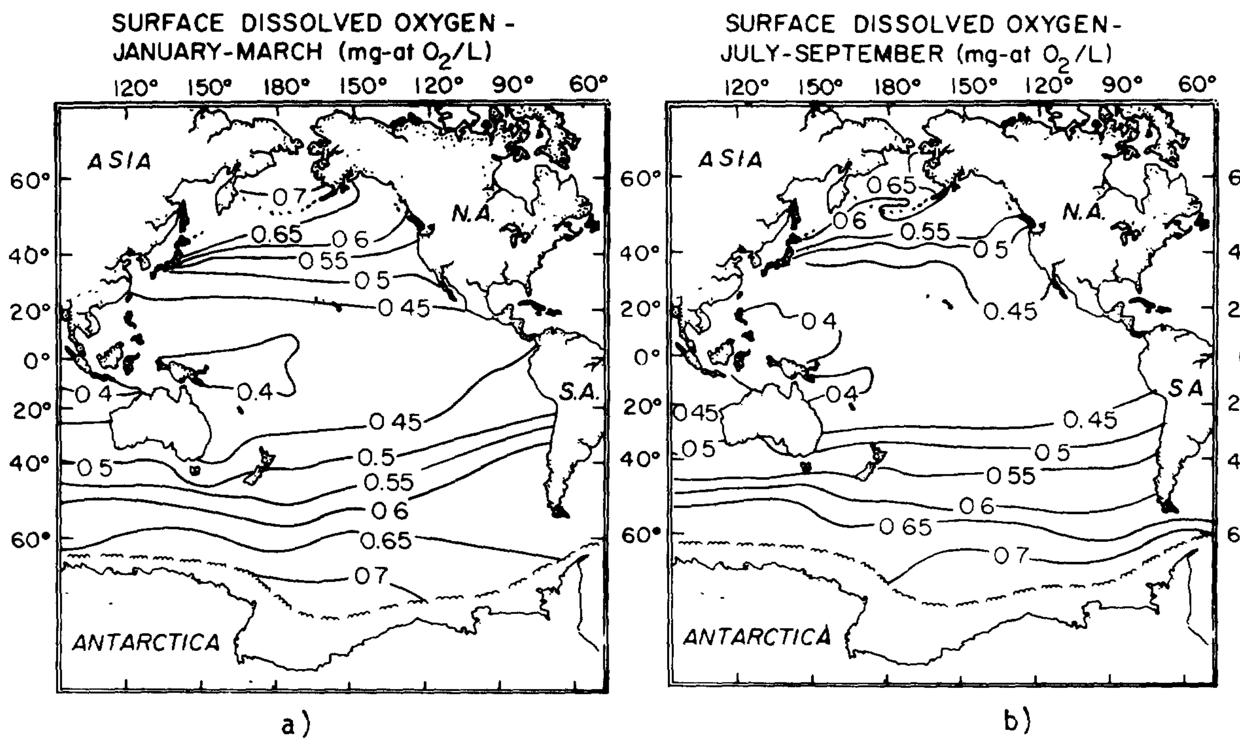


Figure 6. Pacific Ocean Surface Oxygen Concentration for a) January - March, and b) July - September.

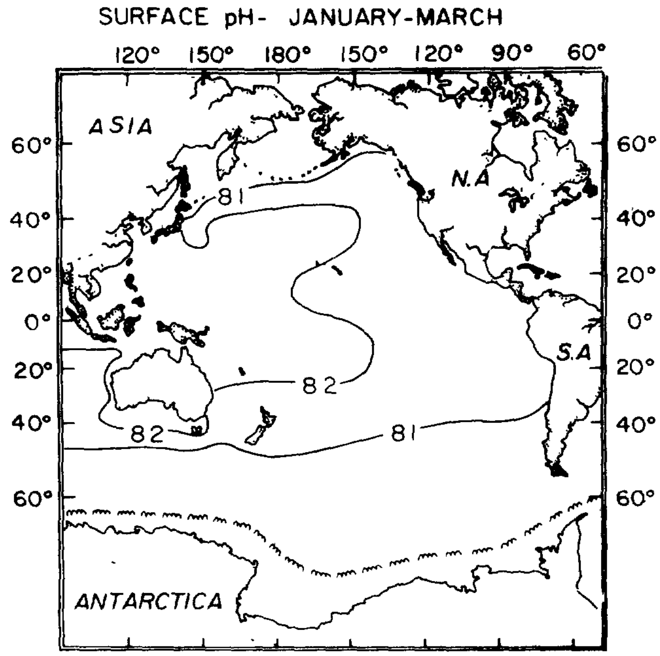


Figure 7. Pacific Ocean Surface pH profile for January - March.

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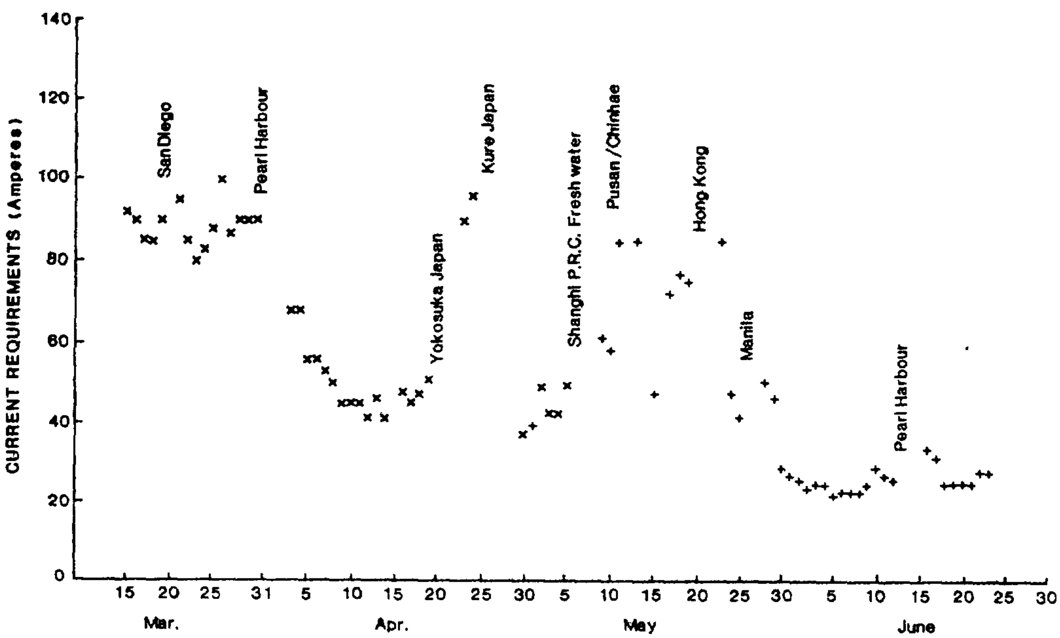

Figure 8. Current Requirements for HMCS TERRA NOVA (Table 2).