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EXPLORATORY CORROSION TESTS IN THE CANADIAN ARCTIC

G.J. Biefer

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EXPLORATORY CORROSION TESTS IN THE CANADIAN ARCTIC

by

G.J. Biefer*

ABSTRACT

To determine both the feasibility and usefulness of a larger-scale investigation, a small number of sea-water and atmospheric corrosion tests were performed in the Arctic, and the results compared with behaviour in southern Canada.

Two sea-water tests on G40.8 Grade B structural steel, performed in inlets of Ellesmere and Devon Islands, showed relatively even corrosion attack and low weight-loss corrosion rates of 57 to 96 μm/yr (2.2 to 3.8 mils/yr). In sea-water tests of the same steel and of an alloy steel, in Halifax Harbour and in the Bay of Fundy, deeply penetrating pits were observed, and corrosion rates were in the range of 154 to 543 μm/yr (6.1 to 21.4 mils/yr).

Atmospheric corrosion tests were performed at Tuktoyaktuk, N.W.T., at a site 70 m (230 ft) from the Beaufort Sea. Weight-loss corrosion rates for G40.8 Grade B and two alloy steels were not much lower than those observed at Ottawa, Ontario, during the first year of exposure. However, over the one- to three-year period, corrosion rates were only about 1.8 μm/yr (0.07 mils/yr), distinctly lower than observed for the same alloys at Ottawa.

*Head, Corrosion Section, Physical Metallurgy Research Laboratories, Canada Centre for Mineral and Energy Technology (CANMET), Department of Energy, Mines and Resources, Ottawa, Canada.

DES ESSAIS PRELIMINAIRES DE CORROSION DANS L'ARCTIQUE CANADIEN

par
G. J. Biefer*

SOMMAIRE

Un petit nombre d'essais de corrosion a été exécuté en milieux atmosphériques et d'eau de mer, dans l'Arctique, dans le but de connaître la practicabilité et l'utilité d'essais semblables, à une plus grande échelle. Les résultats furent comparés à ceux d'essais effectués dans le sud du Canada.

A la suite de deux tests effectués en eau de mer sur un acier de construction G40.8 de classe B, dans les îles d'Ellesmere et de Devon Island, on observa une certaine uniformité de la corrosion ainsi que des taux de corrosion à faible perte de poids de l'ordre de 57 à 76 µm/année (2.2 à 3.8 mils/année). Les essais effectués en eau de mer sur le même acier et sur un acier allié dans le port d'Halifax et à la Baie de Fundy, révélèrent des piqûres très profondes et des taux de corrosion variant entre 154 et 543 µm/année (6.1 à 21.4 mils/année).

A Tuktoyaktuk dans les Territoires du Nord-Ouest, des essais atmosphériques ont été exécutés dans un site situé à 70 m (230 pi.) de la Mer de Beaufort. Les taux de corrosion à perte de poids des aciers G40.8 de classe B et des deux aciers alliés n'étaient pas beaucoup plus bas, pendant la première année d'exposition, que ceux observés à Ottawa, Ontario. Par contre, sur la période d'un à trois ans, les taux de corrosion étaient d'environ 1.8 µm/année (0.07 mils/année) seulement, c'est-à-dire plus bas que ceux observés dans le cas des mêmes alliages à Ottawa.

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*Chef, Section de la corrosion, Laboratoires de recherche en métallurgie physique, Centre canadien de la technologie des minéraux et de l'énergie, Ministère de l'Energie, des Mines et des Ressources, Ottawa, Canada.

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INTRODUCTION

There were virtually no experimental data in the open literature on atmospheric and sea-water corrosion in the Canadian Arctic prior to January 1973. It appears that there should be at least a minimal amount of data available to design and operating engineers in view of the increasing economic importance of this region and it was decided, therefore, that the Physical Metallurgy Research Laboratories (PMRL) would undertake a limited number of exploratory low-cost tests to determine whether a larger-scale, more systematic program would be both useful and feasible. The present report summarizes the results obtained during the period 1973-76. Some hitherto unreported results obtained earlier on steel specimens immersed in the Bay of Fundy at Musquash Harbour, N.B., are also included to provide additional perspective.

This research has been performed under what was then the Minerals Research Program, Utilization Activity, Technological Investigations Project. The Project Element is entitled "Corrosion Behaviour of Metals in the Arctic". Its primary aim is to provide a technical basis for developing federal government policies and plans.

Information regarding the corrosivity of Arctic environments would be expected to aid in the selection of metals and alloys and anti-corrosion systems in Arctic installations and vehicles.

EXPERIMENTAL

Sea-Water Tests

a) Musquash Harbour (Bay of Fundy), N.B.

Two Stelco "General Purpose" experimental steels were used in this test in the form of 3.2-mm thick as-rolled plate. Their chemical analyses are given in Table 1.

Two panels, approximately 150 x 50 mm, were prepared for each steel, the rolled surfaces being left in the as-received condition. Under the direction of R.K. Buhr of PMRL, two specimen racks were fabricated (Fig. 1). Each was designed to hold two specimens, one of each alloy, the specimens being isolated from galvanic effects by means of rubber spacers. The rack could then be clamped onto some suitable submerged structure. Under the supervision of F. McKinnon of the Department of Transport, the two racks were installed on the mooring chain of a buoy at Musquash Harbour, N.B., in the Bay of Fundy, a few miles west of Saint John. The buoy was in 18 m of water at low tide; one assembly was 4.5 m below the buoy and the other 13.7 m below the buoy. The average difference in level between high and low tide at Musquash Harbour has been stated to be approximately 6 m.

The specimens were immersed November 23, 1962, and removed in the first week of June 1963 for evaluation by PMRL. Best information available from the Department of Environment suggests that water temperatures ranged from 1 to 13°C, and salinity was 28.5 to 33.5%.

b) d'Iberville Fiord (Ellesmere Island), N.W.T.

The steel tested was Stelco G40.8 Grade B (since 1973, G40.21 Grade 38T) 12.5-mm thick plate having the composition shown in Table 1. Specimens about 50 x 80 x 12.5 mm were cut from the plate. After surface-finishing on a belt grinder using 80 grit, four specimens were mounted on a Type 304 stainless steel "birdcage" rack, shown in Fig. 2. Care was taken to electrically insulate the specimens from the rack.

Personnel of the Frozen Sea Research Group (Environment Canada) immersed the rack of specimens in sea water at d'Iberville Fiord (80°35'N, 80°00'W) on March 28, 1973. Because the fiord was frozen over, it was necessary to drill a hole through the ice. An anchor was fastened to the bottom of the rack and a float to the top, and the assembly was lowered through the hole. A flag was used to mark the position of the rack (Fig. 3). Operational

requirements of the Frozen Sea Research Group necessitated recovery of the specimens on June 18, 1973. This involved drilling a hole through the ice, hooking the float, and raising the assembly to the surface. The rack and specimens were then dried immediately in warm air and stowed in a dessicated plastic bag for shipment to PMRL. Figure 2 illustrates phases of the recovery operation.

R.A. Lake, who was in charge of the operation, supplied the sketch reproduced in Fig. 3, showing how the rack was suspended about 2.5 m above the bottom, in sea water about 10 m deep. Lake stated that, in April, the sea water had the following characteristics: temperature, -1.28°C; salinity, 31.20 0/00; pH, 7.4-7.8;* dissolved oxygen, 10 mℓ/ℓ; current velocity (estimate), ~1 cm/sec or less.

c) Halifax Harbour, N.S.

It was decided to perform a sea-water test of similar duration to the one at d'Iberville Fiord, but in a more southerly latitude. R.S. Hollingshead of the Dockyard Laboratory, Defence Research Establishment Atlantic (DREA), arranged for a test to be performed using a special barge moored in Halifax Harbour. A "birdcage" rack holding four specimens of G40.8 Grade B steel was immersed in sea water at a depth of 3.5 m on July 4, 1973. Maximum water temperature during the summer is apparently about 15°C (2). Two of the specimens were removed on September 24, 1974, and sent to PMRL. The remaining two specimens were removed October 18, 1974, and the test terminated. One of the four specimens had inadvertently been grounded to the stainless rack and, therefore, did not provide useful experimental data.

d) Jones Sound (S. of Ellesmere Island), N.W.T.

Through the co-operation of J.A.H. Carson, Defence Research Establishment Pacific (DREP), Esquimalt, B.C., the Department of National Defence (DND) agreed to emplace and subsequently

*pH determinations were performed at PMRL on as-received water samples from d'Iberville Fiord.

retrieve corrosion specimens in connection with their own studies in Arctic waters. A rack, holding four electrically isolated G40.8 Grade B specimens, was therefore prepared and subsequently affixed to a larger DND assembly. It was reported that the assembly was immersed in deep water in Jones Sound in the summer of 1973. Two attempts were made in the summer of 1974 to retrieve the assembly, but these failed. The assembly was never recovered and the test had to be written off.

e) Devon Island (N. of Lancaster Sound), N.W.T.

Subsequent to the attempted test in Jones Sound described above, DND proposed the immersion of another similar rack of alloy specimens in deep Arctic sea water near shore, retrieval being ensured by a cable running from the rack to the shore. A rack holding four electrically isolated specimens of G40.8 Grade B steel was, therefore, prepared, and subsequently immersed under the supervision of J.A.F. Wilson in an inlet on the south coast of Devon Island on September 6, 1975. The depth of immersion was 30 m and the rack of specimens was held above the sea bottom by a float, in the way illustrated in Fig. 3. The water was described by Wilson as being completely free of man-made pollution and exhibiting no signs of underwater vegetable matter. It was further noted by Wilson that cables having steel armour strands on the outside corrode more severely in the inlet than in deeper water off shore. Water temperature was said to be a maximum of about 5°C during a typical year.

The rack was recovered by Wilson and co-workers on August 27, 1976, and the specimens dismounted, dried thoroughly, and packed in plastic bags for shipment to PMRL.

Atmospheric Tests

It was decided to perform exploratory atmospheric tests at Tuktoyaktuk, N.W.T., on the Beaufort Sea near the mouth of the Mackenzie River. Tuktoyaktuk is the most important harbour in the area, and gas and oil strikes have been made in the vicinity. It is also the location of the main base camp of the Polar Continental Shelf Project (PCSP) of the Department of Energy, Mines and Resources.

An atmospheric corrosion testing station was constructed at Tuktoyaktuk, July 1-10, 1973, by PMRL personnel assisted by local labourers provided by PCSP. It consisted of conventional south-facing racks protected by a 2-m high chain link fence enclosing a compound about 6 x 3.7 m in size. The compound was located adjacent to the PCSP base camp and the Tuktoyaktuk landing strip and was about 70 m from the Beaufort Sea (Fig. 4).

Three structural steels were available as 12.5-mm thick commercial plate for use in the atmospheric testing. One of these was the 40.8 Grade B steel used in most of the sea-water tests. The other two were Stelcoloy S and Stelcoloy G (Steel Co. of Canada Ltd.) "weathering" steels, which are designed to develop a corrosion-resistant rust coating when exposed to the atmosphere. Chemical analyses of the steels are given in Table 1.

Specimens about 100 x 150 x 12.5 mm in size were prepared from each of the three alloys, all surfaces being grit-blasted to a uniform appearance. Five specimens of each of the three alloys were put on test at Tuktoyaktuk, July 9, 1973. One specimen of each alloy was retrieved on July 10, 1974, and another specimen on July 15, 1976.

RESULTS

Sea-Water Tests

a) Musquash Harbour (Bay of Fundy), N.B.

The as-received specimens were free from adherent organic growth, but were pitted and partially coated with loose rust. The specimens were de-rusted in inhibited acid, then weighed and examined. The appearance of the de-rusted specimens, shown in Fig. 5, indicates that pitting was more severe at the 13.7-m depth. Weight losses are given in Table 2.

Sections through some of the specimens disclosed the maximum penetrations by pits given in Table 2. There was also a strongly intensified 'crevice' attack on the exposed metal immediately adjacent to the edge of the clamp; maximum depths of corrosion measured in this region are given in Table 2.

b) d'Iberville Fiord (Ellesmere Island), N.W.T.

The as-received specimens exhibited loosely adhering red rust and light-coloured crystalline deposits, as shown in Fig. 6. Analysis of the latter showed them to be primarily calcite ($CaCO_3$). After de-rusting in inhibited acid, specimen surfaces showed only a very slight, uniform etching in some areas and virtually no attack in other areas. Pitting was negligible.

Weight losses are given in Table 2. These indicate a very light corrosion attack and similar behaviour for the four specimens.

c) Halifax Harbour, N.S.

Specimen 3 (82 days' exposure) showed relatively uniform corrosion attack but the other two specimens, immersed 107 days, showed definite pitting attack. An example of this is given in Fig. 7, photographed after the specimen had been de-rusted in inhibited acid. Weight losses are given in Table 2.

It was reported that, on removal from the water, the specimens had been covered with a copious organic growth. This had been removed before sending the specimens to PMRL.

d) Devon Island, N.W.T.

Surfaces of the as-received specimens were mostly covered by thick layers of red rust. Examination, using a low-power stereomicroscope, showed the remains of two different types of marine organisms, each about 1 mm long, partially embedded in the rust. In some areas, the outermost rust layer was smooth, dense, and shiny, resembling purple-brown high-gloss paint.

Subsequent to de-rusting in inhibited acid, weight losses by corrosion were shown to be those in Table 2. Specimen surfaces were relatively smooth, with only large, shallow pits and etched areas to be seen (Fig. 8). The depths of some of these were measured relative to the very lightly corroded rim which had been in contact with a plexiglass backing. The maximum depths thus measured (not necessarily the deepest penetrations) are shown in Table 2.

X-ray diffraction analyses of the corrosion products were performed at PMRL. The thick layers of red rust were found to consist of a mixture of α FeOOH (goethite) and γ FeOOH (lepidocrocite). Corrosion product from the dense, shiny purple-brown layers contained the same constituents and a minor quantity of Fe_3O_4 (magnetite).

Atmospheric Tests

After exposure to the atmosphere at Tuktoyaktuk for one year, the structural steel specimens showed rusty surfaces, as did all uncoated steel nuts, bolts, etc., used in the construction of the compound and the racks. The galvanized steel was in excellent condition except for minor staining at a few places. These features can be seen in Fig. 9, showing the specimens after exposure for one year at Tuktoyaktuk. Very little additional corrosion appeared to have occurred after three years exposure.

Both the one-year and the three-year sets of specimens exhibited tightly adherent rust coatings. De-rusting in inhibited acid showed the light, shallow pitting usually seen in atmospheric corrosion attack, complicated by the presence of angular indentations produced by the grit blasting. Weight losses are shown in Table 3.

A mild steel chain, used to secure the gate of the compound, exhibited rusty surfaces after a one-year exposure. X-ray diffraction analysis of the rust showed α FeOOH (goethite), β FeOOH (akaganeite), γ FeOOH (lepidocrocite) and Fe_3O_4 (magnetite). SiO_2 (quartz) was also present.

Element identification of the rust was performed using energy dispersive X-ray analysis, employing both the scanning electron microscope (SEM) and the electron microprobe. Results are tabulated below.

Element	SEM	Microprobe
Fe	major	major
Si	minor	detected
S	trace	~1% max
Cℓ	"	~1% max
Ca	"	detected
Ti	"	-
Mn	"	-
Na	-	detected

DISCUSSION OF RESULTS

Sea-Water Tests

Steels in low-velocity sea water generally show their most rapid corrosion rates immediately after immersion; there is then a decline in the corrosion rate which may approach a steady state, usually after a year or more on test(1). This is illustrated by the results reproduced in Fig. 10.

Sea water corrosion rates, based on weight loss per unit area (Table 4), are presented in terms of average penetration per year. In every case, the calculation assumes constant corrosion rates during the relevant immersion period. Maximum penetration rates, obtained from metallographic sections and depth gauge measurements are also presented. These data were calculated on the basis of constant penetration rate.

Corrosion rates for each specimen are plotted versus exposure time (Fig. 11). It can be seen that corrosion rates in the Arctic tests are considerably lower than those observed in Maritime waters. Comparison with the data in Fig. 10 suggests that corrosion rates in Maritime waters are somewhat higher than those generally observed at the surface of the Atlantic and Pacific oceans. The corrosion rates observed in the Arctic, on the other hand, resemble those obtained in deep sea water, with d'Iberville Fiord providing the least corrosive conditions of the four test locations.

Temperature alone would not be expected to bring about the differences shown. Maximum temperatures in Halifax Harbour and in the Bay of Fundy were probably about 15°C, as compared with -1 to +5°C in the Arctic waters. It is considered that a 30°C decrease in temperature would be required (all other factors held constant) to halve the corrosion rate (3). Furthermore, the greater oxygen solubility in the colder Arctic waters would be expected to lead to increased corrosion rates, tending to cancel any effect of lower temperatures.

It is probable that other factors operated to increase corrosion rates at the Maritime sites. At Halifax Harbour, and to a lesser extent at Musquash Harbour, the presence of pollutants may have had a significant deleterious effect. Fouling organisms became attached to submerged surfaces at both Maritime locations. This may have been related to the appearance of deeply penetrating pits in specimens exhibiting the highest corrosion rates. Such pits were not seen in the specimens tested in the Arctic. It also appears that average water velocities may have been higher at the maritime sites, and this would favour higher corrosion rates.

Specimen surfaces tested in Arctic waters remained essentially free from the copious fouling usually seen at more southerly latitudes. In discussing the effect of fouling on corrosion rate, Southwell and Bultman (4) have suggested that the steady-state corrosion rate of steel in sea water is 50 to 75 µm/yr, in terms of average reduction in thickness. However, this rate is applicable only when corrosion proceeds in anaerobic conditions, under a self-healing layer of biofouling, through the agency of sulphate-reducing bacteria. Noting that the pertinent bacteria, Desulphovibrio, thrive between 10 and 40°C, the authors suggest that, in waters where oxygen is present but where marine fouling cannot thrive (e.g., in the Arctic), corrosion rates may be higher. This, of course, is not in accordance with the results obtained in the present investigation.

Definite conclusions cannot be drawn from the rather scanty data presented here, particularly in view of the fact that H. Arup (5), in preliminary tests in the Danish waters of Davis Strait in 1976, obtained indications of high corrosion rates.

It can be concluded that a much more comprehensive test program will be needed to obtain a realistic picture of the sea-water corrosion behaviour which might be expected in the Arctic and in other Canadian waters of interest.

Atmospheric Tests

The results obtained in the test at Tuktoyaktuk are presented graphically in Fig. 12. Also shown are the results obtained in tests on the same alloys and a mild steel (see Table 1 for composition) performed on the roof of the PMRL Building, Ottawa. The corrosion rates are evidently lower at Tuktoyaktuk, averaging 1.6-1.9 µm/yr for all three alloys over the one- to three-year period (Table 3). Average penetration by corrosion after three years is about 20 µm. It is interesting to note that obvious differences between the three structural steels in Ottawa are not observed in the Tuktoyaktuk tests.

Gibbons (6) has reported atmospheric corrosion behaviour for carbon and alloy steels in a number of different sites in Canada. It was observed that rates in Norman Wells, N.W.T., were very low, amounting to an average penetration of only 10-13 μm after ten years. Other more southern sites exhibited more corrosive atmospheres than observed in the present work at Tuktoyaktuk.

Relative to Norman Wells, atmospheric corrosion during the first year at Tuktoyaktuk appears to have been accelerated by the presence of chloride from the nearby Beaufort Sea. This was indicated by the elemental analyses of the rust formed on a chain exposed at Tuktoyaktuk. Furthermore, according to the work of Misawa et al (7), the β FeOOH found in the rust on the chain is often found in the rust layer on steels which have been exposed to marine atmospheres. It is also worth noting that some of Serada's work (8) indicates that atmospheric corrosion in the presence of an electrolyte can occur at -20°C.

It is not planned at present to perform conventional atmospheric corrosion tests at additional sites in the Arctic. Rather, research is under way aimed at developing a small, inexpensive wire-on-bolt device which can be exposed for a one-year period at a number of different locations, and which will provide a general index of atmospheric corrosivity.

SUMMARY

Exploratory sea-water and atmospheric corrosion tests on structural steels have been performed in the Arctic and off the east coast of Canada. The results obtained were as follows:

1. At Musquash Harbour (Bay of Fundy), N.B., a 195-day sea-water test was performed on Stelcoloy G.P. alloy steel in which weight-loss corrosion rates were 234-543 μm/yr. Deeply penetrating pitting and crevice attack were observed, with maximum penetration rates over 2000 μm/yr.

2. In d'Iberville Fiord, Ellesmere Island, N.W.T., a 82-day sea-water corrosion test was performed on G40.8 Grade B steel. Corrosion rates ranged from 57-66 μm/yr. Attack was relatively uniform and no biofouling was observed.

3. In Halifax Harbour, N.S., 82- and 107-day sea-water corrosion tests were performed on G40.8 Grade B steel. Corrosion rates were 154-402 μm/yr. Deeply penetrating pitting and biofouling were observed.

4. At Devon Island, N.W.T., a 355-day sea-water corrosion test was performed on G40.8 Grade B steel. Corrosion rates were 83-96 μm/yr, and attack was relatively uniform. Biofouling was minimal.

5. At Tuktoyaktuk, N.W.T., at a location 70 m from the Beaufort Sea, an atmospheric corrosion test was performed on G40.8 Grade B steel and two proprietary weathering steels. After three years, performance of the three alloys was almost identical. The average penetration by corrosion was less than 20 μm, and the weight-loss corrosion rate over the one- to three-year period was 1.8 μm/yr. This represented distinctly lower corrosion rates than observed for the same alloys in Ottawa.

CONCLUSIONS

1. As compared with the results of tests in Maritime sea water, corrosion rates in Arctic sea water were unexpectedly low.

2. The present exploratory work showed the feasibility of corrosion testing in Arctic environments. Larger-scale, systematic studies employing more sophisticated procedures are needed to gain a realistic picture of atmospheric and sea-water corrosion behaviour in Canada's northern regions.

ACKNOWLEDGEMENTS

The preparation of specimens and racks, and the subsequent assessment of corroded specimens, were for the most part performed by J.G. Garrison, formerly with the Corrosion Section, PMRL, but now with National Defence Headquarters, Ottawa. Valuable assistance was given by A. Blouin of the Corrosion Section and D. Linkletter, then of the Corrosion Section, but now with the Non-Ferrous Metals Section of PMRL, and the Photographic and Drafting Services of PMRL. Analysis of corrosion products, using X-ray diffraction, the electron probe, and the scanning electron microscope, was performed by C.M. Mitchell, E.J.-C. Cousineau, K.M. Pickwick, V.E. Moore and R.H. Packwood, all of the Metal Physics Section of PMRL.

The helpfulness of personnel responsible for emplacing and retrieving specimens in the sea-water tests (some of whom are named in the body of the report) is gratefully acknowledged.

The Steel Company of Canada, Hamilton, Ontario, provided all the alloy steel used in the tests, without charge. Thanks are due particularly to J. Orton, D. Clay and D.W. Belanger of Stelco.

GJB:gt

REFERENCES

1. Fink, F.W. and Boyd, W.K. "The corrosion of metals in marine environments"; Defence Metals Information Center, Columbus, Ohio, DMIC Report 245; May 1970.

2. Jordan, F. "Oceanographic data of Halifax Inlet"; Bedford Institute of Oceangraphy, Report BI-D-72-8; Mar. 1972.

3. Uhlig, H.H. "Corrosion and corrosion control"; Second ed., John Wiley and Sons Inc.; 1971.

4. Southwell, C.R. and Bultman, J.D. "The effects of biological activity on the corrosion rate of carbon steel in sea water"; Proc. Fourth Inter-Naval Conference on Marine Corrosion, Washington, D.C.; Oct. 10-13, 1972.

5. Arup, H., Korrosionscentralen ATV, Glostrup, Denmark. Private communication; Dec. 13, 1976.

6. Gibbons, E.V. "The corrosion behaviour of the major architectural and structural metals in Canadian atmospheres. Summary of ten-year results of Group 1", National Research Council of Canada Report NRCC 11630; Oct. 1970.

7. Misawa, T., Asami, K., Hashimoto, K., and Shimodaira, S. "The mechanism of atmospheric rusting and the protective amorphous rust on low alloy steel"; Corrosion Science, v. 14, pp 279-289; Apr. 1974.

8. Sereda, P.J. "Weather factors affecting corrosion of metals"; ASTM Spec. Tech. Publ. 558; June 1973.

Table 1. Chemical analyses of steels (1)

	Element, %								
	C	P	S	Mn	Si	Cu	Cr	Ni	Others
Stelcoloy General Purpose	0.08	0.078	0.023	0.66	0.30	0.47	0.44	0.55	--
Stelcoloy G.P., (U-added)	0.11	0.06	0.029	0.63	0.37	0.39	0.46	0.39	0.047 U
Stelco G40.8 Grade B	0.20	0.004	0.025	1.36	0.19	--	--	--	0.005 N
Stelcoloy S	0.12	0.008	0.014	1.03	0.17	0.30	0.35	0.25	0.01 V
Stelcoloy G	0.12	0.08	0.020	0.63	0.24	0.48	0.49	0.60	--
Mild steel (2)	0.05	0.01	0.005	0.35	0.01	0.062	0.075	0.065	$\leq$0.002; Mo,Al,Sn,V

(1) Supplied by the Steel Co. of Canada, Hamilton, Ontario, Canada.

(2) Spectrochemical Analysis by Mineral Sciences Laboratory, CANMET (MSL-S-75-5079).

Table 2. Results of tests in sea water.

Test Location	Immersion Time, Days	Alloys	Specimen Number	Weight Loss, mg/cm^2	Average Penetration, µm	Maximum Penetration Measured, µm	
						In pits	At crevices
Musquash Harbour, N.B.							
4.5 m depth	195	Stelcoloy G.P.	1	99.4	125	500	970
	"	" (U-added)	2	187	240	-	1130
13.7 m depth	"	Stelcoloy G.P.	3	225	290	750	760
	"	" (U-added)	4	194	245	-	650
d'Iberville Fiord, N.W.T.							
	82	G40.8 Grade B	1	11.0	13.9	-	-
	"	"	2	11.7	14.8	-	-
	"	"	3	10.0	12.7	-	-
	"	"	4	11.5	14.6	-	-
Halifax Harbour, N.S.	107	G40.8 Grade B	2	92.6	118	-	-
	82	"	3	27.3	34.7	-	-
	107	"	4	42.6	54.2	-	-
Devon Island, N.W.T.	355	G40.8 Grade B	A	71.8	93	150	-
	"	"	B	63.1	81	165	-
	"	"	D	67.1	86	175	-

Table 3. Results of atmospheric corrosion tests at Tuktoyaktuk, N.W.T.

Alloy	Specimen Number	Years on Test	Weight Loss, mg/cm^2	Average Penetration, μm	Corrosion Rate, μm/yr	
					0-1 yr	1-3 yr
G40.8 Grade B	003-04-2	1	12.7	16.2	16.2(0.64 mils/yr)	1.6(0.06 mils/yr)
" "	003-02-2	3	15.0	19.3		
Stelcoloy S	001-03-2	1	12.0	15.3	15.3(0.60 mils/yr)	1.9(0.07 mils/yr)
"	001-01-2	3	14.8	19.0		
Stelcoloy G	002-01-2	1	12.9	16.4	16.4(0.65 mils/yr)	1.8(0.07 mils/yr)
"	002-04-2	3	15.5	19.9		

Table 4. Corrosion rates and maximum penetration rates in sea-water tests.

Test Location	Specimen No. and Days of Immersion	Corrosion Rate, µm/yr	Maximum Penetration Rate Measured, µm/yr	
			In pits	In crevices
Musquash Harbour, N.B.				
4.5 in depth	1 (195)	234 (9.2 mils/yr)	936 (36.8 mils/yr)	1816 (71.5 mils/yr)
	2 (195)	449 (17.7 ")	-	2115 (83.3 ")
13.7 " "	3 (195)	543 (21.4 ")	1404 (55.3 ")	1423 (56.0 ")
	4 (195)	459 (18.1 ")	-	1217 (47.9 ")
d'Iberville Fiord, N.W.T.	1 (82)	62 (2.4 mils/yr)	-	-
	2 (82)	66 (2.6 ")	-	-
	3 (82)	57 (2.2 ")	-	-
	4 (82)	65 (2.6 ")	-	-
Halifax Harbour, N.S.	2 (107)	403 (15.8 mils/yr)	-	-
	3 (82)	154 (6.1 ")	-	-
	4 (107)	185 (7.3 ")	-	-
Devon Island, N.W.T.	A (355)	96 (3.8 mils/yr)	154 (6.1 mils/yr)	-
	B (355)	83 (3.3 ")	170 (6.7 ")	-
	D (355)	88 (3.5 ")	180 (7.1 ")	-

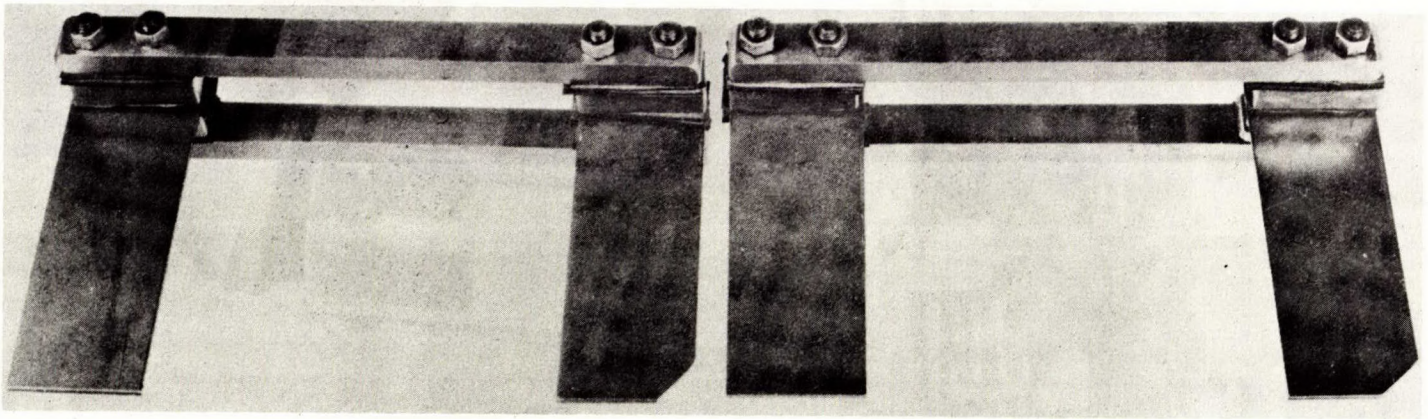


Fig. 1. Specimens in racks prior to sea-water test at Musquash Harbour, N.B.
X 1/3

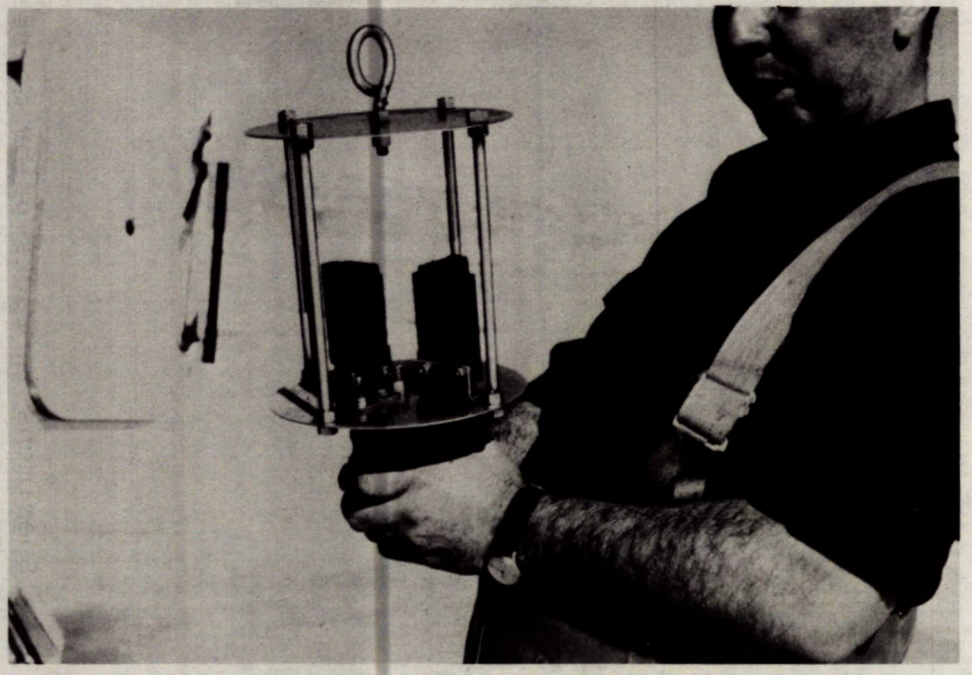


Fig. 2. Recovery of specimens at d'Iberville Fiord:
(a) drilling a hole through the ice;
(b) specimen rack.
(Photographs supplied by R.A. Lake of Environment Canada).

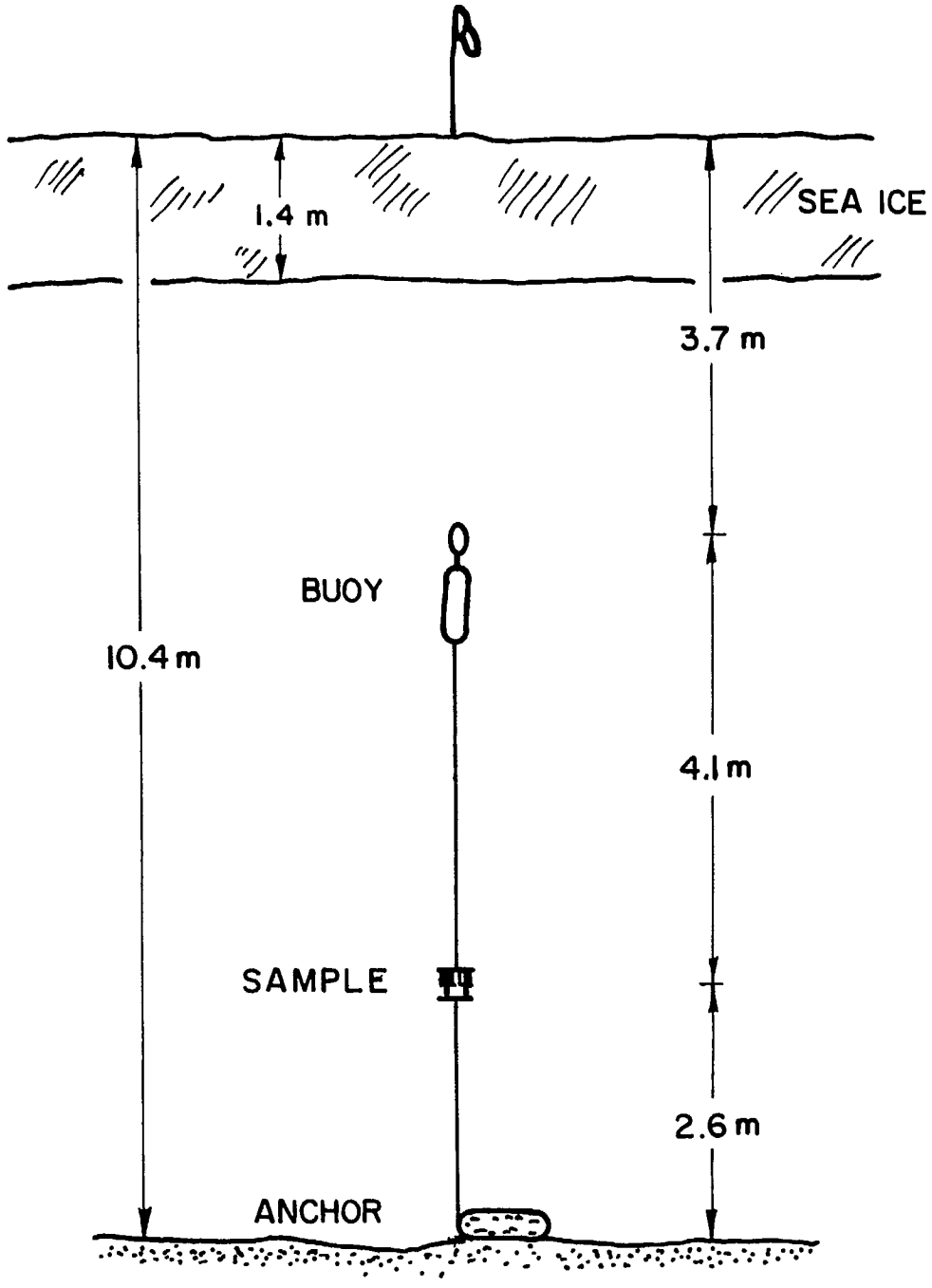


Fig. 3. Sketch showing method used to moor specimens at d'Iberville Fiord (supplied by R.A. Lake of Environment Canada).

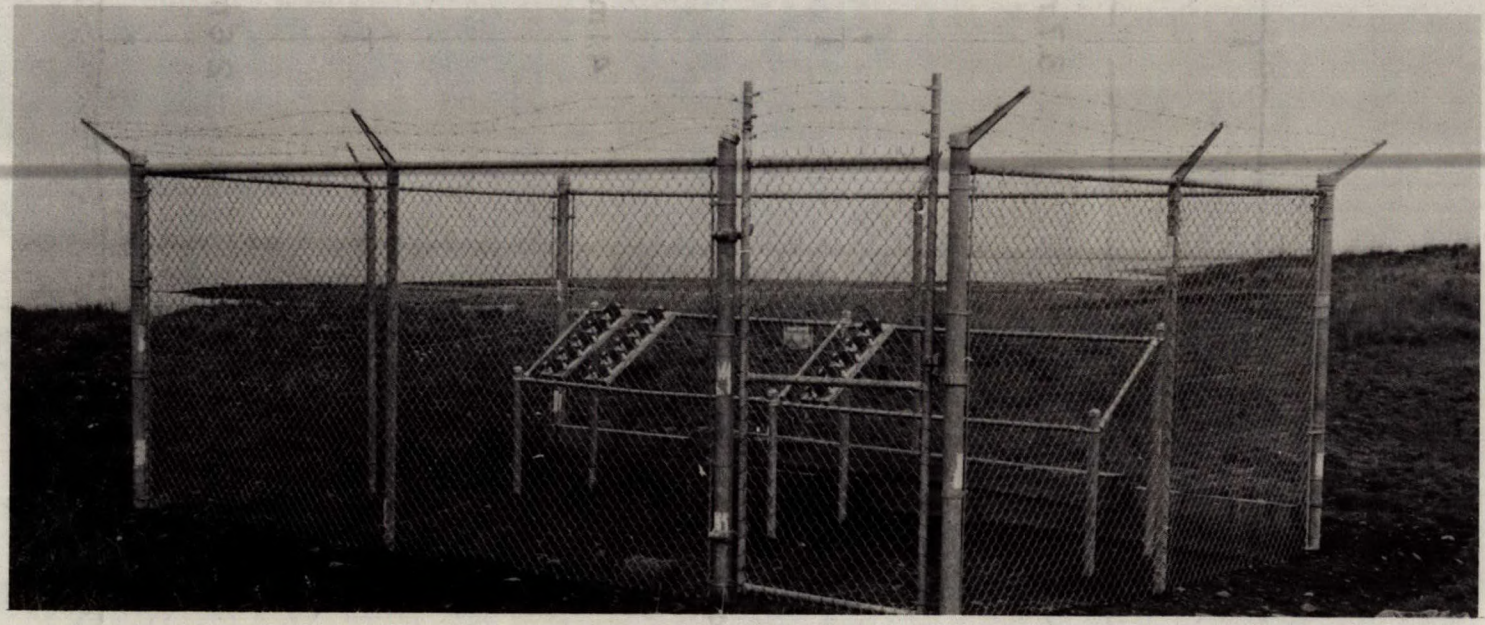
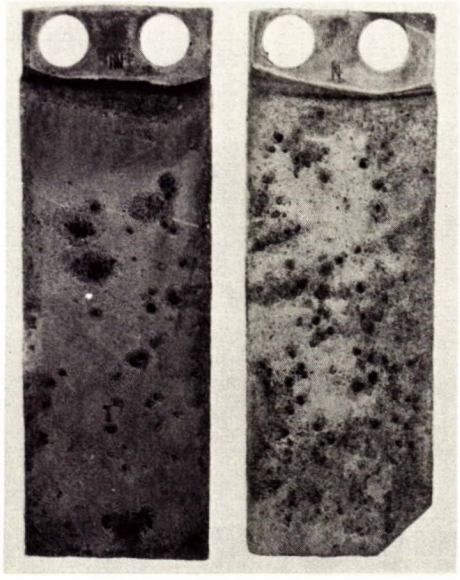
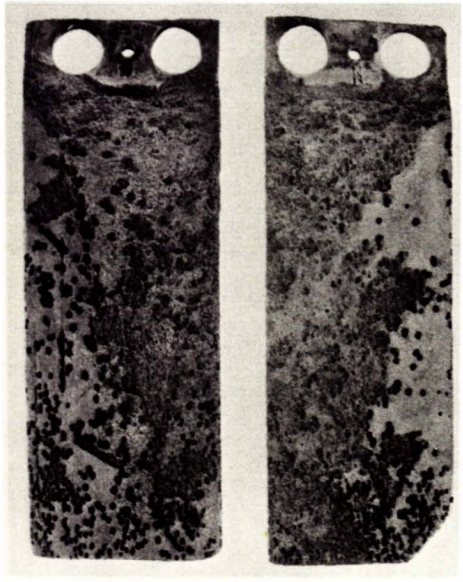


Fig. 4. Atmospheric testing station at Tuktoyaktuk, N.W.T., July 1973.



(a)



(b)

Fig. 5. De-rusted specimens after 195-day test at Musquash Harbour, N.B.
(a) specimens at 4.5-m depth;
(b) specimens at 13.7-m depth. X 1/2

Fig. 6. Edge view of specimen 4 after immersion in d'Iberville Fiord for 82 days, showing $CaCO_3$ deposits. X2

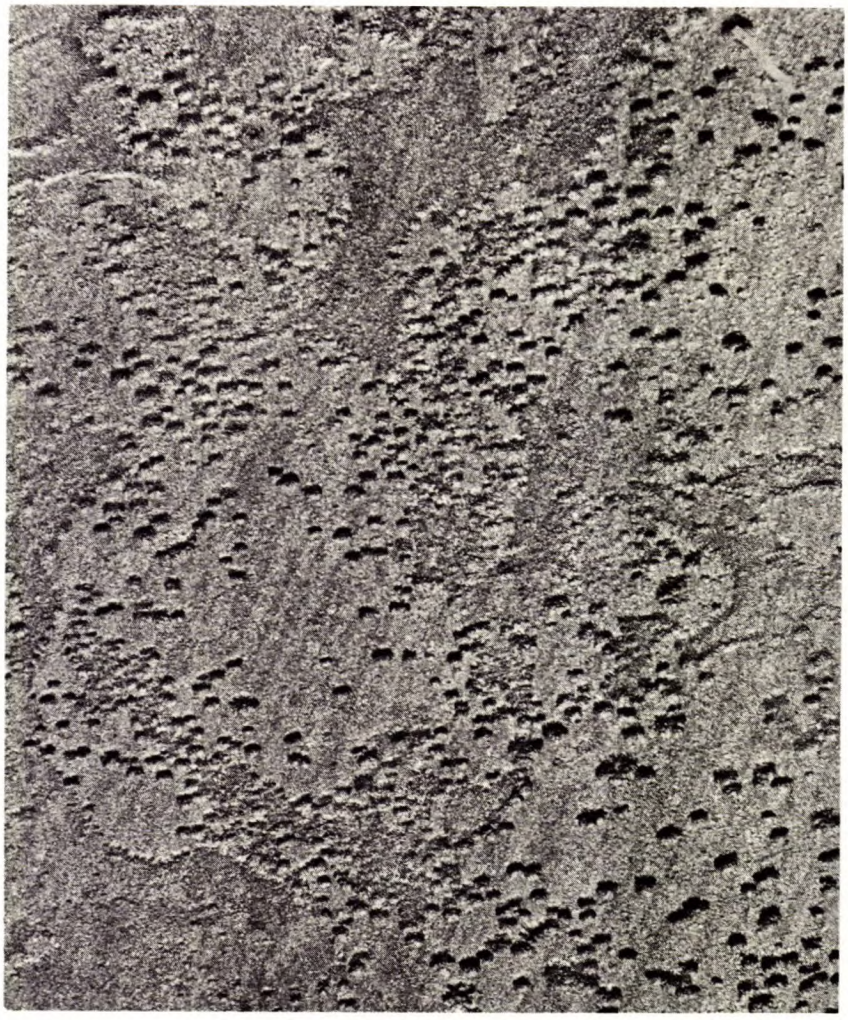


Fig. 7. Surface of specimen 2, after immersion for 107 days in Halifax Harbour, showing corrosion pits. Because of an optical illusion, these may appear either as depressions (correct) or protuberances. X3

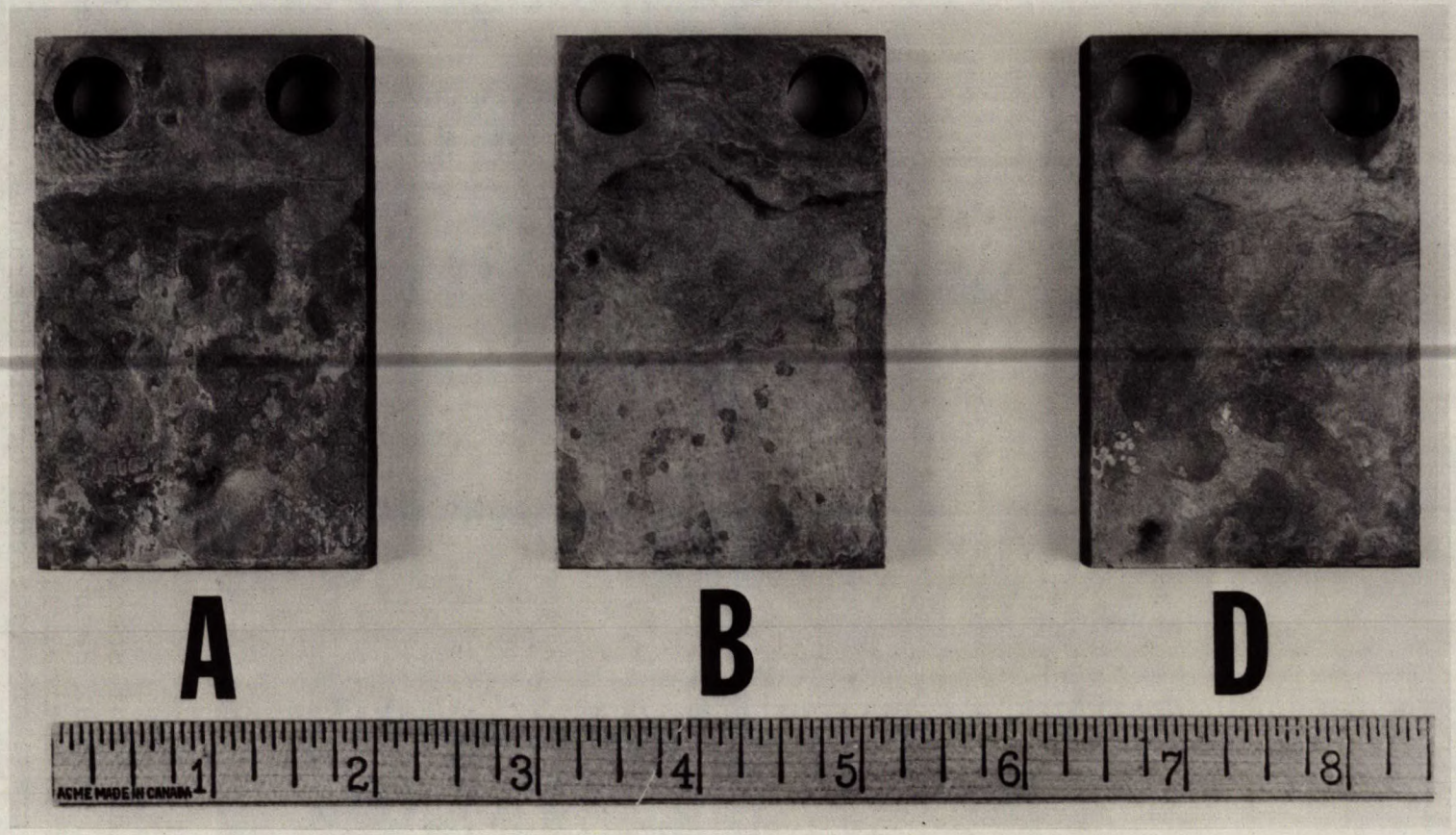


Fig. 8. De-rusted specimens after 1 year in sea water at Devon Island, N.W.T.

Fig. 9. Specimens of structural steel after one-year's exposure at Tuktoyaktuk, N.W.T.

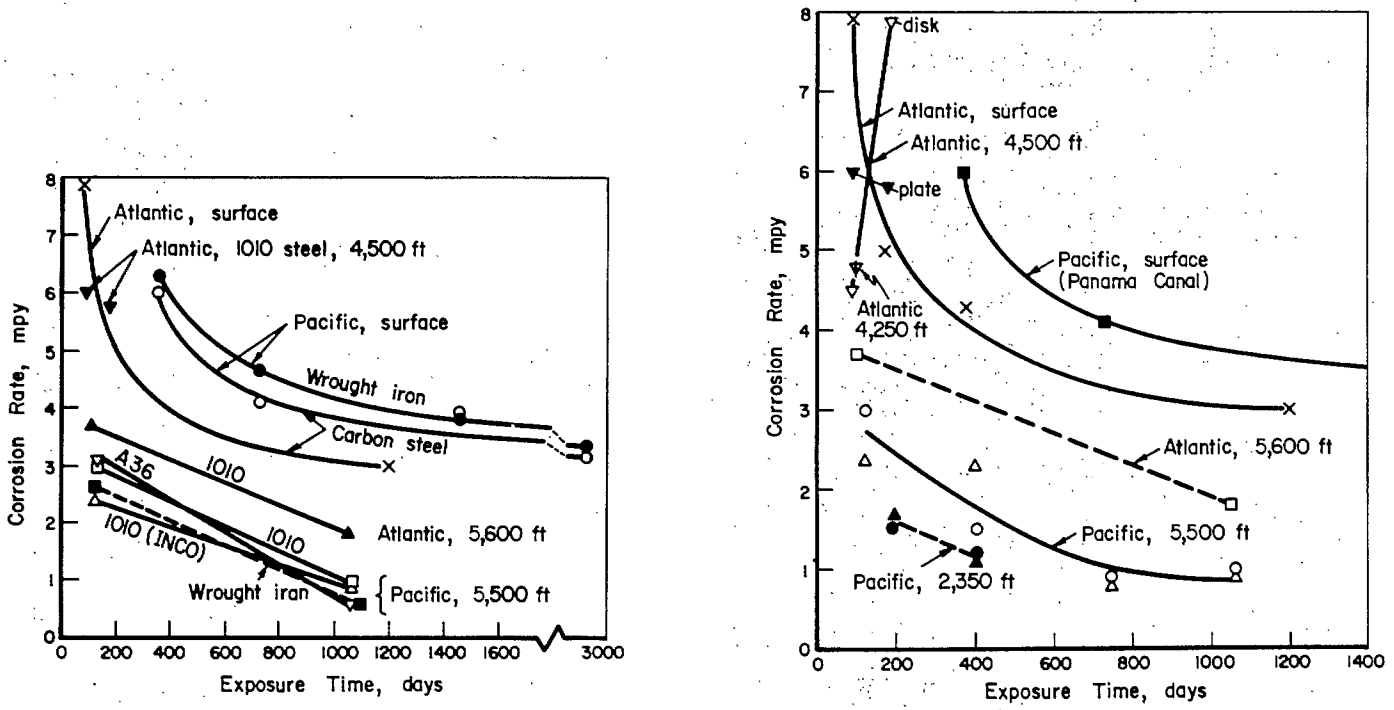


Fig. 10. Figures extracted from reference (1), showing sea-water corrosion rates as a function of exposure time (1 mil = 25.4 μm).

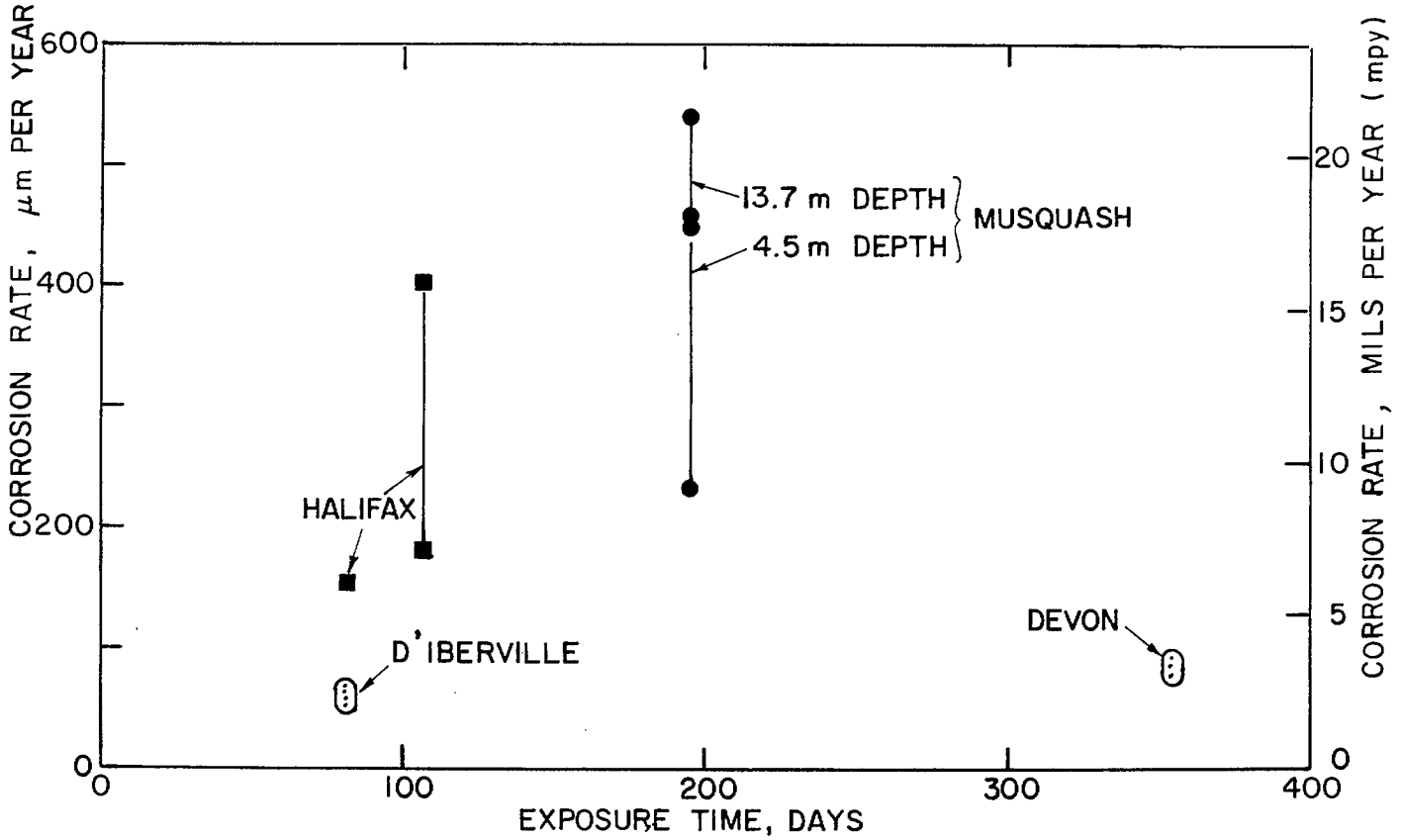


Fig. 11. Average corrosion rates of carbon and alloy steels in the sea-water tests.

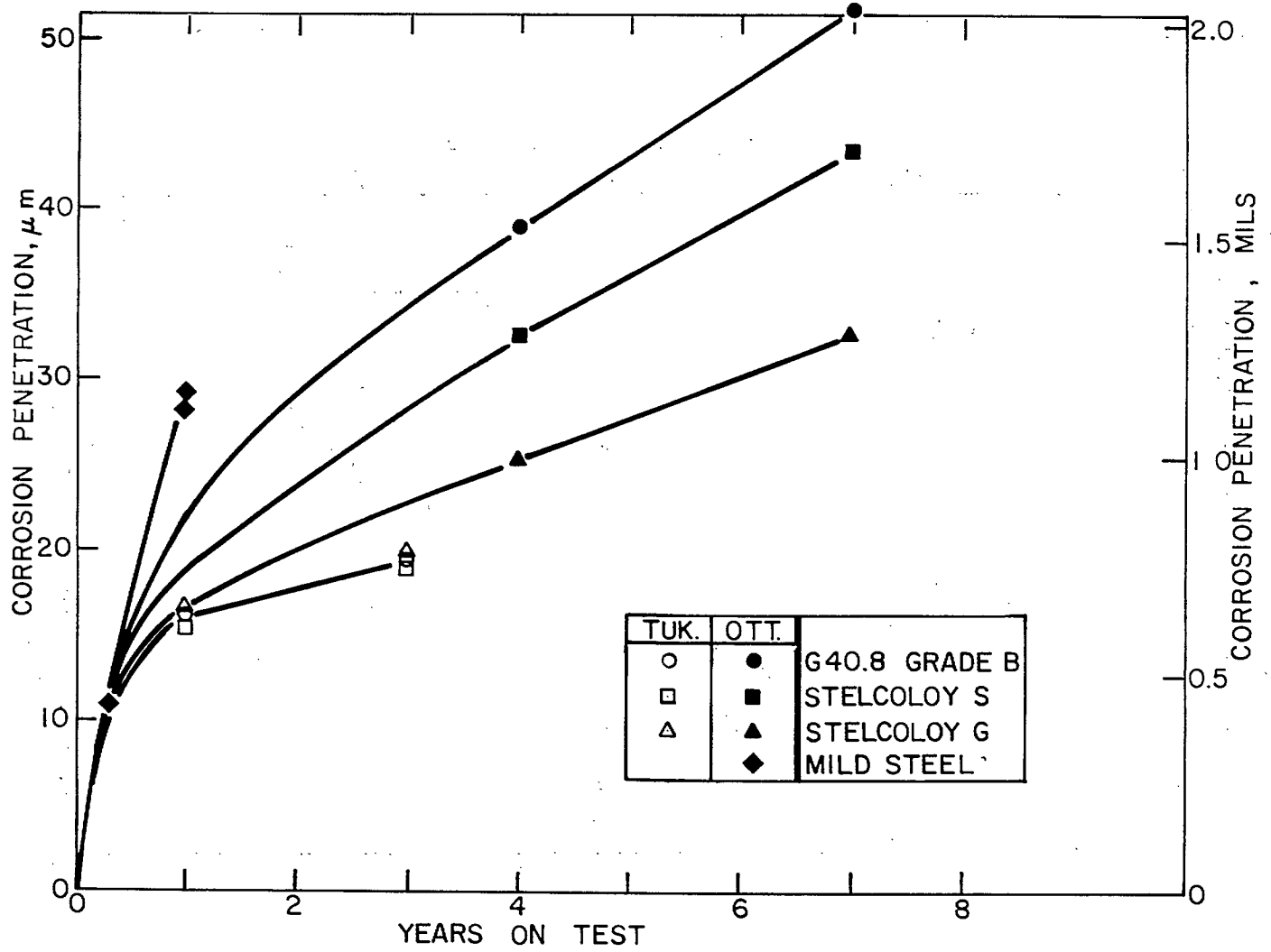


Fig. 12. Atmospheric corrosion behaviour of steels at Tuktoyaktuk, N.W.T., and Ottawa, Ontario.

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