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ABSTRACT

A series of exposure trials has been conducted to characterise the corrosivity of the atmosphere at 16 Defence bases in Eastern and Northern Australia. Atmospheric corrosivity was assessed by measuring the corrosion rates of specimens of steel, zinc and two high strength aluminium alloys when exposed on racks in the open air for periods of one to four years during the period 1988 to 1993.

The results are presented in summary in Tables 12 and 13 which list the bases in increasing order of severity of atmospheric corrosion, and group them into atmospheric corrosivity categories (low to very high) according to the International Standard, ISO 9223: 1992(E), to enable a direct comparison with world standards.

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Atmospheric Corrosivity of Defence Bases in Northern and Eastern Australia

Executive Summary

Only limited quantitative information is available regarding the corrosivity of environments at Defence bases around Australia, particularly in the tropical north where higher humidity and temperature can exacerbate corrosion. This study examined the environment at 16 Defence bases in Eastern and Northern Australia which were chosen because they provided an extensive range of atmospheric conditions.

Atmospheric corrosivity was assessed by measuring the corrosion rates of steel and zinc specimens (standard reference materials) and two aluminium aircraft alloys which were chosen specifically to address the needs of the RAAF. The specimens were exposed in the open for from one to four years. The findings have enabled bases to be assembled in order of severity of atmospheric corrosion. Bases are also grouped in atmospheric corrosivity categories (low to very high) in accordance with the International Standard.

RAAF Tindal's environment was found to be the least corrosive while at the other end of the scale RAAF Williamtown, Cocos Islands and Cowley Beach (AMRL-Queensland) were consistently the three most corrosive sites.

These results will provide essential guidance for the selection of adequate protective measures for materiel in use or storage at the various Defence bases and allow decisions on material selection to be made on a rational basis.

Contents

1. Introduction

Little information is available regarding the corrosivity of the environments at the many Defence bases around Australia. While the Bureau of Meteorology has recorded for many years the traditional rainfall, wind and temperature data, these are of limited use for the prediction of atmospheric corrosivity. Other variables such as salinity, sulphur dioxide content, humidity, specimen orientation and time of wetness of the surface also affect the rate of the corrosion process. Over many years reliable methods for measuring and recording these parameters have been developed and attempts have then been made to use such data to characterise or calibrate atmospheres. Notable among these are several of the papers collected in the ASTM Special Technical Publications STP 435 (1968), STP 767 (1982) and STP 965 (1987). The complexity of accurate prediction of the corrosivity of atmospheres is emphasised in these publications which review many variables in the quest to find a suitable model for predicting corrosivity, so far not entirely successfully. It is, therefore, still appropriate and cost-effective to expose metal specimens directly to the environment of interest and calculate corrosion rate from weight loss over a known time. This is particularly so when information is required from remote areas where the necessary skilled support for other measurements is not available.

The current project was undertaken on this basis with the aim of providing quantitative information on the severity of atmospheric corrosion at a number of Defence Base locations, particularly those in Australia's tropical north. From the data base derived from this study it will be possible to assess the stringency of corrosion preventive measures required to protect equipment installed at particular locations. This should lead to improved management of maintenance schedules for Defence materiel and also cost benefits, in that the complexity of anticorrosive treatment applied may then be tailored to suit the intended service environment.

The procedure was based on the BISRA method[1] and was similar to that used in studies by King and others at CSIRO, Melbourne[2-5]. Zinc and copper-containing steel were chosen because they are the standard materials commonly used to characterise atmospheric corrosivity and would therefore allow comparison of these results with other surveys conducted both within Australia and also in other countries (e.g. Coburn et al[6] used steel and zinc to study the atmospheric corrosivity of 46 sites world wide; Kucera et al[7] conducted similar tests at 32 Scandinavian sites). An advantage in using copper-containing steel is that, although its corrosion rate is somewhat lower than that of normal mild steel, it is more uniform and relatively insensitive to small variations in composition[8].

To relate this survey more closely to the needs of RAAF, two aluminium aircraft alloys were also included in the programme. These alloys were exposed in the unclad form to enable assessment of the corrosion sensitivities of the structural materials rather than the cladding, although it is acknowledged that in practice the alloys are always used in a clad form.

Vertical panel orientation was chosen as it permitted direct comparison of this survey with the other Australian surveys noted above. An added advantage for this orientation is that past workers[9] have found it to be the most sensitive to climatic conditions in that it causes consistently higher weight losses than angled orientations (about 20% higher for steel).

To fully utilize the opportunity offered by this project several other materials were included. These were electroplated coatings of zinc and zinc-nickel on steel, aircraft paints on aluminium, ion vapour deposited coatings on steel, and lap-shear adhesive joints in aluminium, Plexiglas 55 and Plexiglas 201. In all, ten different materials were exposed for up to four years each. However, only four - steel, zinc and the two unclad aluminium alloys - had direct relevance to the corrosivity assessment and these four are the subject of this report.

The performance of other materials exposed will be reported separately.

2. Experimental Method

2.1 General Description

Sixteen ADF sites were chosen for this survey. They ranged from major RAAF bases on Australia's east coast to a remote Defence exercise area in the north-west (Figure 1). The sites are described in more detail in Table 1, where, as noted below, they are listed in anticlockwise order from south to north-west.

All the corrosion test panels were mounted vertically on racks consisting of a single galvanized steel post with tubular galvanized steel cross arms (Figure 2). Brackets held the arms at different distances out from the post (the lowest being furthest out) so that no panels were mounted directly beneath others.

At each site, one rack was erected in an open area with its post embedded firmly in the ground and oriented such that the test panels faced north (Figure 3).

Duplicate panels of each material were exposed for each time period. Assessment of corrosion rate was by weight loss, this being obtained by cleaning and weighing the panels both before and after exposure.

Table 1. Exposure site locations

LOCATION	CODE LETTER	CLIMATE	RAINFALL		SOUTH LATITUDE	DIST. TO COAST km	TYPE OF COAST
			AVERAGE ANNUAL mm	DISTRIBUTION			
Laverton	V	Temperate	570	uniform	37° 53′	5	Bay
Maribyrnong	H	"	570	uniform	37° 00′	11	Bay
Williamtown	W	Temperate, marine	1,150	uniform	32° 48′	4	Ocean
Amberley	A	Subtropical, inland	890	summer	27° 38′	75	-
Townsville	O	Tropical, marine	1,200	summer	19° 15′	3	Ocean
Innisfail - Hot Wet Cleared	IC	Tropical	3,460	summer	17° 32′	10	Ocean
Innisfail - Cowley Beach	IB	Tropical, marine	3,460	summer	17° 32′	0.05	Ocean
Weipa	E	"	1,990	summer	12° 38′	2	Inlet
Gove	G	Tropical	1,360	summer	12° 15′	11	Ocean
Darwin	D	"	1,600	summer	12° 26′	5	Ocean
Tindal	T	Tropical, inland	910	summer	14° 27′	280	-
Mt Goodwin	M	Tropical	1,460	summer	14° 14′	10	Inlet
Curtin (South Derby)	S	Tropical, inland	550	summer	17° 40′	30	Gulf
Port Hedland	P	Subtropical, dry	310	summer	20° 23′	8	Ocean
Learmonth	L	Subtropical, dry, marine	400	variable	21° 48′	3	Gulf
Cocos Islands	C	Tropical, marine	2,000	summer *	12° 12′	0.05	Ocean

* longer than summer

2.2 Organisation of the Trial

Exposure racks and panels were installed at the two Innisfail sites, the RAAF Base Townsville, the RAAF Base Laverton, AMRL-Maribyrnong and the Cocos Islands by various AMRL staff members visiting the sites.

Exposure racks and panels were installed at the other ten sites by staff from AMRL-Melbourne during a RAAF flight anticlockwise round Australia from Melbourne to Learmonth in the first week of November, 1988.

Each year at the appropriate time a small number of new panels was sent to each site with a request for trained personnel to remove specific panels and install the replacements. Only two errors in panel handling occurred over the entire program.

Exposed panels were returned to AMRL, chemically cleaned, weighed, examined and then stored.

2.3 Materials Exposed

The materials described below were exposed at all sites. Their chemical compositions are listed in Table 2.

(a) hot rolled copper-bearing steel sheet, 3.5 mm thick, from BHP-MRL,
(b) zinc alloy sheet, 3 mm thick, from F.H. Booth, Sydney,
(c) aluminium-lithium alloy 2090-T8E41 (unclad) sheet, 1.6 mm thick, source as above.
(d) aluminium alloy 7075-T6 (unclad) sheet, 1.6 mm thick, from Alcoa through G.H. Jackson, Melbourne.

The first two materials above were used to enable comparison of the results with those of other corrosivity surveys. The zinc alloy sheet was used because no supplier of pure (99.9%) zinc sheet could be found and the aluminium alloys were used to compare the corrosion resistance of the newer aluminium-lithium alloy with the widely used 7075 alloy in service environments.

Table 2. Composition of exposed materials

(a) Copper-bearing Steel

C	Si	Mn	Cu	Ni	Cr	P	S	Mo	Other
0.11	0.08	0.61	0.24	0.26	0.11	0.012	0.024	< 0.01	< 0.01

(b) Zinc

Cu	Ti	Fe	Zn
0.14	0.11	0.02	Rem.

(c) Aluminium Alloys

		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Li	Other	
												each	total
Alloy 2090 - T8E41	max.	0.10	0.12	3.0	0.05	0.25	0.05	0.10	0.15	0.15	2.6	0.05	0.15
	min.			2.4						0.08	1.9		
Alloy 7075 - T6	max.	0.40	0.50	2.00	0.30	2.90	0.28	6.10	0.20	-	-	0.05	0.15
	min.			1.20		2.10	0.18	5.10					

2.4 Specimen Preparation

Exposure panels (100 x 50 mm) were guillotined from sheet stock. Edges were abraded to remove burrs and sharp corners and a mounting hole was drilled in the centre to accommodate the Delrin spacer and stainless steel mounting screw. Each panel was stamped for identification purposes.

Surfaces of the steel panels were prepared by pickling for half to one hour in 5 vol% hydrochloric acid at 80 - 100°C to remove the hot rolling scale, followed by scrubbing with a bristle brush in hot running water, rinsing in ethanol and drying in a warm air stream. The zinc and aluminium panels were degreased in trichloroethylene, then swabbed twice with cotton wool soaked in acetone.

All panels were wrapped in tissue paper and stored in desiccators. Shortly before groups of panels were required for exposure they were given a final solvent rinse (or brief pickle, in the case of steel) and were then weighed.

2.5 Method of Attachment

The method of attaching test panels to the arms of the rack is shown in Figure 4. A stainless steel screw was inserted through a hole drilled in the centre of the panel and attached to the arm with a 'Nylock' self-locking nut. A Delrin polymer spacer and a fibre washer insulated the test panel from the arm and the mounting screw. The Delrin spacers performed excellently, but the fibre washers only just survived the longest exposure periods.

2.6 Exposure Times

Duplicate panels of each metal were exposed for 1 year, 3 years and 4 years. A one-year exposure was conducted during each of the 4 years of the program.

Except for those at Townsville, Innisfail and Cocos Islands, all initial exposures commenced in the first week of November, 1988. Townsville and Innisfail exposures commenced one month later in the first week of December, 1988, while Cocos Islands exposures began in July, 1989. All further panel changes at the respective sites were carried out at these times of year.

2.7 Post-exposure Treatment of Panels

Returned panels underwent chemical treatment to remove corrosion products. A specific procedure was chosen for each metal after preliminary experiments to determine efficiency in removing corrosion products. The methods used are listed in Table 3, together with the immersion time and the number of successive treatments needed to completely remove the corrosion products. Average blank losses were determined by treating unexposed panels to the same pickling conditions. Blank losses were subtracted from measured weight losses to obtain final corrected weight losses which were then converted into corrosion rates expressed as micrometers of surface penetration per year.

Table 3. Chemical cleaning treatments

METAL	CHEMICAL SOLUTION	TEMP. ^0C	TIME minutes	NUMBER OF TREATMENTS	BLANK LOSS mg/pickle
Steel	Clarke's solution: conc. HCl + 55 g/l $SnCl_2$ + 22.5 g/l Sb_2O_3, stirred.	Room	15	2-4*	20
Zinc	10% glacial acetic acid	Room	1	2-3	3
Al 2090 - T8E41	20 g/l CrO_3 + 50 ml/l conc. H_3PO_4	80	10	2-3	First: 24 Others: 3
Al 7075 - T6	As for Al 2090 above	80	10	2-3	2

* The number of pickles required depended on the severity of corrosion.

Final treatments for the panels after pickling were:

1. Steel: scrubbed with a firm bristle brush in hot water, rinsed in ethanol, dried in a hot air stream. (While the blank loss for steel was greater than for the other metals, its proportion to the total weight loss was not very different.)
2. Zinc: scrubbed with a soft bristle brush while in the pickle, then washed in warm water, rinsed in ethanol, dried in a warm air stream.
3. Al 2090: washed in hot water with a light rub to remove smut, rinsed with ethanol and dried in a warm air stream. It was found that the initial pickle on unexposed panels resulted in an average weight loss of 24 mg due to the removal of a thick factory-formed oxide film; subsequent pickles caused only a 3 mg loss. This was allowed for in calculating the weight losses, as indicated in the table above.
4. Al 7075: washed in hot water with a light rub to remove smut, rinsed with ethanol and dried in a warm air stream.

3. Results

The weight losses for all exposure panels are given in Tables 4 - 7. It can be seen that weight losses for duplicates were generally in very good agreement, although with the aluminium-lithium alloy panels there were a number of exceptions. For the one year exposures at each site, annual variations in weight loss indicated that the atmospheric corrosivity often varied considerably. However, examination of available climatic data[10] for the period of the exposure trial failed to reveal any conclusive correlation with corrosion rates. This is a common outcome with exposure testing and has resulted in considerable effort being expended internationally in attempts to more positively define and measure the relevant climatic variables[11].

Corrosion rates, calculated from the weight loss data, are shown in Tables 8-11. The values are the average of two panels per site, except for the 1 year averages which are the mean of eight panels per site - two panels per year for each of the four years. Figures 5 - 8 provide a graphical representation of the average corrosion rates of each of the four metals after 1, 3 and 4 year exposures (the data from Tables 8 - 11). It can be seen that, in general, the corrosion rate slows as the period of exposure lengthens. This is normal behaviour for most metals and is a result of the thickening of surface oxide films on the metal surfaces exerting a controlling influence on the diffusion of reactants between the atmosphere and the metal surface. Zinc is sometimes considered an exception, as some researchers have reported an almost linear time/corrosion relationship for this metal (see below under '*Zinc*').

Dust coloured the white corrosion products on zinc and aluminium panels at some of the more arid sites, particularly Port Hedland. Where prevailing weather conditions were directionally biased, corrosion tended to be more severe on one surface than another. This was particularly noticable at Innisfail's Cowley Beach and at Port Hedland.

The following comments are specific to the individual metals.

3.1 Copper-Steel

The appearance of the rust on the specimens varied: although it was always a mixture of glossy dark brown nodules and lighter orange coloured spots, there was a definite trend to lighter coloured rust on 1 year panels and where corrosion rates were lowest (Figure 12). Thicker, somewhat flaky, dark brown rust was dominant after longer exposures and at sites of high corrosion rate (Figure 13). After cleaning, some end grain corrosion was observed at edges when corrosion had been severe, but otherwise corrosion was reasonably uniform without significant pitting. Testing for retained chlorides in corrosion products from panels exposed at marine locations detected only traces, even on panels from the most severe sites at Cowley Beach and Cocos Islands. The experience of Raman[12] was similar - he detected less than 10 ppm of chloride in rust from steel bridges on the Gulf of Mexico. It is presumed that in these regions deposited chloride is periodically leached out by rain.

Corrosion rates for copper-steel determined in this study (Figure 5) fall within the broad range of rates for steels found elsewhere over many years. Copper-steels and other low alloy steels generally have lower corrosion rates than carbon structural steels in any given environment[13-15], the type used in this exercise being considered to corrode at about half the rate of structural steel.

Duplication was very good, in that more than 90% of duplicate pairs had weight loss differences well within 10% of each other (87 of 96 pairs).

Variation in corrosion rate from year to year was considerable at some sites, particularly Cocos Is, South Derby (Curtin), Cowley Beach, Innisfail-HWC, Tindal and Weipa. There seems to be no geographical correlation linking this group. At Innisfail-HWC and Weipa, results for three years were almost identical but one year was exceptional. As noted previously, a scan of Bureau of Meteorology annual records showed no obvious correlations.

At all sites the 3 and 4 year corrosion rates were considerably lower than the average of the 1 year rates, indicating a slowing of the corrosion rate with time. This is the normal behaviour of steel in atmospheric exposure situations. Over the sixteen sites the annual corrosion rate during 4 years of exposure was, on average, only 59% of the rate for the single year exposures. The two beach sites - Cocos Is and Cowley Beach - were exceptional in that the 4 year rates at these sites were close to 80% of the 1 year rates, an indication of the severity of wind, sand and salt spray conditions at these locations.

3.2 Zinc

The corrosion rates for zinc are shown in Figure 6 and are comparable to those found by other workers for similar climatic conditions. As can be seen in the comparison chart of Figure 9, zinc corroded far more slowly than steel in the various locations. Typical panels are shown in Figures 14 and 15. Note the staining by red dust at Port Hedland and the effect of prevailing wind direction at Cowley Beach.

Duplication of results was generally quite good, particularly for the longer exposures where weight losses were higher. Panel surfaces dulled to varying degrees but were often still quite bright after 1 year of exposure in the less corrosive environments. Corrosion occurred as a very fine pattern of tiny pits scattered fairly evenly over the surfaces, the density of the pattern being proportional to the corrosivity of the atmosphere. Mild crevice corrosion occurred under the fibre washer but not under the Delrin spacer. There were no unusual edge effects.

Unlike the other metals, chloride was easily detected in the corrosion products of all zinc panels exposed to coastal environments. It would appear that sea salts are more readily absorbed and retained in the zinc corrosion products (mainly basic zinc carbonate) than in those of the other metals.

It is commonly considered that the corrosion rate of zinc is nearly independent of time of exposure[16], i.e. that its average corrosion rate over 3, 4 or more years will be similar to its corrosion rate over one year, in contrast to that of steel. This is true of two locations (Laverton and Amberley) in this study; however, it can be seen in Figure 6 that for the remainder of the sites the corrosion rates over the longer periods are often similar, but are significantly less than the one year results. For example the 4 year rates are on average only 77 % of the corresponding 1 year rate.

3.3 Aluminium Alloy 2090

The corrosion rates for alloy 2090 are shown in Figure 7. In contrast to the other alloys, the longest exposure periods did not always produce the lowest corrosion rates (for example, see Cocos Is results). Corrosion at all sites was much more severe than for alloy 7075, as shown in Figures 10 and 11, and considerably higher than the rate for zinc at most locations. Typical panels from mild and severe sites are shown respectively in Figures 16 and 17.

Duplication of results was very poor with this alloy; quite large variations in weight loss were frequently observed and a few very large variations occurred from one year to the next. The effects could not be correlated with exposure time, geography or climate of locations. Nor, considering the more typical behaviour of the other alloys, could rack position or micro-weather variations be considered responsible.

Before cleaning, the panels had areas of surface covered with white corrosion products and other areas little affected. The thickness of the corrosion product and the area of surface covered were in proportion to the severity of the environment. On one year panels from the less corrosive sites there were indications of filiform corrosion beneath the surface oxide film, but on more severely corroded panels the effect was obscured by thicker corrosion products. The difference in appearance between short and long term exposure was marked, as illustrated in Figure 18. Corrosion was more severe in marine than in humid atmospheres. Crevice corrosion occurred beneath the fibre washer on most panels and was usually somewhat more severe than corrosion on the main surface, but did not significantly affect results. The appearance of this alloy was much worse than that of the 7075 alloy. The weight losses and calculated corrosion rates confirmed this observation.

After the removal of corrosion products clusters of shallow pits could be observed which, on most panels, had broadened into areas of intergranular corrosion. This was detected in the surface layers in the form of exfoliation and tiny blisters. In no instance, however, was attack found to have penetrated deeply, even at the most severe sites;

nor was there any evidence of stress corrosion cracking as found in the 7075 alloy. It is possible that the surface exfoliation was the reason for the variability in weight losses noted above as, even after cleaning, flakes of loosely attached metal were visible on many of the panels, particularly those more severely corroded. The maximum depth of corrosion on these panels was 50 μm on the main surfaces and 100 μm at edges.

The predominant anions of sea water (chloride and sulphate) were detectable in trace quantities in the corrosion products, but only on panels from the most severe marine sites.

3.4 Aluminium Alloy 7075

Duplication of results was generally very good, although not as consistent as for steel. Corrosion was mild compared to that on the 2090 alloy panels, with shallow microscopic pitting being the dominant form. Typical exposed panels from mild and severe environments are shown in Figures 19 and 20. Surface blistering and exfoliation did not occur on this alloy. Marine atmospheres caused the most severe attack but, except in one or two instances, sea salt anions could not be detected in the corrosion products of this alloy.

Crevice corrosion under the fibre washers was a little worse than general surface corrosion, and edge corrosion appeared more pronounced. Corrosion rates (Figure 8) were the lowest of the four alloys exposed, and much lower than those for the 2090 alloy (Figures 10 and 11).

Generally the longer the exposure time, the lower the corrosion rate, but there were a few exceptions as can be seen in Figure 8. Intergranular stress corrosion cracking was detected on edges of some of the most severely corroded panels, with very fine cracks penetrating to a maximum measured depth of 1.5 mm after 3 year's exposure.

4. Discussion

This exercise aimed to rank the sites in order of corrosivity as judged by the corrosion rate of steel and zinc. This method has been used widely and allows reasonable comparisons to be made between locations in various countries. Certainly, within Australia, sites can be compared directly with the well documented AMRL sites at Innisfail where steel and zinc corrosivity, and climatic data have been continuously recorded for many years[17].

Table 12 ranks the present sites in ascending order of the average one year corrosion rates of steel and zinc (i.e. from mildest to most severe) and groups them into internationally recognised general classifications. These are defined in International Standard ISO 9223[18] and are based on the corrosion rates of metals exposed to the atmosphere for one year. There are five corrosivity categories from Very Low (C1) to Very High (C5) and a corrosion rate range is defined for each metal in each category. The metals considered in the Standard are unalloyed carbon-steel, zinc (98.5% min.), copper (99.5% min.) and aluminium (99.5% min.). As noted earlier, the copper-steel used in the present work corrodes at only about half the rate of the carbon-steel quoted in the Standard. It has therefore been necessary to adjust the corrosion rate ranges of the corrosivity categories for steel in Table 12 to permit comparison.

A similar table (Table 13) can be constructed for the two aluminium alloys, although the Standard uses commercially pure aluminium to set its corrosion ratings. In this instance, as the data on comparable corrosion rates between commercial aluminium and the two exposed alloys are much less precise than for the steels, the corrosivity category ranges of the Standard have not been changed. Hence the ratings given to alloys 7075 and 2090 are relative to the corrosion rate of commercially pure aluminium. For this reason, the corrosion rate of the corrosion-prone aluminium-lithium alloy reaches the "Extreme" category in the most severe environments, showing that it is a particularly sensitive material.

The Relative Corrosivity column of each Table has been derived by dividing one-year corrosion rates by the lowest rate for that metal (and rounding to the nearest half). This shows the corrosion rate at each site as a multiple of the corrosion rate at the least corrosive site, perhaps the easiest way to visualise the differences between sites.

The order of the sites in the Relative Corrosivity column differs a little in detail but is otherwise similar for all metals. It can be seen that the highest corrosion rates occurred at the sites where the marine influence was greatest, because of either close proximity to the shore (Cocos Is, Cowley Beach) or favorable prevailing wind conditions continuously bringing salt mist from the ocean (Williamtown). (There was no significant industrial influence at any of the sites in this programme). The lowest corrosion rates, on the other hand, were at two of the sites which were in hot climates and farthest from the sea (Tindal and Curtin).

5. Conclusions

1. The corrosivities of 16 Defence locations in eastern and northern Australia ranged from 'low' to 'high' (2 to 4 on a scale of 1 - 5), based on the classifications of International Standard ISO 9223:1992(E) and using the corrosion rates of steel and zinc over a four year period as the measuring standard.
2. Locations where there was a strong marine influence were the most corrosive. The most important of these from the RAAF point of view was Williamtown, which, although in a temperate climate, matched the severe tropical sites for intensity of corrosion.

3. Locations with the lowest corrosivities were distant from marine influences but varied in climate from temperate (e.g. Laverton) to tropical (e.g. Tindal).

4. Two aluminium aircraft alloys (2090 and 7075, both in unclad form) exposed for the same period gave generally similar results to those of steel and zinc: the best and worst locations were the same in all instances; however, the order among the remaining locations varied somewhat.

5. In the context of ISO 9223, alloy 7075 conformed to the guidelines suggested for aluminium; however, the corrosion rate of the unclad alloy 2090 was always much higher, due to the observed widespread surface exfoliation, which makes it mandatory for this alloy (as for 7075) to be used in the clad condition in service.

6. Tables listing the exposure sites in order of corrosivity and showing the ISO 9223 categories are provided in Tables 12 and 13. These tables offer the data in a convenient format for assisting in the selection of appropriate corrosion preventive measures to cope with the expected severity of corrosion at the various locations.

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Table 4. Corrosion weight losses in grams for all steel specimens

LOCATION	1 YEAR EXPOSURES				3 YEAR EXPOSURE	4 YEAR EXPOSURE
	1st YEAR	2nd YEAR	3rd YEAR	4th YEAR		
Maribyrnong	1.090	1.012	0.932	0.970	1.927	2.358
	1.143	0.958	0.924	0.920	2.144	2.445
Laverton	1.073	1.079	0.758	0.963	1.833	2.119
	1.169	1.071	0.842	0.877	1.983	2.160
Williamtown	2.491	2.537	2.320	2.407	5.061	6.218
	2.583	2.446	2.415	2.214	5.068	6.205
Amberley	0.892	0.813	0.877	0.731	1.695	1.813
	0.963	0.798	0.901	0.789	1.654	2.011
Townsville	1.429	1.287	1.294	1.287	2.482	2.803
	1.468	1.283	1.428	1.280	2.394	2.831
Innisfail, Cowley Beach	3.801	4.072	5.155	2.589	11.233	12.477
	4.029	4.516	5.069	2.545	9.208	13.279
Innisfail, Hot, Wet, Cleared	1.916	1.786	2.671	1.650	3.692	4.455
	1.740	1.857	2.487	1.944	3.529	4.307
Weipa	0.869	1.08	0.958	1.578	1.996	2.429
	0.896	1.013	1.047	2.021	1.993	2.413
Gove	1.750	1.676	1.636	1.699	3.462	4.096
	1.756	1.718	1.736	1.516	3.468	4.045
Tindal	0.220	0.188	0.262	0.310	0.548	0.544
	0.230	0.202	0.315	0.430	0.567	0.617
Darwin	0.966	0.889	1.041	1.024	2.000	2.286
	0.984	0.902	1.094	1.068	1.997	2.201
Mt. Goodwin	0.793	0.776	0.987	0.818	1.607	1.760
	0.769	0.753	0.953	0.827	1.594	1.878
Curtin	0.381	0.393	0.627	0.466	1.068	1.098
	0.393	0.405	0.650	0.449	1.090	1.179
Port Hedland	1.273	1.142	1.236	0.959	2.425	2.845
	1.236	1.124	1.184	0.952	2.405	2.915
Learmonth	0.672	0.988	0.893	0.856	1.438	1.650
	0.680	0.968	0.914	0.881	1.404	1.722
Cocos Islands	5.677	3.068	3.758	3.169	10.219	12.236
	5.739	3.214	3.828	3.252	10.072	12.198

Table 5. Corrosion weight losses in grams for all zinc specimens

LOCATION	1 YEAR EXPOSURES				3 YEAR EXPOSURE	4 YEAR EXPOSURE
	1st YEAR	2nd YEAR	3rd YEAR	4th YEAR		
Maribyrnong	0.024	0.014	0.014	0.020	0.045	0.058
	0.025	0.011	0.018	0.024	0.043	0.055
Laverton	0.026	0.018	0.018	0.019	0.053	0.069
	0.025	0.017	0.015	0.018	0.055	0.071
Williamtown	0.092	0.065	0.114	0.093	0.242	0.321
	0.090	0.055	0.145	0.095	0.237	0.330
Amberley	0.023	0.012	0.019	0.019	0.051	0.068
	0.024	0.012	0.017	0.018	0.051	0.068
Townsville	0.038	0.036	0.048	0.034	0.091	0.116
	0.042	0.038	0.048	0.031	0.087	0.110
Innisfail, Cowley Beach	0.216	0.159	0.216	0.098	0.485	0.628
	0.214	0.160	0.199	0.102	0.444	0.568
Innisfail, Hot, Wet, Cleared	0.037	0.042	0.037	0.025	0.079	0.086
	0.039	0.044	0.046	0.029	0.074	0.087
Weipa	0.050	0.023	0.029	0.036	0.082	0.110
	0.056	0.023	0.030	0.026	0.092	0.115
Gove	0.069	0.060	-	0.035	0.123	0.152
	0.048	0.061	-	0.032	0.118	0.144
Tindal	0.018	0.014	0.021	0.014	0.037	0.044
	0.016	0.009	0.018	0.014	0.039	0.049
Darwin	0.045	0.051	0.052	0.042	0.115	0.142
	0.048	0.052	0.057	0.040	0.118	0.147
Mt. Goodwin	0.030	0.015	0.028	0.014	0.052	0.066
	0.026	0.014	0.029	0.015	0.055	0.068
Curtin	0.019	0.010	0.023	0.012	0.036	0.041
	0.020	0.008	0.018	0.013	0.041	0.043
Port Hedland	0.081	0.064	0.087	0.091	0.167	0.224
	0.075	0.063	0.084	0.088	0.180	0.226
Learmonth	0.054	0.065	0.092	0.089	0.152	0.192
	0.052	0.068	0.081	0.076	0.152	0.190
Cocos Islands	0.122	0.233	0.057	0.094	0.276	0.376
	0.120	0.233	0.062	0.079	0.265	0.364

Table 6. Corrosion weight losses in grams for aluminium alloy 2090

LOCATION	1 YEAR EXPOSURES				3 YEAR EXPOSURE	4 YEAR EXPOSURE
	1st YEAR	2nd YEAR	3rd YEAR	4th YEAR		
Maribyrnong	0.085 0.057	0.035 0.041	0.048 0.045	0.100 0.089	0.288 0.278	0.363 0.352
Laverton	0.034 0.063	0.033 0.069	0.067 0.075	0.090 0.091	0.214 0.130	0.146 0.096
Williamtown	0.096 0.073	0.406 0.282	0.340 0.277	0.362 0.328	1.038 0.410	0.680 0.443
Amberley	0.029 0.006	0.017 0.027	0.039 0.005	0.041 0.046	0.028 0.088	0.039 0.031
Townsville	0.088 0.046	0.053 0.097	0.134 0.044	0.132 0.123	0.144 0.234	0.198 0.405
Innisfail, Cowley Beach	0.145 0.228	0.318 0.178	0.365 0.312	0.210 0.164	0.135 0.167	0.192 0.311
Innisfail, Hot, Wet, Cleared	0.005 0.005	0.055 0.021	0.069 0.013	0.087 0.071	0.099 0.026	0.223 0.046
Weipa	0.015 0.008	0.033 0.021	0.046 0.010	0.111 0.087	0.043 0.047	0.115 0.092
Gove	0.088 0.063	# #	0.188 0.075	0.111 0.105	0.311 0.172	0.460 0.464
Tindal	0.000 0.005	0.009 0.009	0.017 0.000	0.020 0.012	0.012 0.010	0.006 0.001
Darwin	0.031 0.051	0.066 0.057	0.064 0.032	0.040 0.055	0.149 0.116	0.163 0.177
Mt. Goodwin	0.010 0.026	0.036 0.038	0.038 0.019	0.040 0.036	0.087 0.047	0.093 0.112
Curtin	0.000 0.012	0.019 0.012	0.020 0.039	0.017 0.010	0.031 0.009	0.026 0.031
Port Hedland	0.030 0.074	0.075 0.065	0.048 0.084	0.068 0.070	0.156 0.098	0.211 0.256
Learmonth	0.014 0.032	0.040 0.062	0.037 0.036	0.047 0.047	0.073 0.071	0.063 0.127
Cocos Islands	0.160 0.148	0.290 0.287	0.101 0.169	0.234 0.100	0.412 0.474	0.171 0.181

Panels lost

Table 7. Corrosion weight losses in grams for aluminium alloy 7075

LOCATION	1 YEAR EXPOSURES				3 YEAR	4YEAR
	1st YEAR	2nd YEAR	3rd YEAR	4th YEAR	EXPOSURE	EXPOSURE
Maribyrnong	0.005 0.007	0.006 0.007	0.008 0.007	0.010 0.009	0.012 0.013	0.014 0.015
Laverton	0.006 0.008	0.007 0.007	0.007 0.007	0.007 0.006	0.012 0.009	0.014 0.014
Williamtown	0.028 0.026	0.031 0.025	0.047 0.045	0.029 0.021	0.063 0.063	0.068 0.072
Amberley	0.005 0.006	0.003 0.003	0.005 0.007	0.003 0.006	0.012 0.012	0.012 0.014
Townsville	0.020 0.020	0.020 0.019	0.027 0.024	0.025 0.026	0.041 0.038	0.045 0.050
Innisfail, Cowley Beach	0.025 0.023	0.026 0.026	0.025 0.029	0.014 0.014	0.043 0.037	0.049 0.045
Innisfail, Hot, Wet, Cleared	0.009 0.009	0.008 0.009	0.008 0.010	0.016 0.010	0.017 0.014	0.015 0.017
Weipa	0.007 0.007	0.011 0.010	0.012 0.014	0.013 0.021	0.040 0.021	0.020 0.021
Gove	0.036 0.034	0.032 0.027	0.044 0.033	0.012 0.010	0.097 0.093	0.101 0.112
Tindal	0.002 0.001	0.001 0.001	0.003 0.004	0.002 0.005	0.005 0.004	0.006 0.004
Darwin	0.012 0.012	0.013 0.013	0.033 0.016	0.014 0.013	0.032 0.032	0.098 0.030
Mt. Goodwin	0.007 0.006	0.005 0.004	0.008 0.006	0.006 0.008	0.015 0.015	0.018 0.016
Curtin	0.001 0.002	0.000 0.001	0.004 0.004	0.004 0.009	0.003 0.005	0.005 0.012
Port Hedland	0.019 0.020	0.019 0.015	0.027 0.025	0.029 0.031	0.068 0.054	0.068 0.071
Learmonth	0.011 0.011	0.007 0.012	0.020 0.021	0.024 0.024	0.025 0.032	0.036 0.035
Cocos Islands	0.034 0.034	0.019 0.021	0.013 0.014	0.021 0.015	0.049 0.054	0.055 0.061

Table 8. Corrosion rates of steel at all sites

Exposure Site	Average Corrosion Rate (μm/yr)						
	One Year Exposures					Three Year Exposures	Four Year Exposures
	1st Year	2nd Year	3rd Year	4th year	One Year Ave		
Maribyrnong	13.1	11.5	10.9	11.1	11.6	7.9	7.0
Laverton	13.1	12.6	9.4	10.8	11.5	7.4	6.2
Williamtown	29.7	29.2	27.7	27.0	28.4	19.8	18.1
Amberley	10.9	9.4	10.4	8.9	9.9	6.5	5.6
Townsville	16.9	15.0	15.9	15.0	15.7	9.5	8.2
Innisfail, Cowley Beach	45.8	50.2	59.8	30.0	46.5	39.9	37.6
Innisfail, Hot, Wet, Cleared	21.4	21.3	30.2	21.0	23.5	14.1	12.8
Weipa	10.3	12.2	11.7	21.1	13.8	7.8	7.1
Gove	20.5	19.9	19.7	18.8	19.7	13.5	11.9
Tindal	2.6	2.3	3.4	4.3	3.2	2.2	1.7
Darwin	11.4	10.5	12.5	12.2	11.7	7.8	6.6
Mt. Goodwin	9.1	8.9	11.3	9.6	9.8	6.2	5.3
Curtin	4.5	4.7	7.5	5.4	5.5	4.2	3.3
Port Hedland	14.7	13.3	14.2	11.2	13.3	9.4	8.4
Learmonth	7.9	11.4	10.6	10.2	10.0	5.5	4.9
Cocos Islands	66.8	36.7	44.4	37.6	46.4	39.6	35.7

Table 9. Corrosion rates of zinc at all sites

Exposure Site	Average Corrosion Rate (μm/yr)						
	One Year Exposures					Three Year Exposures	Four Year Exposures
	!st Year	2nd Year	3rd Year	4th Year	One Year Average		
Maribyrnong	0.31	0.16	0.20	0.28	0.24	0.19	0.18
Laverton	0.33	0.22	0.21	0.24	0.25	0.23	0.22
Williamtown	1.16	0.77	1.66	1.20	1.20	1.02	1.04
Amberley	0.30	0.15	0.23	0.24	0.23	0.22	0.22
Townsville	0.51	0.47	0.61	0.42	0.50	0.38	0.36
Innisfail, Cowley Beach	2.75	2.04	2.66	1.28	2.18	1.98	1.91
Innisfail, Hot, Wet, Cleared	0.49	0.55	0.53	0.35	0.48	0.33	0.28
Weipa	0.68	0.29	0.38	0.40	0.44	0.37	0.36
Gove	0.75	0.77	-	0.43	0.65	0.51	0.47
Tindal	0.22	0.15	0.25	0.18	0.20	0.16	0.15
Darwin	0.60	0.66	0.70	0.52	0.62	0.50	0.46
Mt. Goodwin	0.36	0.19	0.36	0.19	0.27	0.23	0.21
Curtin	0.25	0.12	0.26	0.16	0.20	0.16	0.13
Port Hedland	1.00	0.81	1.09	1.15	1.01	0.74	0.72
Learmonth	0.68	0.85	1.11	1.06	0.92	0.65	0.61
Cocos Islands	1.55	2.98	0.76	1.11	1.60	1.16	1.18

Table 10. Corrosion rates of aluminium alloy 2090 at all sites

Exposure Site	Average Corrosion Rates (µm/yr)						
	One Year Exposures					Three Year Exposures	Four Year Exposures
	1st Year	2nd Year	3rd Year	4th Year	One Year Average		
Maribyrnong	2.48	1.33	1.63	3.31	2.19	3.31	3.13
Laverton	1.70	1.78	2.48	3.17	2.28	2.01	1.06
Williamtown	2.96	12.04	10.80	12.08	9.47	8.47	4.91
Amberley	0.61	0.77	0.77	1.52	0.92	0.68	0.31
Townsville	2.35	2.63	3.12	4.46	3.14	2.21	2.64
Innisfail, Cowley Beach	6.53	8.68	11.85	6.54	8.40	1.77	2.20
Innisfail, Hot, Wet, Cleared	0.17	1.33	1.43	2.76	1.43	0.73	1.18
Weipa	0.40	0.95	0.98	3.46	1.45	0.53	0.91
Gove	2.64	-	4.60	3.78	3.67	2.83	4.04
Tindal	0.09	0.32	0.30	0.56	0.32	0.13	0.03
Darwin	1.44	2.15	1.68	1.66	1.73	1.55	1.49
Mt. Goodwin	0.63	1.29	1.00	1.33	1.06	0.78	0.90
Curtin	0.21	0.54	1.03	0.47	0.56	0.23	0.25
Port Hedland	1.82	2.45	2.31	2.41	2.25	1.49	2.04
Learmonth	0.80	1.79	1.28	1.65	1.38	0.84	0.83
Cocos Islands	5.39	10.10	4.72	5.84	6.51	5.18	1.54

Table 11. Corrosion rates of aluminium alloy 7075 at all sites

Exposure Site	Average Corrosion Rate (µm/yr)						
	One Year Exposures					Three Year Exposures	Four Year Exposures
	1st Year	2nd Year	3rd Year	4th Year	One Year Average		
Maribyrnong	0.21	0.22	0.26	0.33	0.25	0.14	0.12
Laverton	0.24	0.24	0.24	0.22	0.24	0.12	0.12
Williamtown	0.93	0.96	1.58	0.86	1.08	0.72	0.60
Amberley	0.19	0.10	0.21	0.15	0.16	0.14	0.11
Townsville	0.69	0.67	0.87	0.87	0.78	0.45	0.41
Innisfail, Cowley Beach	0.82	0.89	0.93	0.48	0.78	0.46	0.40
Innisfail, Hot, Wet, Cleared	0.31	0.29	0.31	0.45	0.34	0.18	0.14
Weipa	0.24	0.36	0.45	0.58	0.41	0.35	0.18
Gove	1.20	1.01	1.32	0.38	0.98	1.08	0.92
Tindal	0.05	0.03	0.12	0.12	0.08	0.05	0.04
Darwin	0.41	0.45	0.84	0.46	0.54	0.36	0.55
Mt. Goodwin	0.22	0.15	0.24	0.24	0.21	0.17	0.15
Curtin	0.05	0.02	0.14	0.22	0.11	0.05	0.07
Port Hedland	0.67	0.58	0.89	1.03	0.79	0.70	0.60
Learmonth	0.38	0.33	0.70	0.82	0.56	0.32	0.31
Cocos Islands	1.17	0.69	0.46	0.62	0.73	0.59	0.50

Table 12. Corrosivity of 16 defence locations in Australia with respect to steel and zinc

STEEL					ZINC				
SITE	AV. 4 YEAR CORR. RATE µm/yr	AV. 1 YEAR CORR. RATE µm/yr	RELATIVE CORROSIVITY (1 yr results)	ISO 9223 CORROSIVITY CATEGORY	SITE	AV. 4 YEAR CORR. RATE µm/yr	AV. 1 YEAR CORR. RATE µm/yr	RELATIVE CORROSIVITY (1 yr results)	ISO 9223 CORROSIVITY CATEGORY
Tindal	1.7	3.2	1	2-Low	Curtin (South Derby)	0.13	0.20	1	2-Low
Curtin (South Derby)	3.3	5.5	1.5	"	Tindal	0.15	0.20	1	"
Mt Goodwin	5.3	9.8	3	"	Amberley	0.22	0.23	1	"
Amberley	5.6	9.9	3	"	Maribyrnong	0.18	0.24	1	"
Learmonth	4.9	10.0	3	"	Laverton	0.22	0.25	1.5	"
Laverton	6.3	11.5	3.5	"	Mt Goodwin	0.21	0.27	1.5	"
Maribyrnong	7.0	11.6	3.5	"	Weipa	0.36	0.44	2	"
Darwin	6.6	11.7	3.5	"	Innisfail- Hot Wet Cleared	0.28	0.48	2.5	"
Port Hedland	8.4	13.3	4	3-Medium	Townsville	0.36	0.50	2.5	"
Weipa	7.1	13.8	4.5	"	Darwin	0.46	0.62	3	"
Townsville	8.2	15.7	5	"	Gove	0.47	0.65	3	"
Gove	11.9	19.7	6	"	Learmonth	0.61	0.92	4.5	3-Medium
Innisfail- Hot Wet Cleared	12.8	23.5	7.5	"	Port Hedland	0.72	1.01	5	"
Williamtown	18.1	28.4	9	4-High	Williamtown	1.04	1.20	6	"
Cocos Islands	35.7	46.4	14.5	"	Cocos Islands	1.18	1.60	8	"
Innisfail- Cowley Beach	37.6	46.5	14.5	"	Innisfail- Cowley Beach	1.91	2.18	11	4-High

Table 13. Corrosivity of 16 defence locations in Australia with respect to aluminium alloys 2090 and 7075

ALUMINIUM-Li ALLOY 2090					ALUMINIUM ALLOY 7075				
SITE	AV. 4 YEAR CORR. RATE μm/yr	AV. 1 YEAR CORR. RATE μm/yr	RELATIVE CORROSIVITY (1 yr results)	ISO 9223 CORROSIVITY CATEGORY	SITE	AV. 4 YEAR CORR. RATE μm/yr	AV. 1 YEAR CORR. RATE μm/yr	RELATIVE CORROSIVITY (1 yr results)	ISO 9223 CORROSIVITY CATEGORY
Tindal	0.03	0.3	1	3-Medium	Tindal	0.04	0.08	1	2-Low
Curtin (South Derby)	0.25	0.6	2	"	Curtin (South Derby)	0.07	0.11	1.5	"
Amberley	0.3	0.9	3	4-High	Amberley	0.11	0.16	2	"
Mt Goodwin	0.9	1.1	3.5	"	Mt Goodwin	0.15	0.21	2.5	"
Innisfail- Hot Wet Cleared	1.2	1.4	4.5	"	Laverton	0.12	0.24	3	3-Medium
Learmonth	0.8	1.4	4.5	"	Maribyrnong	0.13	0.25	3	"
Weipa	0.9	1.45	5	"	Innisfail- Hot Wet Cleared	0.14	0.34	4	"
Darwin	1.5	1.7	5.5	"	Weipa	0.18	0.41	5	"
Maribyrnong	3.1	2.2	7.5	5-Very High	Darwin	0.55	0.54	7	"
Port Hedland	2.0	2.25	7.5	"	Learmonth	0.31	0.56	7	"
Laverton	1.1	2.3	7.5	"	Cocos Islands	0.50	0.73	9	"
Gove	4.0	2.8	9	"	Innisfail- Cowley Beach	0.40	0.78	10	4-High
Townsville	2.6	3.1	10	"	Townsville	0.41	0.78	10	"
Cocos Islands	1.5	6.5	22	Extreme	Port Hedland	0.60	0.79	10	"
Innisfail- Cowley Beach	2.2	8.4	28	"	Gove	0.92	0.98	12	"
Williamtown	4.9	9.5	32	"	Williamtown	0.60	1.08	13.5	"

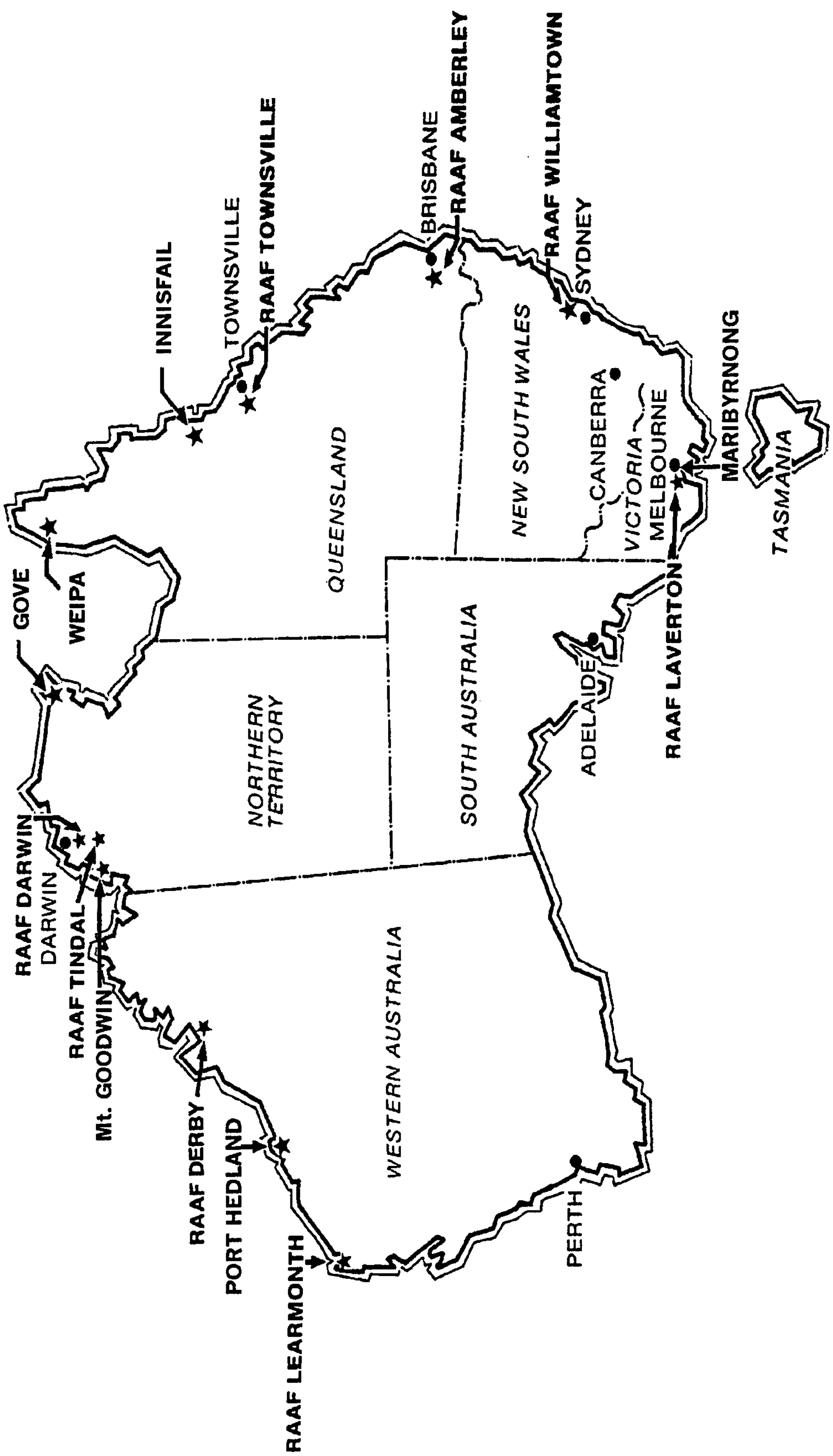
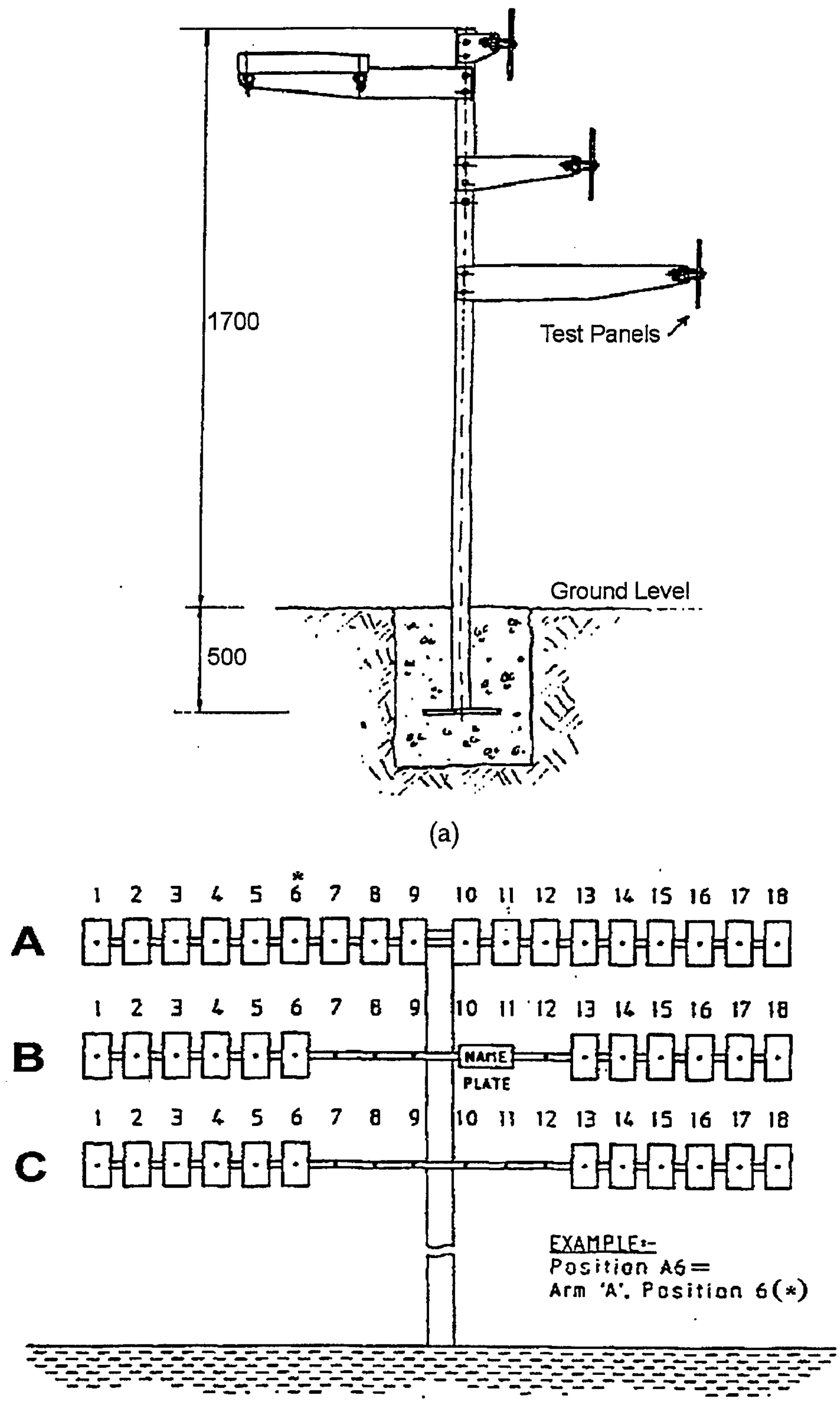


Figure 1. Map of exposure sites (RAAF Publication R83/1426)



(b)

Figure 2. The exposure rack: (a) side view, (b) front view.

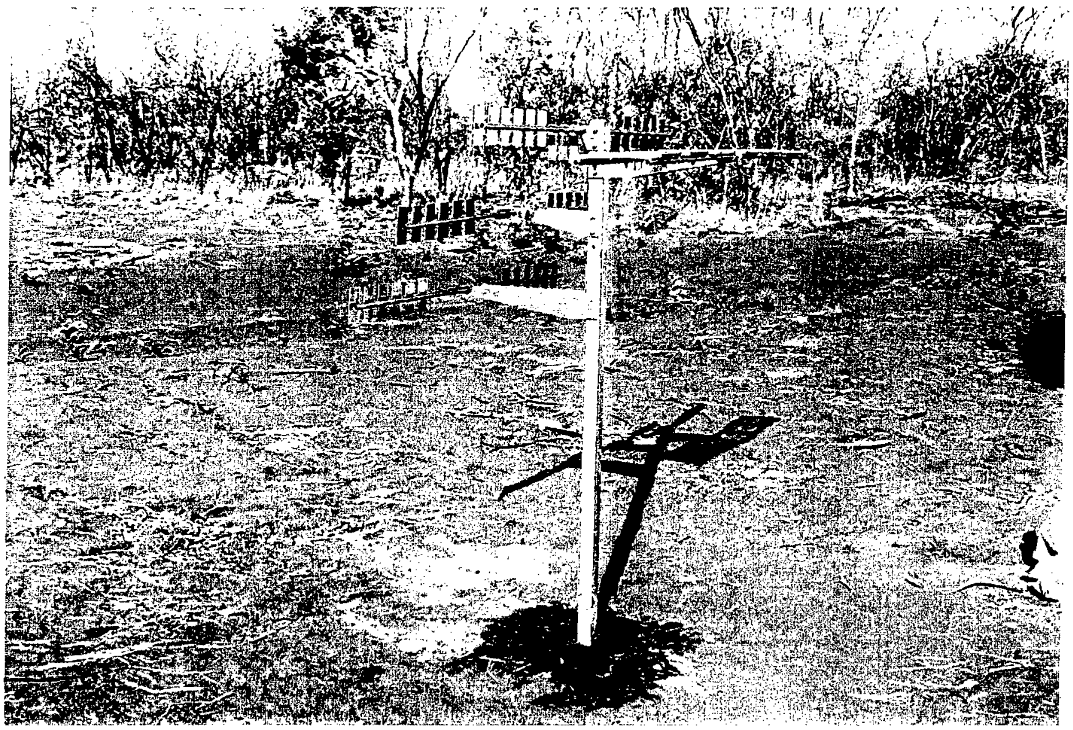


Figure 3. A typical rack, installed at the Curtin site.

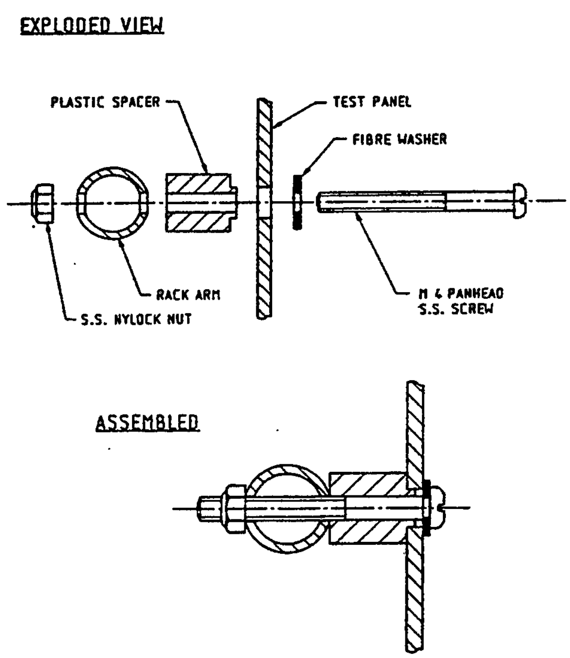


Figure 4. Method of attaching panels to the rack.

FIGURE 5

CORROSION RATES OF STEEL AT THE VARIOUS SITES

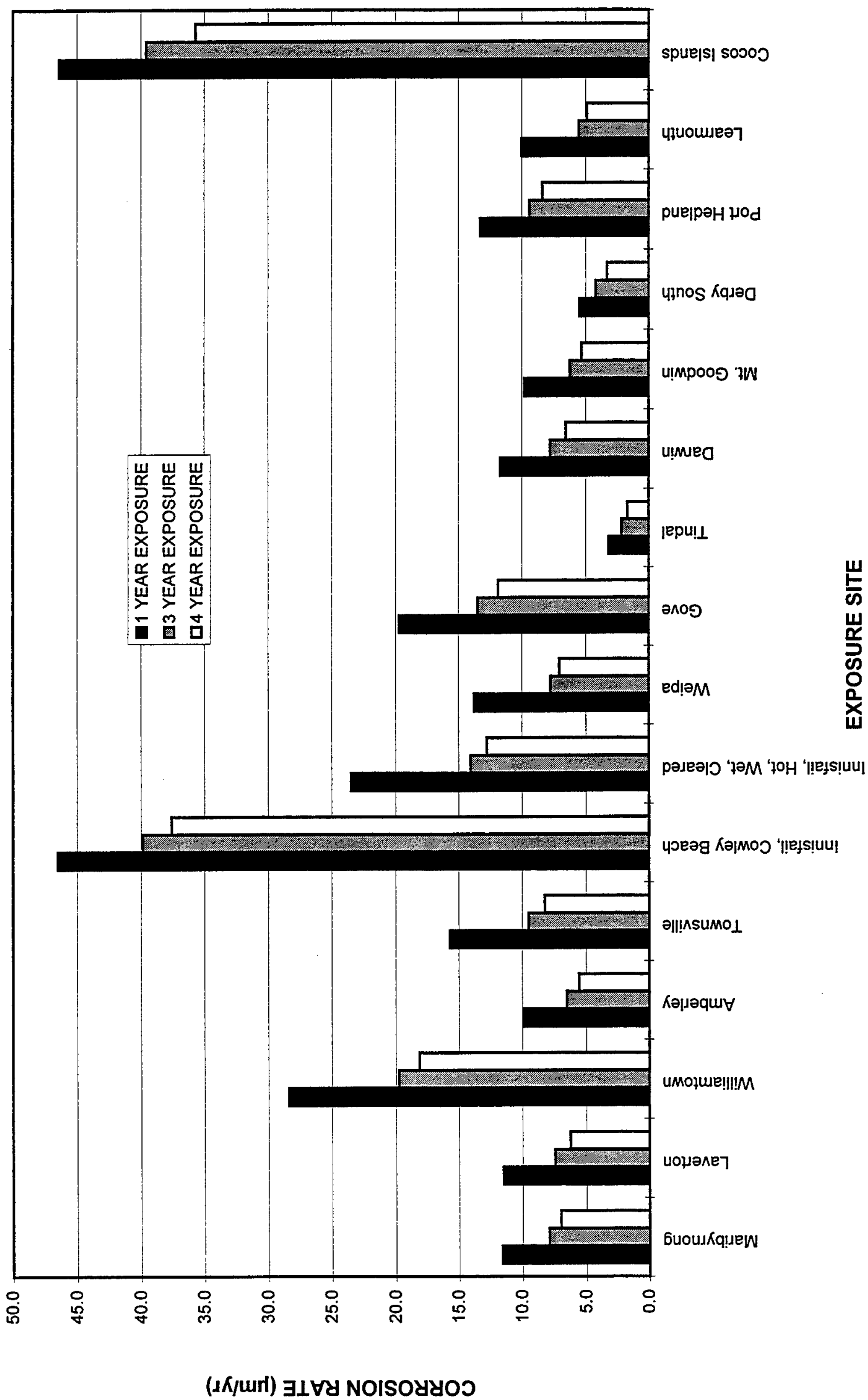


FIGURE 6

CORROSION RATES OF ZINC AT VARIOUS SITES

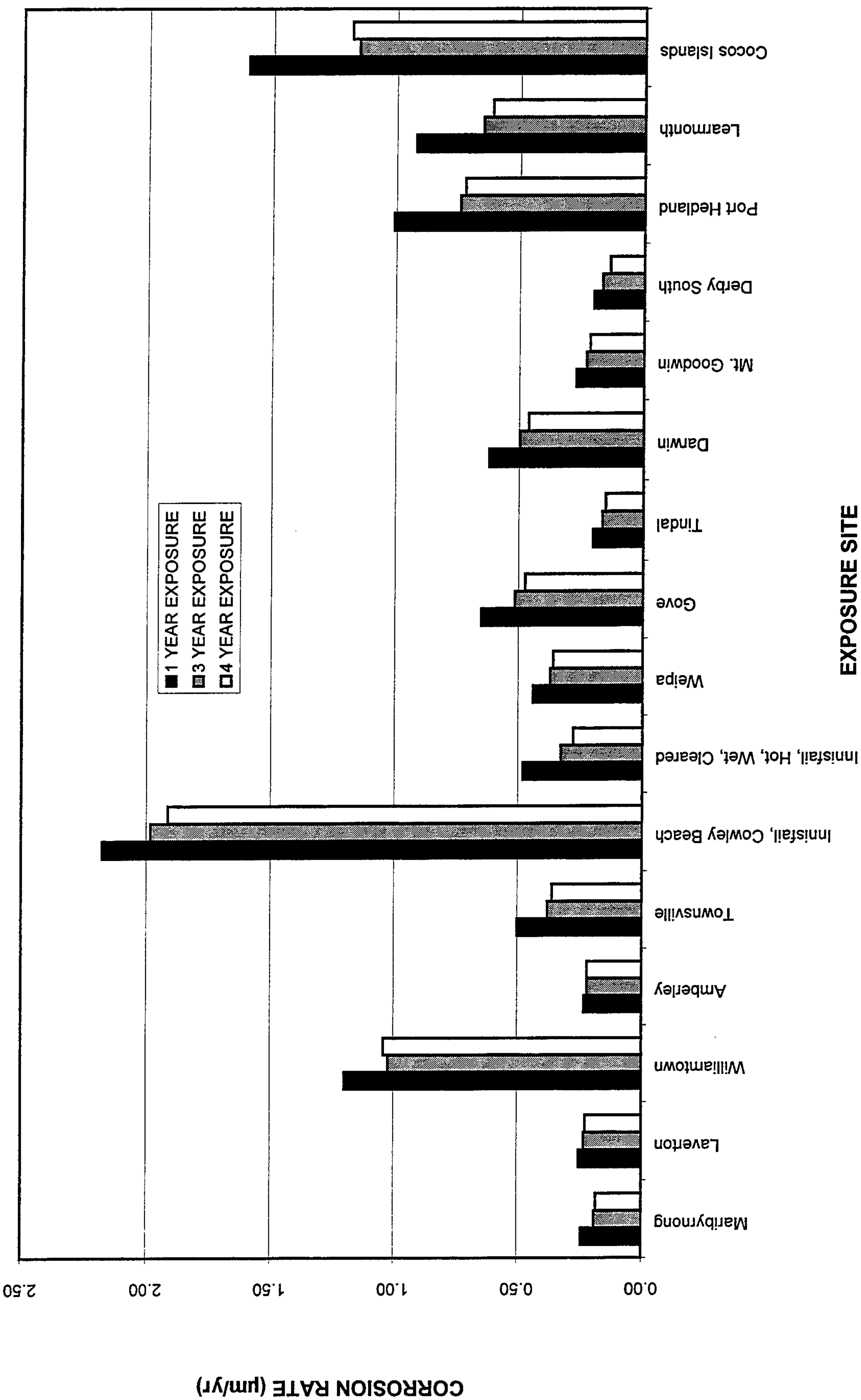


FIGURE 7

CORROSION RATES OF ALUMINIUM/LITHIUM ALLOY 2090 AT VARIOUS SITES

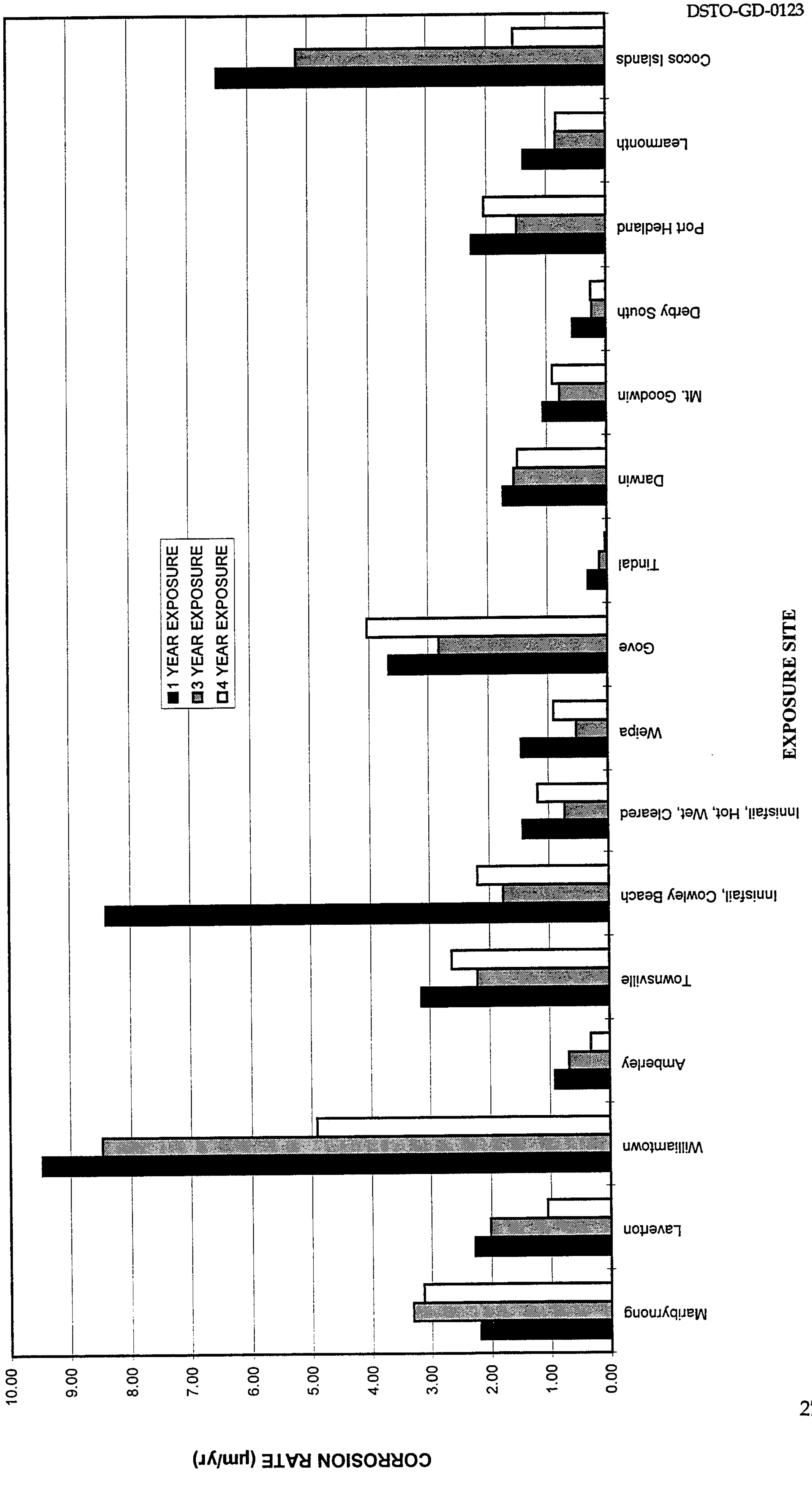


FIGURE 8

CORROSION RATES OF ALUMINIUM ALLOY 7075 AT VARIOUS SITES

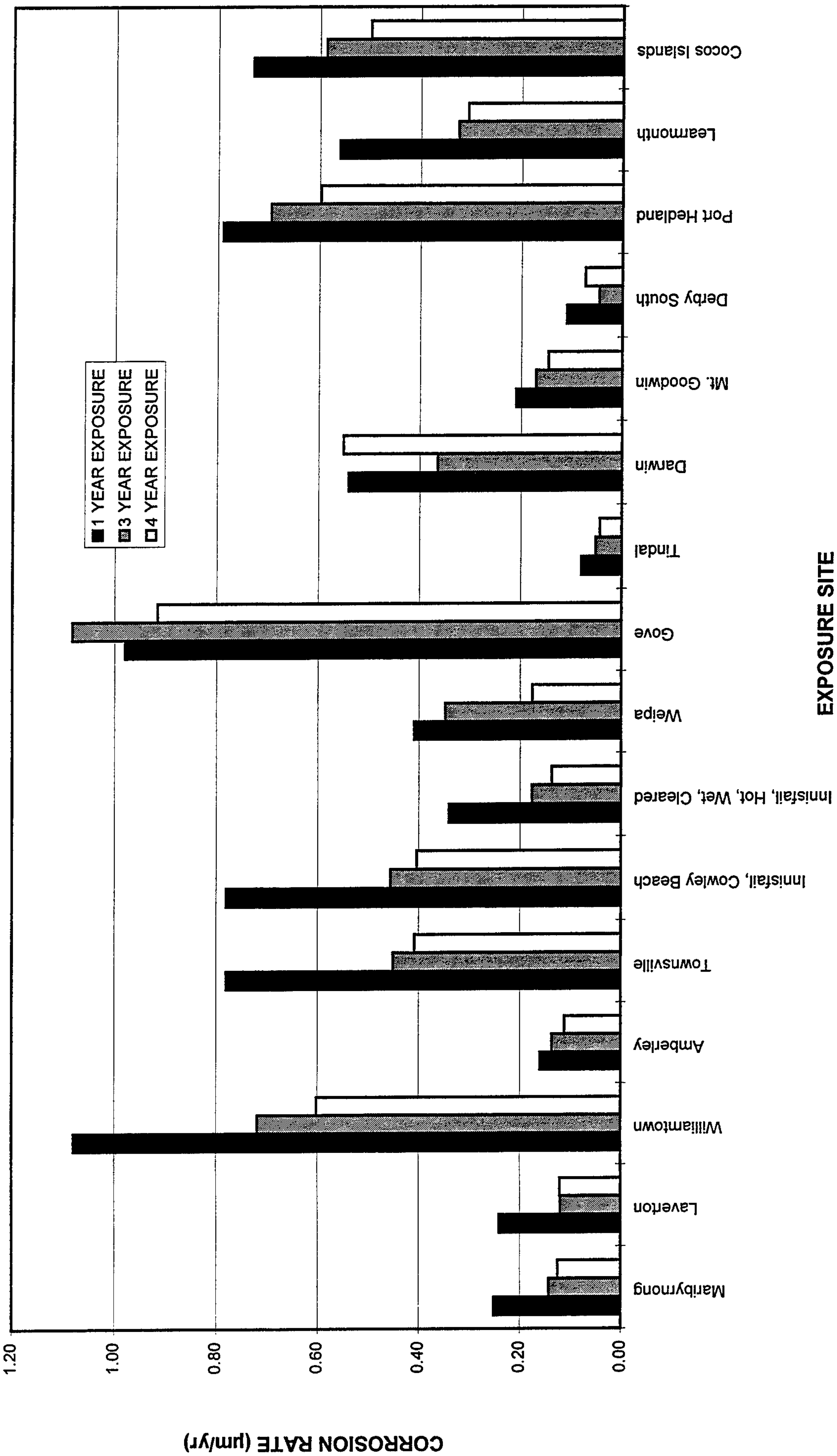


FIGURE 9

COMPARISON OF THE FOUR YEAR CORROSION RATES OF STEEL AND ZINC

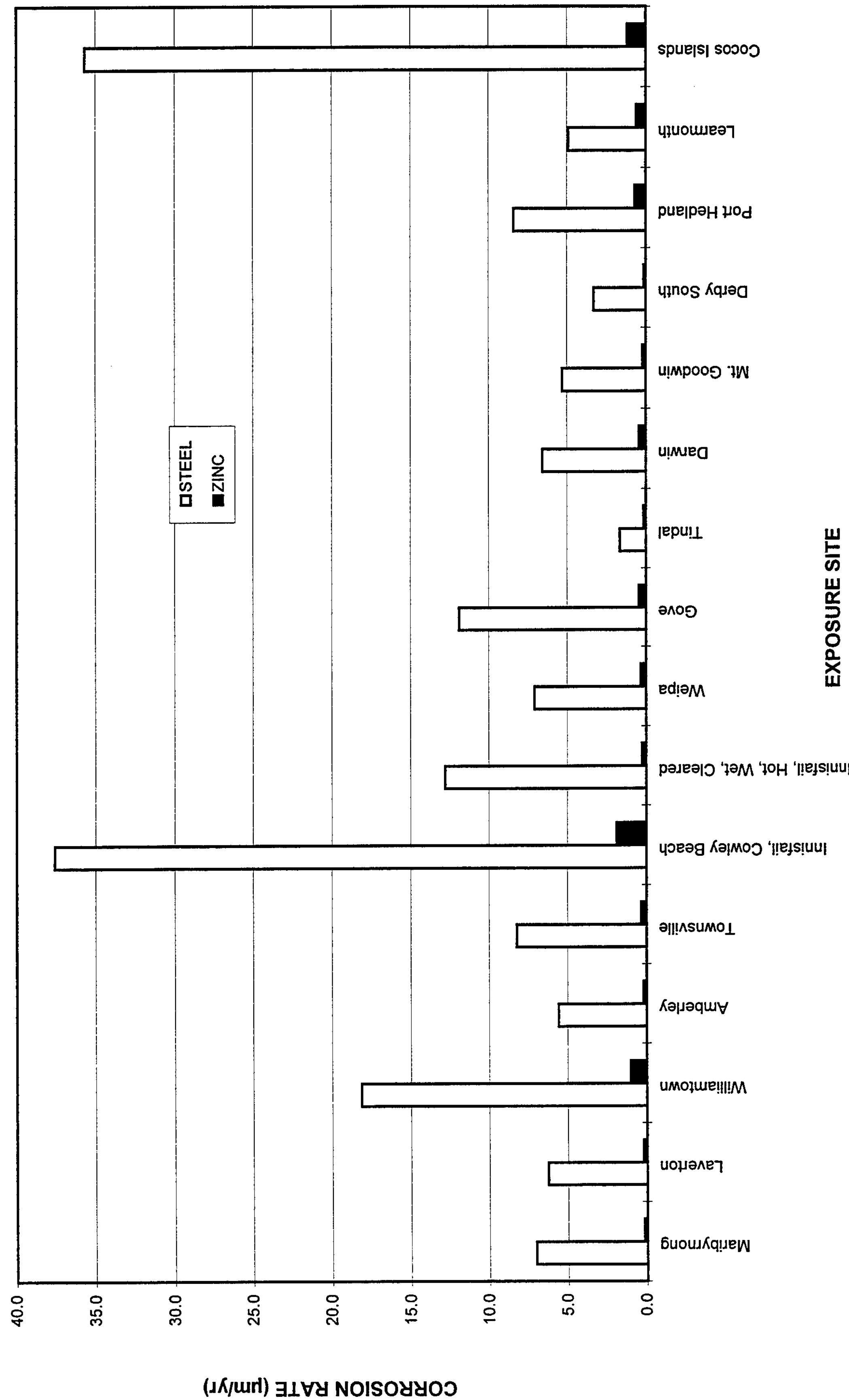


FIGURE 10

COMPARISON OF THE ONE YEAR CORROSION RATES OF THE TWO ALUMINIUM ALLOYS

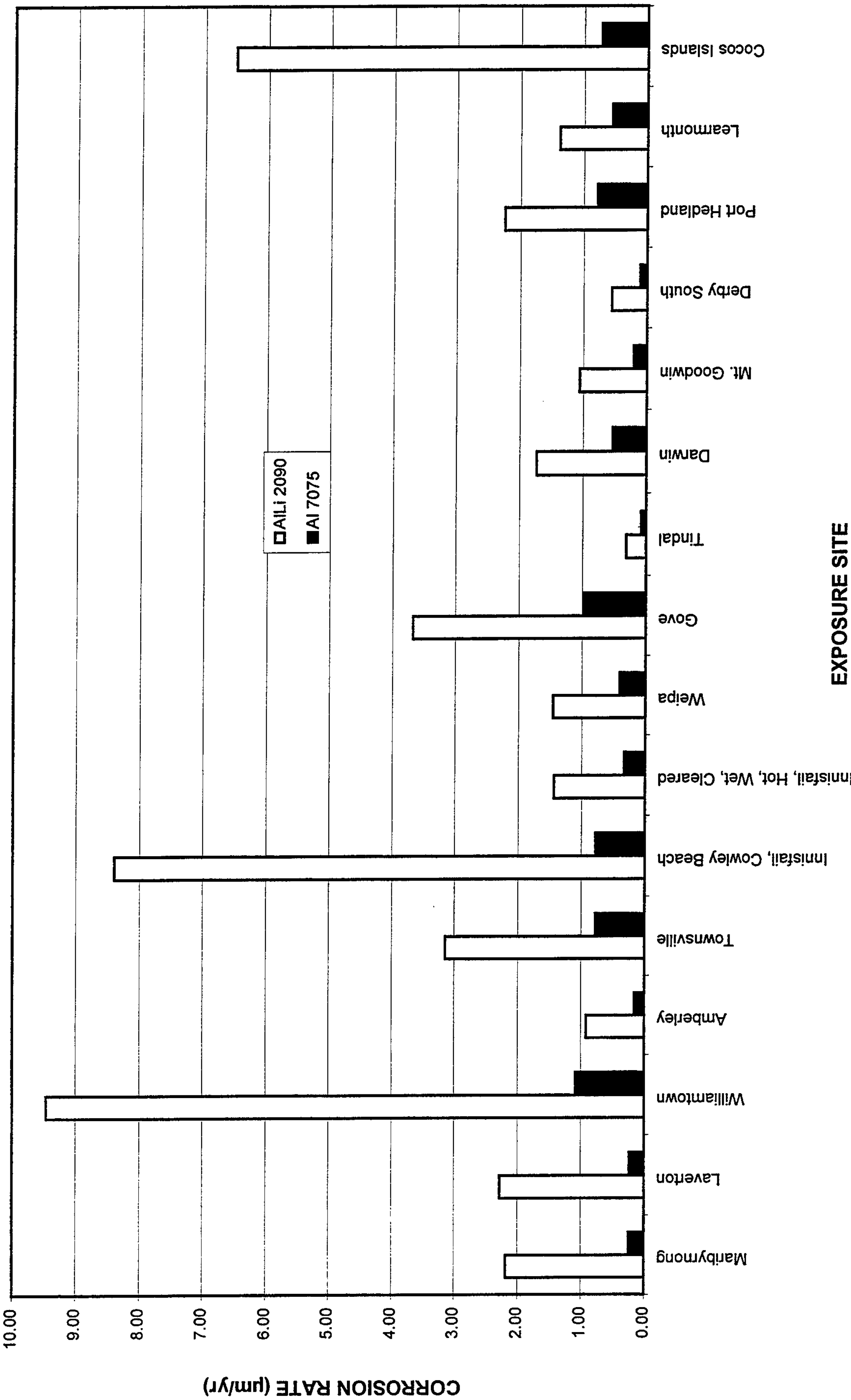
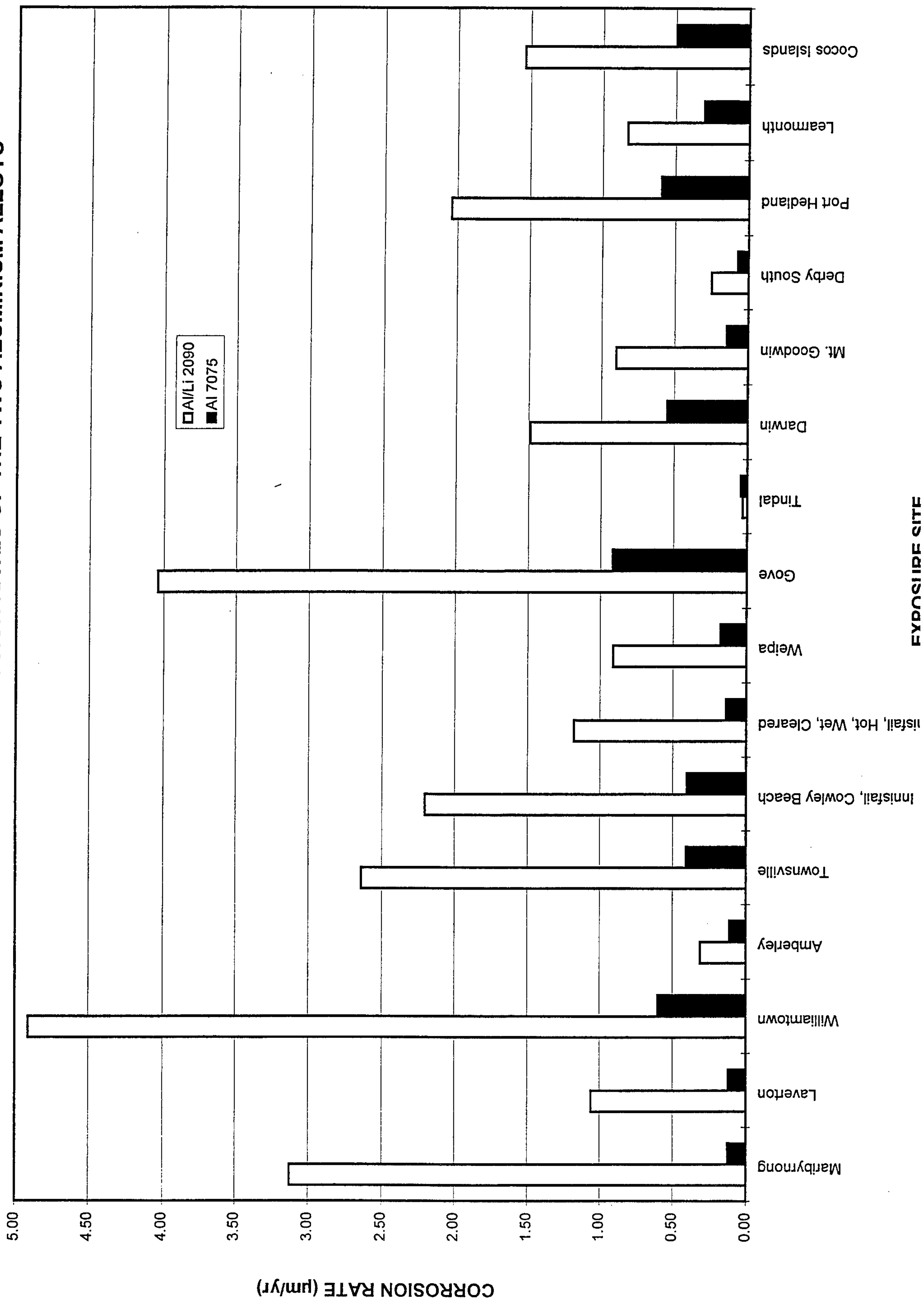


FIGURE 11

COMPARISON OF THE FOUR YEAR CORROSION RATES OF THE TWO ALUMINIUM ALLOYS



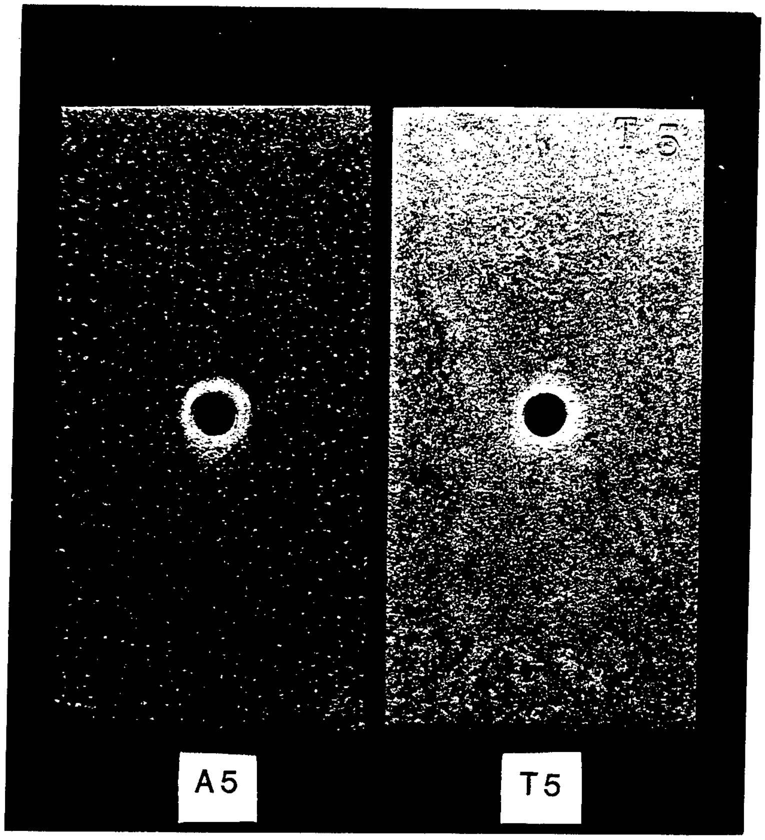


Figure 12. Steel panels after 4 years at Amberley (A5) and Tindal (T5) .

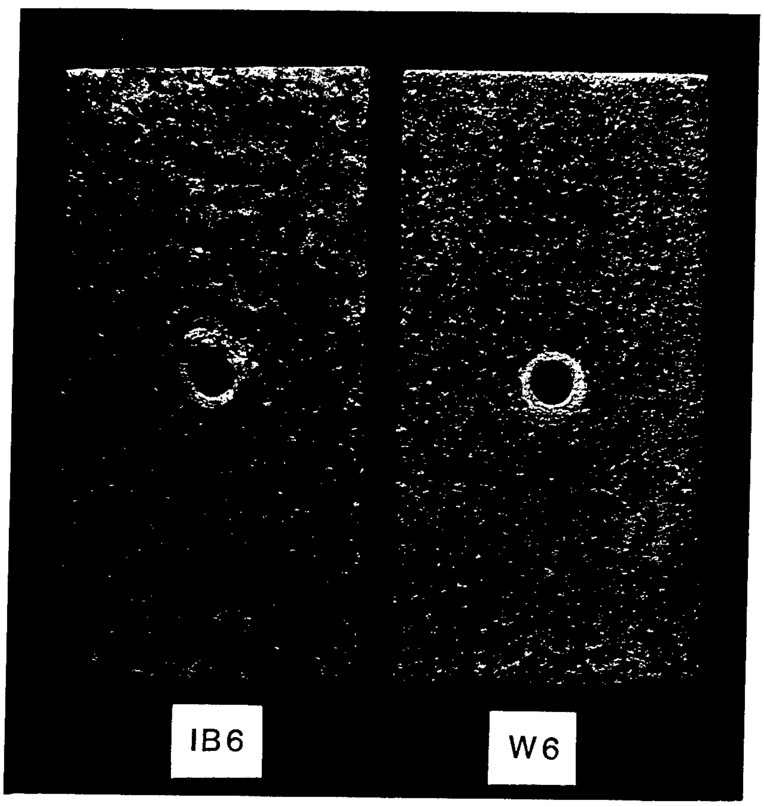


Figure 13. Steel panels after 4 years at Cowley Beach (IB6) and Williamtown (W6)

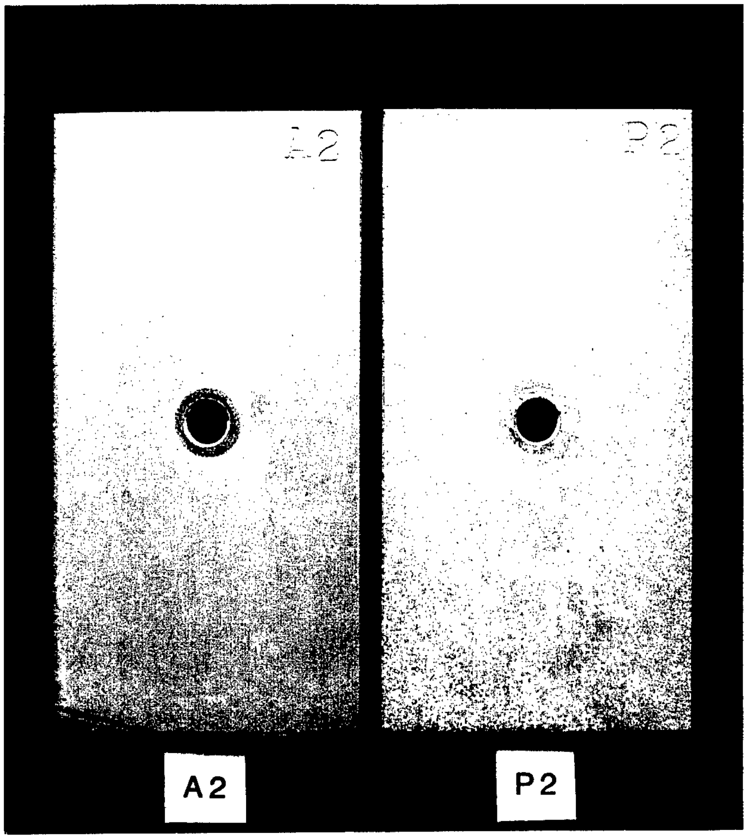


Figure 14. Zinc panels after 4 years at Amberley (A2) and Port Hedland (P2).

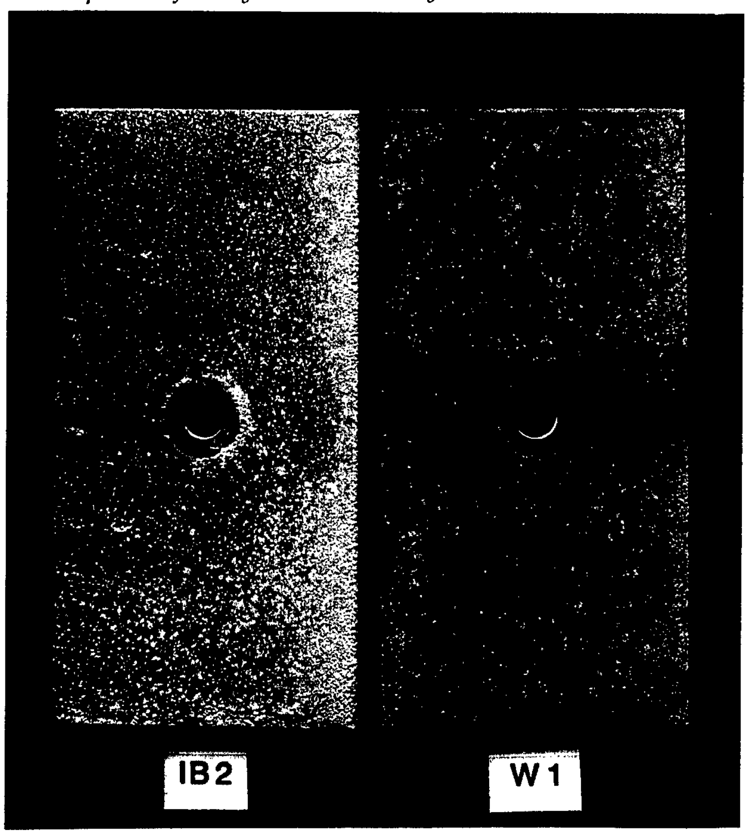


Figure 15. Zinc panels after 4 years at Cowley Beach (IB2) and Williamtown (W1).

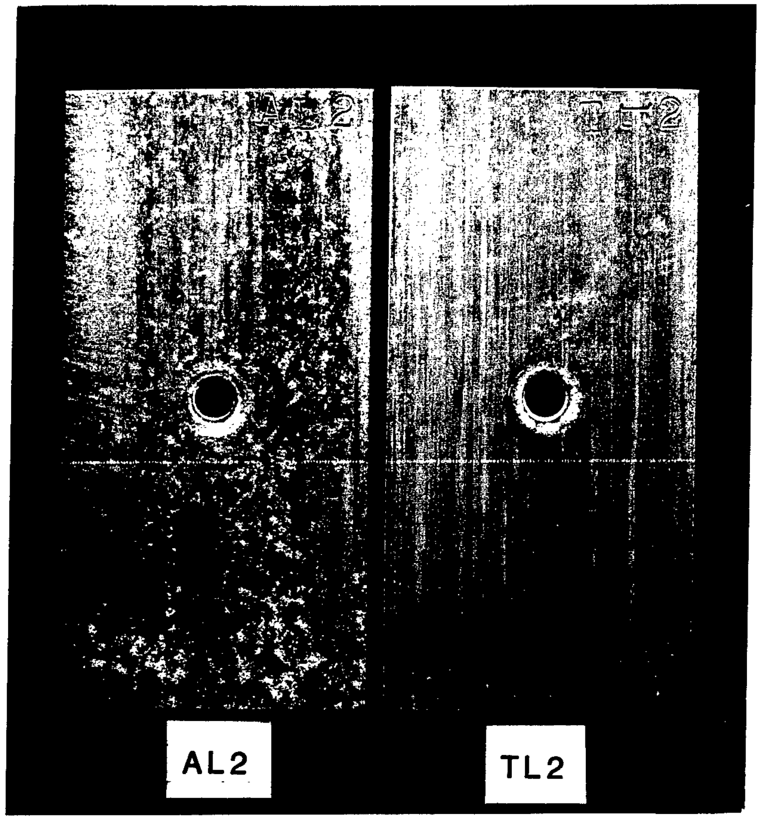


Figure 16. Alloy 2090 after 4 years at Amberley (AL2) and Tindal (TL2).

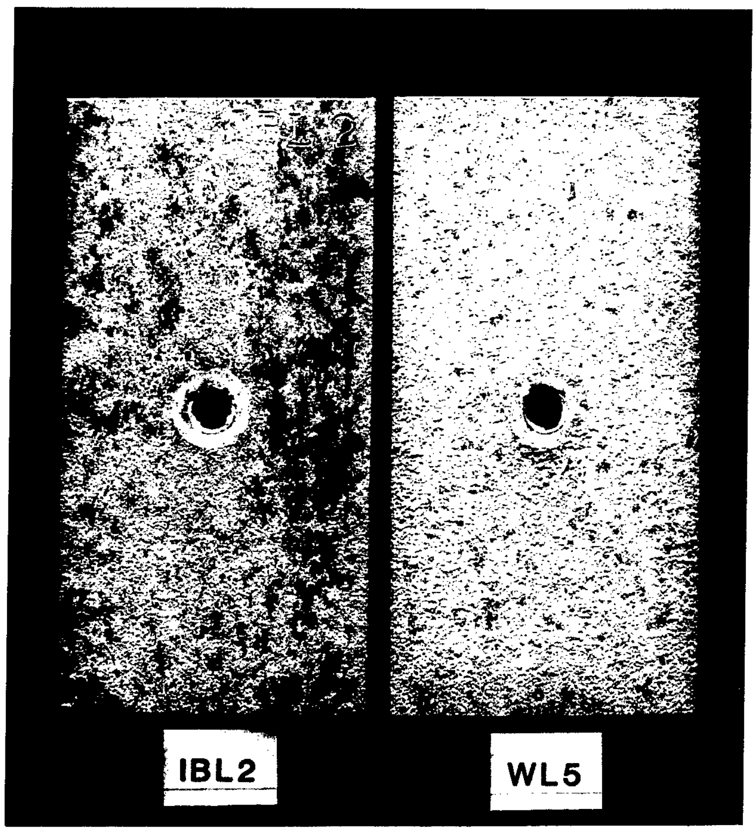


Figure 17. Alloy 2090 after 4 years at Cowley Beach (IBL2) and Williamtown (WL5).

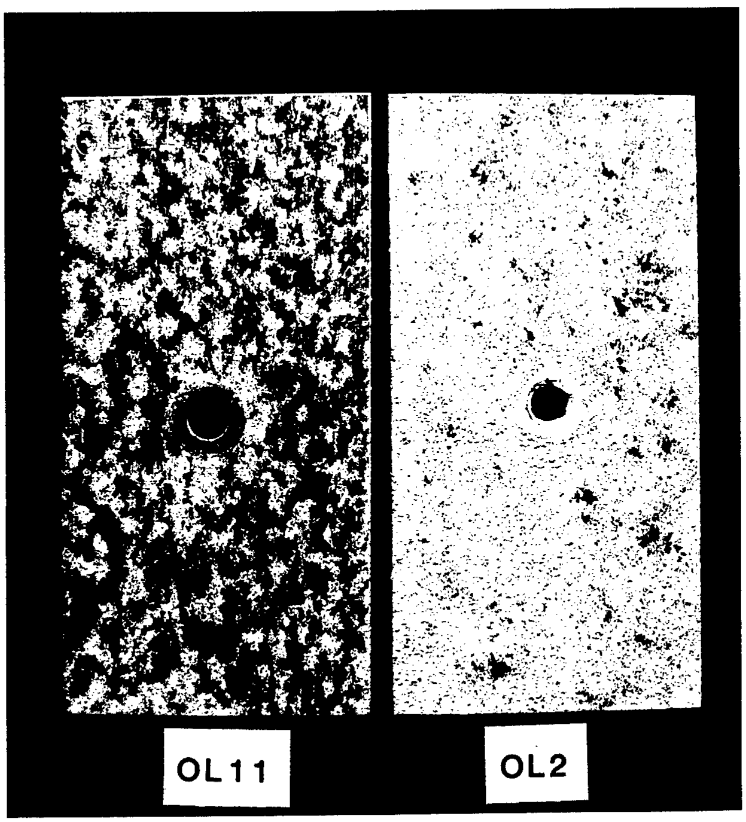


Figure 18. Alloy 2090, Townsville - A comparison of the appearance of 1 year (left) and 4 year (right) exposures.

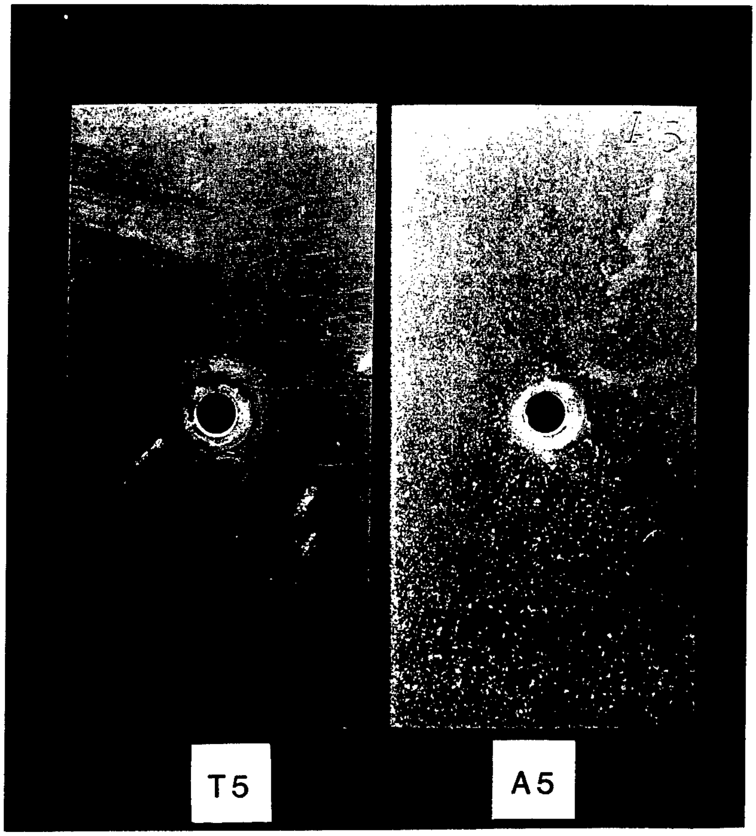


Figure 19. Alloy 7075 panels after 4 years at Tindal (T5) and Amberley (A5).

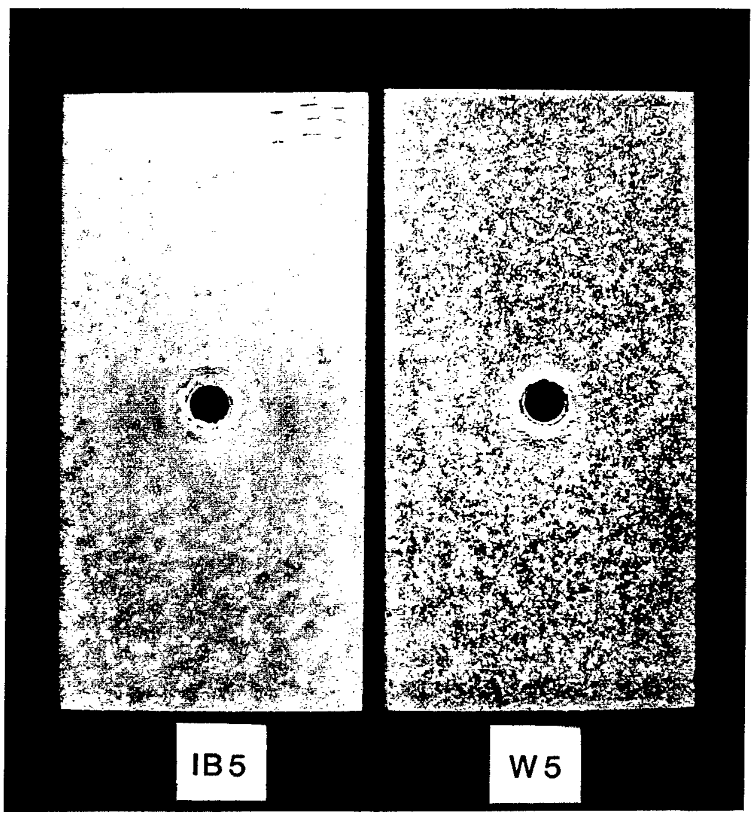


Figure 20. Alloy 7075 panels after 4 years at Cowley Beach (IB5) and Williamtown (W5).

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E.J. Duxbury, B.T. Moore and B.S. Smith

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19. ABSTRACT

A series of exposure trials has been conducted to characterise the corrosivity of the atmosphere at 16 Defence bases in Eastern and Northern Australia. Atmospheric corrosivity was assessed by measuring the corrosion rates of specimens of steel, zinc and two high strength aluminium alloys when exposed on racks in the open air for periods of one to four years during the period 1988 to 1993.

The results are presented in summary in Tables 12 and 13 which list the bases in increasing order of severity of atmospheric corrosion, and group them into atmospheric corrosivity categories (low to very high) according to the International Standard, ISO 9223: 1992(E), to enable a direct comparison with world standards.