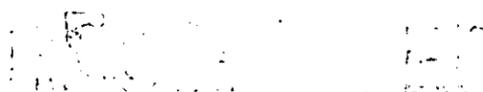**▲BRANZ**

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Some Apparent Limitations in Using the ISO Atmospheric Corrosivity Categories

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Some Apparent Limitations in Using the ISO Atmospheric Corrosivity Categories

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The International Organization for Standardization (ISO) has developed a standard (9223) which predicts corrosion rate classes for steel and zinc, based on meteorological and pollution factors. This paper analyses actual measurements of corrosivity of these metals in a range of countries. It shows that ISO 9223 has shortcomings in predicting corrosivity levels in a number of regions of the world, and suggests that the definition of "time of wetness" is not always valid. The adoption of an alternative standard test material to the "mild" steel proposed in a companion standard (ISO 9226) is also suggested.

INTRODUCTION

Atmospheric corrosion of materials in man's built environment generally proceeds unabated until the element concerned is rendered unsightly or unserviceable. Knowledge of the severity of an atmospheric environment is important as it enables the optimum selection of materials or level of corrosion protection to minimise maintenance costs and reduce the overall life-cycle costs of the element or structure. Barton[1] asserts that approximately half the cost of corrosion is attributable to atmospheric corrosion, and several surveys in different countries (e.g. famously the Hoar report in the UK,[2] and that by Batelle[3] in the USA, which has subsequently been updated) have shown the cost to

an economy of corrosion is 3–4% of GDP. It is therefore important that tools which purport to provide prediction of corrosion rates are reasonably accurate, so that the life-cycle costs of projects are not affected by over- or underspecification of protective measures.

Early work established a link between corrosivity and the nature of the atmospheric environments which were described as industrial, marine, urban, rural etc. Much work was done under the auspices of the American Society for Testing and Materials (ASTM) initially in the US and Canada. In 1960–64 specimens of carbon steel and zinc were used to "calibrate the corrosivity of the atmosphere" at 46 sites around the world for periods of 1 and 2 years.[4] This was an important study which examined the site corrosivity in different periods and found significant variations. It also found "decided differences" in the relative corrosion performance of steel and zinc for some of the sites. A further conclusion was that it would be desirable to have multiple test sites within a given location to categorise the nature of that location with greater precision.

The ISO standards[5] that finally emerged from consideration of the collected wisdom proposed two approaches to characterise the aggressiveness of the environment. The first (ISO 9223) involves identifying and quantifying the environmental factors controlling corrosion, viz. meteorological factors (which

control the "time of wetness") and pollutant levels. The principal pollutants influencing corrosion rates were found to be SO_2 and airborne salinity. The second approach, which offers a relatively low-cost and simple-to-interpret alternative, is the exposure of standard metal specimens for a fixed term and measurement of the rate at which they corrode (ISO 9226). The procedure has been widely used to measure the corrosivity at specific isolated sites deemed representative of different types of environment.

This paper considers some results which have been collected in a range of countries, including those of the authors, and contrasts the actual measurements with the predictions that would have been made by ISO 9223. The overwhelming conclusion is that ISO 9223 fails the test posed in the first paragraph above; that is, it is not "reasonably accurate" in predicting the levels of corrosion protection needed for a significant number of regions of the world.

BACKGROUND TO AND DEVELOPMENT OF THE ISO STANDARDS

A technical committee working group of the International Organization for Standardization (ISO/TC 156/WG 4) conducted work through the late 1970s and 80s which led to the development of four standards defining corrosivity categories, and the techniques to meas-

ure corrosivity using standard specimens and pollutant levels.[5] These standards were based on the statistical evaluation of results from corrosion tests at more than 200 sites with a range of environments.[6] The system aims to enable determination of a corrosivity category using one-year exposures of the standard metals or annual averages of the environmental parameters. Notwithstanding this, the working group recognised that the use of data based on different methodologies should be complemented with a coherent test program (ISO CORRAG) which was begun in 1987–89.[6]

The ISO standard on classification (ISO

Figure 1. ISO corrosivity categories for steel and zinc in outdoor atmospheres with SO_2 pollution classifications P_0 and P_1

9223)[5] defines five categories for time of wetness (TOW) and four categories for each of the pollutants SO_2 and airborne salinity. (Two of the TOW categories relate to indoor environments and are not relevant to the subsequent discussion here.) The standard defines five categories for corrosivity (based on the first year corrosion rates of carbon steel, zinc, copper, and aluminium) and it has been stated[6] that this number is sufficient to cover the range of design and corrosion protection measures that may be required for practical purposes.

RATIONALE FOR PLOTS OF CORROSIVITY DATA FOR STEEL VERSUS ZINC AND WHAT THEY CAN PROVIDE

The corrosion mechanisms of carbon steel and zinc are quite different, with the rate-determining steps in zinc corrosion occurring at the corrosion product/air interface, while for carbon steel the rate-determining steps occur at the corrosion product/metal interface.[1] Consequently, the different levels of environmental factors at a site may introduce different corrosivity for the different metals. Though the densities of steel and zinc are not dissimilar, the rates of metal loss (as shown in Tables 5 and 6 of ISO 9223) can therefore be predicted to be quite different in any particular environment. For simplicity, ISO 9223 has attempted to match corrosion rate ranges for the different metals to individual sets of environmental characterisation measures.

Using the three outdoor levels of TOW, and three each of SO_2 and airborne salinity (categories zero and one are combined for both SO_2 and salinity in Table 6) there is a total of 27 combinations of environmental classes. In just over half of the cases (14), the Standard places the corrosivity of steel and zinc in the same class, in 44% of the cases (12) potentially separated by one class, and in one case ($\tau_3 S_2 P_3$) potentially separated by two classes.

In Australia and New Zealand SO_2 levels are much lower than in Europe, North America, and some of the developing regions of Asia. Data from continuous air monitoring at some 27 sites in New South Wales was analysed and only two sites (near a steelworks/industrial complex) fell even within category P_1 (19 μg/m³, with a range for P_1 of $12 < P_1 \leq 40$ μg/m³). In Victoria the highest figures for annual average SO_2 are of the order of 9–14 μg/m³. Thus, except for very localised microenvironments in

the vicinity of industrial plants (or the geothermal regions in the case of New Zealand), all of Australia and New Zealand can be considered to fall within the ISO categories of P_0 or P_1 for SO_2 pollution, with only a very few regions falling within even the P_1 category.

This enables the ISO table for estimated corrosivity categories (Table 6) to be effectively simplified for Australian/New Zealand conditions so that only two environmental parameters—chloride deposition and TOW—need to be considered. Furthermore, it enables the proposed theoretical relationship between corrosivity category, chloride deposition, and TOW to be easily represented on a two-dimensional plot.

This has been done in Figure 1. The chloride deposition rate has been plotted using a logarithmic scale (y axis) to enable the four categories (S_0 to S_3) of airborne salinity to be shown clearly. The x-axis shows the ISO TOW using two alternatively presented scales—total annual hours and percentage of total time. The values which represent the limits of the categories τ_3, τ_4, and τ_5 are total annual hours (in accord with Table 1 of ISO 9223). The estimated corrosivity categories for carbon steel and zinc according to Table 6 of ISO 9223 are shown for the various ranges of the two environmental parameters. The vast majority of locations in temperate climates would be characterised with a τ_4 TOW and salinity categories of either S_0, S_1, or S_2. These environmental combinations on the plot are shown as a shaded grey area. It is seen that according to the standard the corrosion rates of steel and zinc fall in the same category not just for the τ_4, S_0–S_2 environmental combinations, but for all levels of salinity at a τ_4 TOW.

A simple way of testing the validity of the hypothesis that both metals can be accommodated in the same description of corrosivity of environments in this fashion is to plot the measured corrosion rates of steel versus zinc for any set of data where simultaneous measurements of the rates have been made, together with lines on the plot defining the limits of the ISO corrosivity categories. These lines are subsequently referred to in this paper as the "ISO boxes". Figure 2 shows this type of plot
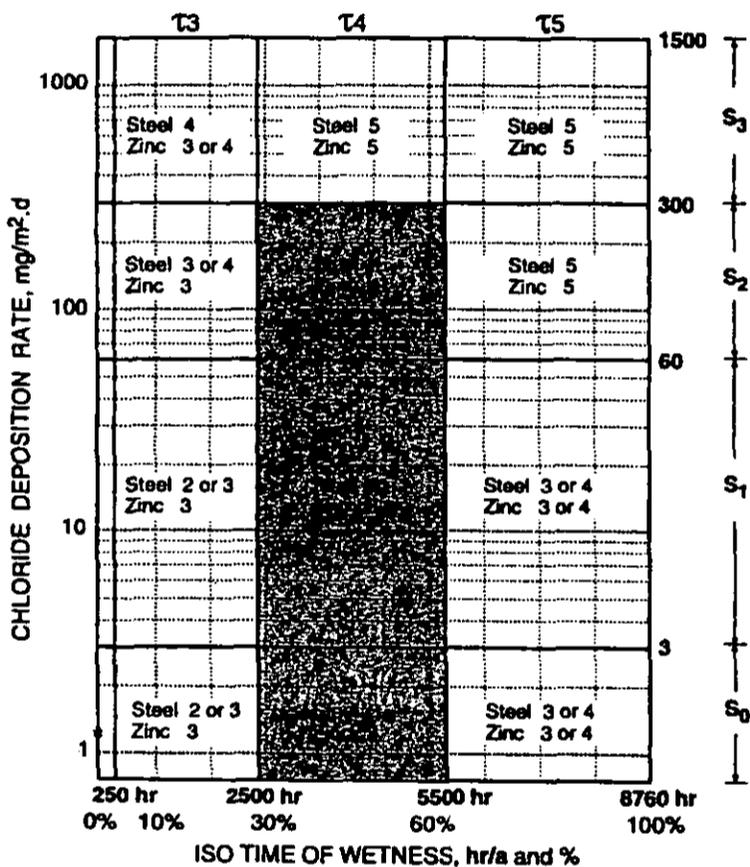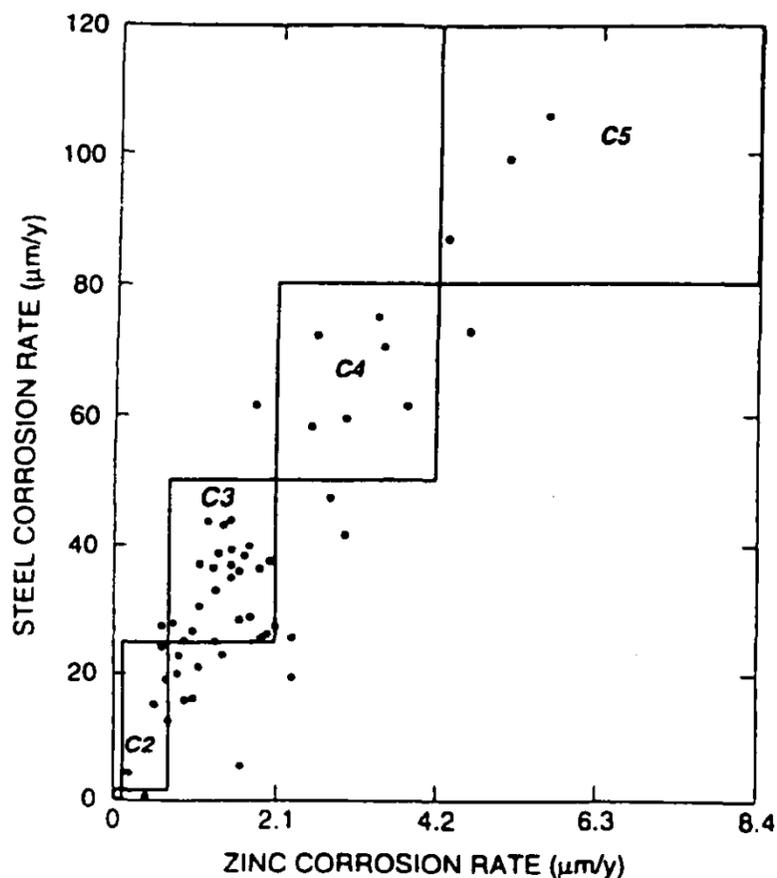
Figure 2.   Plot of one-year corrosion rates for steel versus zinc for ISOCORRAG sites (ref. 6), together with ISO corrosivity categories.

for the ISO CORRAG data.[6] The unit μm/y (as opposed to g/m².y) has been used for the plots in this paper as most data has been presented thus previously and it also takes account of the small density difference in steel and zinc.

The compliance of the data with the estimated ISO corrosivity categories is calculated as a percentage of the total number of cases in the data set where the measured corrosivity of steel and zinc are in the same category (i.e. point inside the box) or differs by one or more categories. Sites where the measured corrosivity of both steel and zinc exceed the C5 category have been excluded from the analyses in this paper as the ISO standard states that they represent environments beyond its scope. However, points where only one of the measured corrosion rates exceeds C5 have been included; some extrapolation of the ISO C5 corrosivity category has been required in these (few) cases.

The results for the ISO CORRAG data set[6] are shown in Table 1 along with 11 other data sets. The ISO CORRAG data includes locations with environmental combinations other than the typical τ_4, S_0–S_2, $P_0 P_1$ found in temperate marine environments. There are 43 sites with SO_2 data of which 33 are in category P_0

or P_1, 33 sites with salinity data of which 29 are in category S_0, S_1, or S_2, and 43 sites with TOW data of which 6 are in τ_3, 30 in τ_4, and 7 in τ_5. Considering this, there is good compliance (71%) with the simplified plot of ISO boxes in Figure 2.

INFLUENCE OF PANEL COMPOSITION ON CORROSION RATE

A seemingly intractable problem in assessing the corrosivity of a site against another assessed in someone else's program is that virtually every study carried out around the world has used a slightly different metallurgical composition for its coupons. This is obviously a problem in the case of carbon steel. ISO 9226 has attempted to address this with a limited definition of particular compositions of metals to be used. There are some grounds to suggest, however, that the boundaries placed upon the composition are not adequately tight.

Kure Beach, North Carolina, is probably the world's best known corrosion test site. The corrosivity of the two exposure sites at 25 m and 250 m from the sea was monitored using one-year exposures of ingot iron (from a single heat) mounted vertically for almost every year from 1949 to 1980. The historical data was kindly supplied by LaQue Corrosion Services. The average rate of corrosion at the 25 m lot was 547 μm/y with a standard deviation of 191 μm/y (coefficient of variation 35%), and at the 250 m lot 63 μm/y with a standard deviation of 16 μm/y (coefficient of variation 25%).

Data collected at Kure Beach since 1984, using A36 grade carbon steel[17] (specification is for steel for general structural purposes) from different heats has produced a much

wider variation in corrosion rates. The data for the A36 steel and zinc exposures each year is shown in Figure 3 together with the ISO boxes. For the heats from 1990–94, the copper contents were always <0.05%, but the carbon contents were low (0.03–0.04%) for 1991–93 and substantially higher (0.15, 0.11%) for 1990 and 1994. This variability in corrosion rate with batch of steel used for the measurement has been reconfirmed by an experiment which involved re-exposure of the 1990–94 heats of steel in 1996. It is clear that steel composition can have a very significant influence on the measurement of corrosivity, and that there becomes a real problem in comparing sites when steel compositions have differed. The issue is raised as to what material should be used as a standard for steel.

In his monograph on corrosion testing, LaQue[18] states: "The great effect of copper in concentrations ordinarily considered as residual serves to make carbon steel of undefined copper content an unsatisfactory basis of comparison in describing the atmospheric corrosion resistance of other steels. A much more satisfactory standard is the ordinary copper steel which contains about 0.20 per cent cop-
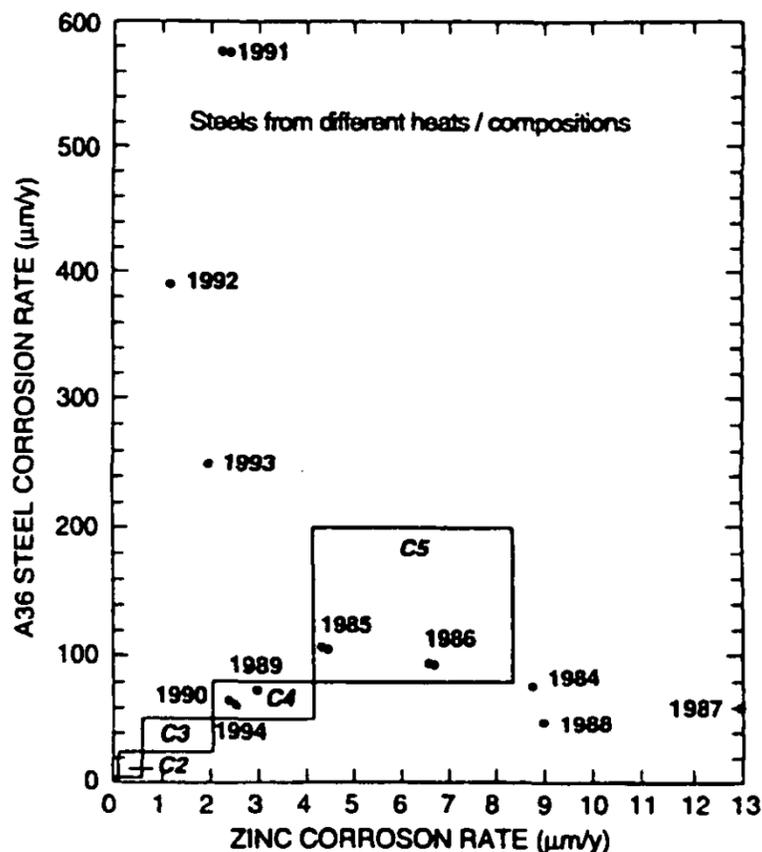

Figure 3 Plot of one-year corrosion rates A36 low carbon steel versus zinc, for Kure Beach (North Carolina) 25 m lot (1984-94), together with ISO corrosivity categories.

per". ISO 9226 specifies as a standard for steel: "unalloyed carbon steel (Cu 0.03–0.10%, P <0.07%)". The A36 steels used at Kure Beach complied with the limit on P, and were within or below the allowable range for Cu but still showed wide variation in corrosivity.

Larrabee and Coburn[19] studied the influence of variations in chromium, copper, nickel, phosphorus and silicon contents individually, and in combination, on the atmospheric corrosion resistance of 270 steels. They found that "the greatest change in corrosion with a relatively small change in composition is that caused by an increase in copper content from 0.01 to 0.04%". At contents of 0.1–0.45% the changes were only slight in comparison. In a discussion of this paper, Vernon[20] stated that "British practice had adopted a steel containing not less than 0.2% Cu as a standard of reference among ferrous materials."[21] Hudson and Stanners[22] had found that for ingot iron (previously used as a standard) the corrosion was markedly affected by minute variations (a few hundredths of a per cent) in its copper content when this was low, and difficulties in controlling the copper content led to the introduction of the copper-bearing steel. King et al.[23] demonstrated that no significant difference was obtained when measuring corrosivity with three batches of copper steel (copper contents 0.21–0.24%).

It seems, therefore, that the ISO 9226 specification is inadequate to ensure composition is not unduly influencing the results. Might it not be better to adopt the proposal of LaQue and use copper steel as a standard? It should also be borne in mind that with the increasing use of recycled material the copper content of steels is generally increasing.

FIT OF STEEL AND ZINC DATA FROM VARIOUS OTHER SURVEYS WITH THE ISO CATEGORIES

Besides the ISO CORRAG work, there have been many other extensive comparative surveys of atmospheric corrosion rates using contemporaneous exposure of carbon steel and galvanised steel or zinc which have more or less met the requirements of ISO 9226 with respect to metal composition and coupon size. The authors have been responsible for programs which have collected substantial amounts of simultaneous data for corrosivity of steel and zinc in Australia,[16,24,25] and New Zealand.[12] In each country, there have been difficulties in relating the predictions of ISO 9223 to the measured corrosion rate data and local meteorological and geographical characteristics. These observations have led to the development of this paper, of which one aim is to examine how well published data from some of the very wide range available on the corrosivity toward steel and zinc obey the relationships implied by ISO 9223.

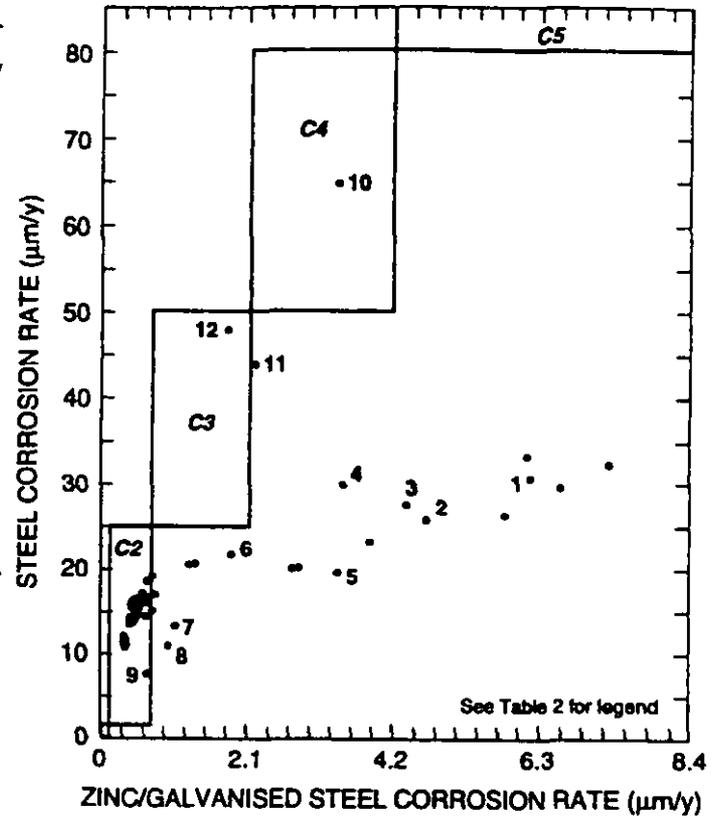The Australian data has been acquired in

Figure 4.   Plot of one- and two-year corrosion rates for steel versus zinc/galvanised steel for sites in south-east Melbourne (Australia) (ref. 18) or Kure Beach (North Carolina), together with ISO corrosivity categories.

different time periods from a region to the south-east of Melbourne as part of several programs, and while the data from sites of "mild to moderate" aggressiveness fits the ISO categories well, that from adjacent marine sites shows very poor compliance. This can be clearly seen in Figure 4. For New Zealand, the TOW classifications of ISO 9223 were found to predict inadequately the corrosion rate of galvanised steel, especially in coastal locations.

While acknowledging that in many countries, especially in the Northern Hemisphere,

Table 1 Compliance of Steel and Zinc Corrosivities with ISO Categories for Various Exposure Programs Worldwide

Data set	Reference	Number of sites/countries. Number of sites in parentheses where corrosivity of both steel and zinc exceed limits of category C5, and excluded from this analysis	Same category	Differ by 1	Differ by 2	Differ by 3
			Percentage of the total of cases in the data set where the measured corrosivity of steel and zinc are in the same ISO category or differ by one or more categories			
ISO CORRAG	6	53/14 (1)	71	27	2	
Czechoslovakia/Sweden 1978*	7	11/2	45	55		
Scandinavia	8	32/4	56	41	3	
MICAT*	9	55/12	56	29	13	2
MICAT – marine sites only		21/12	43	33	19	5
MICAT – urban sites only		9/8	67	33		
MICAT – rural sites only		22/9	64	27	9	
Spain	10	102	77	22	1	
Barcelona – period 1	11	74	50	50		
Barcelona – period 2		42	86	14		
New Zealand	12	166 (2)	81	18	1	
ASTM world survey[c]	4	44 (2)	45	45	5	5
Philippines[d]	13	10 [40 cases]	10	85	5	
Former far-eastern Soviet Union	14, 15	28	25	64	11	
South–east Melbourne[e]	16	56	82	7	11	

[a] Results in reference given in g/m^2 and converted to $\mu m/y$ for this paper by dividing by 7.8 for steel and 7.14 for zinc.

[b] The study has a total of 72 sites. Simultaneous data for steel and zinc is available for 55 only. The results used in this table are in most cases the means of two or three one-year exposure periods.

[c] Results in reference given in grams mass loss for 6 x 4 inch specimens and converted to $\mu m/y$ as in footnote a.

[d] Total of 10 sites but with 2 start periods and 2 batches of materials.

[e] Exposure period of 2 years.

the question of levels of SO_2 present is more complicated than that for Australia and New Zealand (where the influence of SO_2 can effectively be ignored), a plot of the measured corrosivity of steel versus zinc together with the ISO boxes can still provide a good indication of how effective is the matrix of environmental categories in predicting corrosivity class. Most of the sites in surveys conducted worldwide still fall into the P_0 or P_1 SO_2 category (e.g. for the MICAT project[9] only about 10% of the 72 sites have a P_2 level of SO_2). Even so, at the τ_4 TOW, Table 6 of the standard states that for a P_2 level of SO_2 the corrosivity classes of steel and zinc should still be the same for salinity categories S_0 and S_1, and at most potentially removed by one class for S_3 and S_1. The results of analyses of 12 data sets are shown in Table 1 with specific comment and plots of the data as follows.

Table 2. Legend to Figure 4.
Details of Exposure for Specimens of Steel and Zinc (Including Galvanised Steel) at Sites South-East of Melbourne (Australia) and Kure Beach (USA)

Identification[a]	Location	Period	Duration (years)	Angle of exposure (°)	Steel details Description	Steel details Dimensions (mm)	Zinc details Description	Zinc details Dimensions (mm)
Unnumbered sites	SE Melbourne[b] (ref. 16)	83–85	2	90	'Mild' steel to AS 1204	100 x 50 x 3	Galvanised steel[b]	200 x 75 x 0.64
1	Navy Base	91–92	1	45	'Mild' steel to AS 1204	150 x 100 x 3	Rolled – LSRM 2400	150 x 100 x 1
2	Navy Base	96–97	1	45	'Mild' steel to AS 1204	150 x 100 x 3	Rolled – LSRM 2400	150 x 100 x 1
3	Navy Base	96–97	1	30	'Mild' steel to AS 1204	150 x 100 x 3	Rolled – LSRM 2400	150 x 100 x 1
4	Navy Base	96–97	1	30	A36 (USA)[c]	150 x 100 x 3	Zinc[c]	150 x 100 x 3
5	Navy Base	91–93	2	45	'Mild' steel to AS 1204	150 x 100 x 3	Rolled – LSRM 2400	150 x 100 x 1
6	Water Board	91–92	1	45	'Mild' steel to AS 1204	150 x 100 x 3	Rolled – LSRM 2400	150 x 100 x 1
7	Water Board	91–93	2	45	'Mild' steel to AS 1204	150 x 100 x 3	Rolled – LSRM 2400	150 x 100 x 1
8	CSIRO	91–92	1	45	'Mild' steel to AS 1204	150 x 100 x 3	Rolled – LSRM 2400	150 x 100 x 1
9	CSIRO	91–93	2	45	'Mild' steel to AS 1204	150 x 100 x 3	Rolled – LSRM 2400	150 x 100 x 1
10	Kure Beach 25 m	96–97	1	90	0.2% Cu steel	100 x 50 x 3	Rolled – LSRM 2400	150 x 100 x 1
11	Kure Beach 250 m	96–97	1	90	0.2% Cu steel	100 x 50 x 3	Rolled – LSRM 2400	150 x 100 x 1
12	Kure Beach 250 m	see footnote d	1	30	A36 (USA)[c]	150 x 100 x 3	Zinc[c]	150 x 100 x 3

[a] Results for cases 1–11 are the means of duplicate results.

[b] The galvanised coating was 550 g/m^2 (2-sided) equivalent to a thickness each side of 39 μm and was chromate passivated. There was a total of 56 sites on a 2 x 2 km grid in a range of environments ranging from moderately severe marine to rural. Single results only for both steel and zinc at each site.

[c] Specimens processed by LaQue Corrosion Services.

[d] Averages for the years 1984–89 and 1991–93 inclusive (9 years).

South–East Melbourne, Australia

The data from a region south-east of Melbourne acquired during several programs is shown in Figure 4. (The legend to the figure is Table 2.) The unnumbered points are from a survey conducted at 68 sites on a 2 x 2 km grid (simultaneous data for steel and zinc is only available for 56 of these sites). The corrosion rate of zinc was obtained using galvanised steel specimens and the exposure period was two years, not one year. This two-year data is plotted along with data obtained from nearby sites and from different time periods (for exposure periods of both one and two years) and fits in with it very well. Numbered points are means of duplicate specimens.

Data points 1–4 are from a severe marine site (Navy Base Flinders[24,25]) with one-year exposures and agree with the trend of the two-year data. Data point 5 is also from the Navy Base but with a two-year exposure; it likewise agrees with the other data. Angle of exposure (points 2 and 3) has little effect on the results, but materials composition, specimen preparation, and thickness does appear to have an effect.

Data point 4 is for standard specimens supplied and processed by LaQue Corrosion Services, Kure Beach, NC. It is for US A36-type low-carbon steel, and zinc (both 3 mm thick) sandblasted prior to exposure. The measured corrosivity of this steel is slightly higher than the Australian steel (data points 2 and 3), but the corrosivity of the LaQue zinc specimens definitely appears lower than that for the zinc used for the ongoing monitoring of these sites. This material was rolled zinc (LSRM 2400) supplied by LaSalle Rolling Mills Illinois, was 1 mm thick, and was exposed degreased but without any other treatment to increase the surface area of the specimens. Although there are slight differences between these materials the general trend still exists; there is poor compliance with the ISO categories (i.e. points outside boxes).

Data points 6 and 7 are for one- and two-year exposures for a mild marine/rural site approximately 1 km from the Navy Base and points 8 and 9 are for CSIRO Highett (mild marine/urban). The two-year data again "fits in" with the one-year results.

At the same time as the data was collected for points 2, 3, and 4, an exchange of specimens was made with LaQue Corrosion Services and the "standard Australian specimens" were exposed at Kure Beach. The results for this one-year exposure are points 10 and 11 (25 m and 250 m sites respectively). A long-term average figure for the Kure Beach 250 m site (9 years) is point 12. It is obvious that the corrosivity of steel and zinc is much more in line with the ISO categories for these US sites.
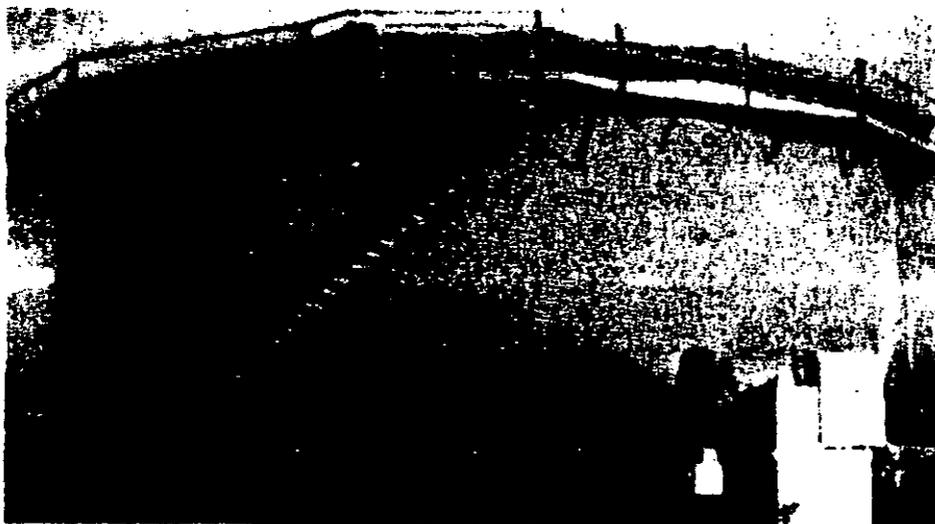
The steel specimens for points 10 and 11 were the low-alloy copper-bearing steel (Cu ~0.2%) which is not a weathering steel. The copper content means this steel falls outside the envelope for composition of carbon steel panels proposed in ISO 9226. As discussed previously, the composition was originally developed by BISRA as a reference material to monitor conditions at atmospheric test sites[21] and
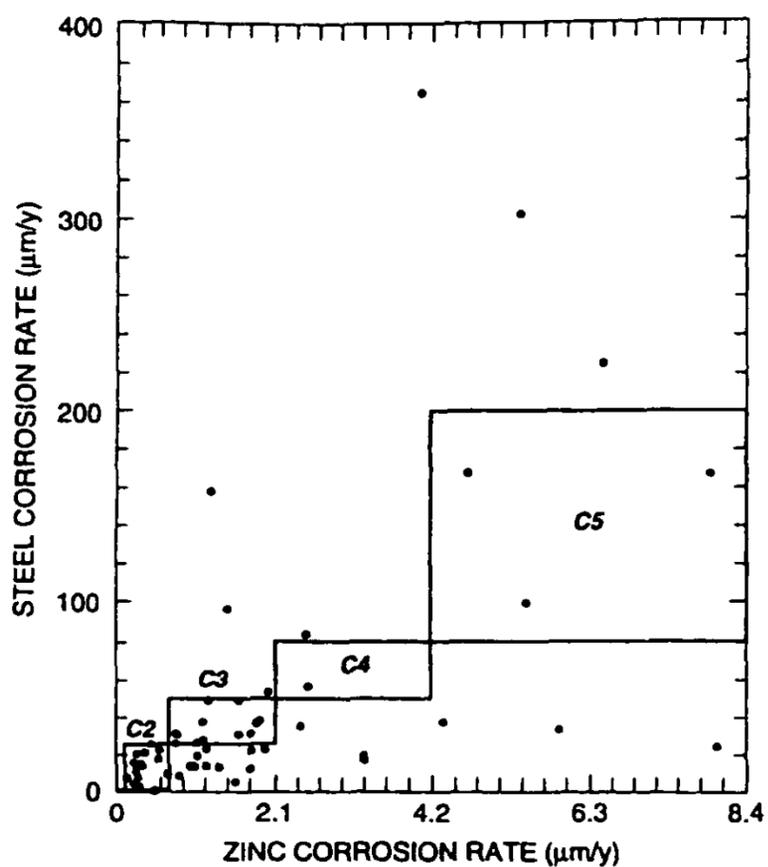
Figure 5. Plot of one-year corrosion rates for steel versus zinc for MICAT sites (refs 9, 10), together with ISO corrosivity categories.
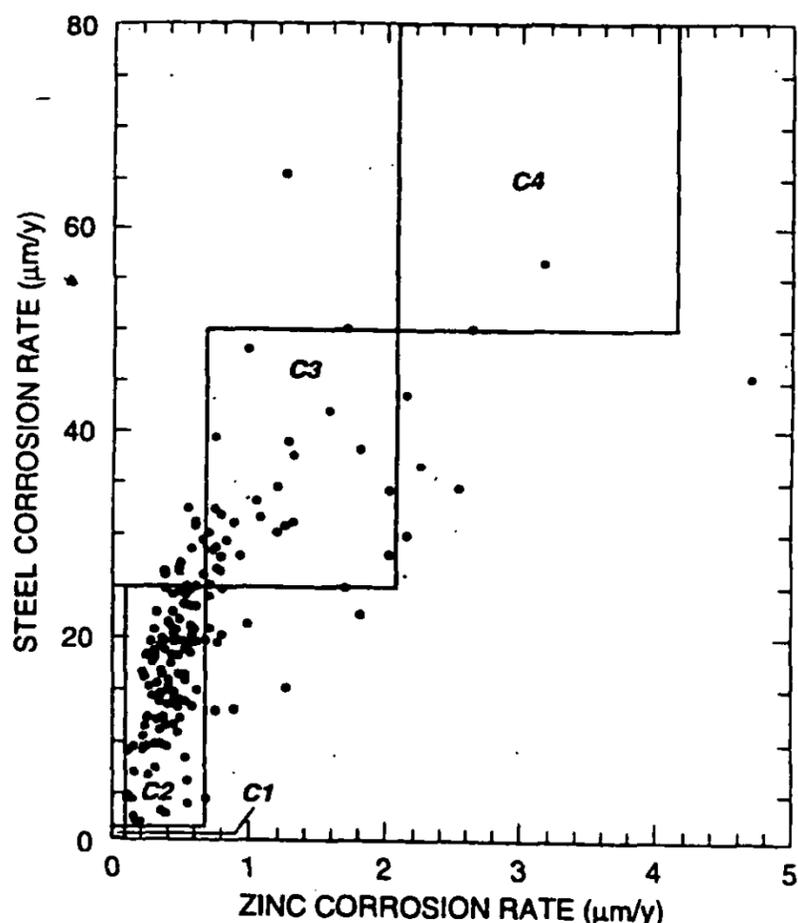

Figure 6. Plot of one-year corrosion rates for steel versus zinc for all of New Zealand (excluding two geothermal sites) (ref. 14) together with ISO corrosivity categories.

the materials' corrosivity is not significantly influenced by small variations in composition as would be expected in different batches, and can therefore adequately reflect changed corrosivity in different time periods with different prevailing environmental conditions. Several studies have shown that the corrosivity of conventional low-carbon "mild" steel is anywhere from the same[26] to 20% greater[27] than that of the copper steel. The extensive Melbourne study[16] found the corrosion rate of the conventional mild steel to be 12% higher than that of the copper steel at 67 sites (R^2 of 0.965).

The sites in south-east Melbourne all fall within the TOW category τ_4, the Navy Base site being on average 55%. The salinity category for the Navy Base is S_2 (average chloride deposition rate of 99 mg/m^2.d over 39 months from April 1993 to July 1995[25]) and the predicted ISO corrosivity category for the Navy Base is C4 for both steel and zinc. The measured corrosivity of zinc is generally category 5 and that for steel at the bottom end of category 3.

MICAT

The data from this very extensive project[9] conducted in 14 Ibero–American countries is plotted in Figure 5. There is significant disparity in the corrosivity categories of steel and zinc. In 29% of cases they are separated

by 1 class, in 13% by 2 classes, and in 2% cases by 3 classes. These figures are worse only the marine sites are considered but in prove for the urban and rural sites. There at only three industrial sites with simultaneou data, for which in two cases the results are i the same class and in one case separated by classes.

New Zealand

Data from the whole of New Zealand[12] (ex cluding that from two very corrosiv geothermal sites) is shown in Figure 6. Galva nised steel was used to determine th corrosivity for zinc. For this very extensiv survey (166 sites conducted in cold to warm temperate climates) the corrosivity of steel an zinc falls within the same class in over 80% of cases but a separate problem exists.

Long-term averaged data from the NZ Me teorological Service shows that for the main towns of New Zealand, the TOW (on the basis of >80% RH and >0°C) typically ranges from 45% (for example, Dunedin) to 65% (for example, Kaitaia or Invercargill).[28] The first year of exposure in the nationwide survey described in reference 12 had TOW values ranging from 43% at Wellington Airport to 64% at Warkworth. Thus, most of New Zealand falls within the τ_4, S_0–S_2 environmental categories (and $P_0 P_1$), i.e. the shaded area in Figure 1 which predicts corrosivity categories of 3 or 4 for both steel and zinc. As can be seen from Figure 5, the vast majority of the data falls within category 2. The ISO Standard markedly overestimates the corrosivity of both steel and zinc for New Zealand.

ASTM World Survey

Agreement of this data with the ISO categories is only fair, with the corrosivity of steel and zinc differing by 2 or 3 classes in a total of 10% of the cases.

Philippines

Galvanised steel was again used to determine the corrosivity of zinc. The study was conducted at only 10 sites (but with 2 batches of materials and 2 start dates). Based on the environmental data, τ_4, S_0, P_0 at nearly all sites the predicted corrosivity category should be

class 3 for both steel and zinc (at one of the sites class 3 or 4). However, as can be seen from the plot of the data in Figure 7, the corrosivity of steel is virtually always in class 2 and there is very poor compliance with the ISO boxes.

Former Far-Eastern Soviet Union

From what are reported[14] as relatively benign sites in the Asian sector of the former Soviet Union, data again shows poor compliance with the ISO categories, as seen in Figure 8.

Cuzco (Peru)

It is worth noting an unusual result reported for this location.[29] The ISO TOW is τ_4 with extremely low pollution which predicts a corrosivity category for steel of C3 (25–50 μm/y). The measured corrosivity was an average 1.4 μm/y.

PROBLEMS WITH DEFINITION OF "TIME OF WETNESS"

One way in which the overestimation of corrosion rates seen in the New Zealand,[12] Philippines,[13] and Peru[29] studies can occur is that the TOW is overestimated. Dean[14] has analysed the US corrosivity data for the ISO CORRAG program and found that ISO 9223 has underestimated some 20% of sites and overestimated for a comparable percentage of other sites, and suggested that some redefinition needs to occur.

The authors do not have a specific proposal for rectification of the method of estimation. However, the proposal by Dean and Reiser[31] that in dew formation a more complex driving force than simply "hours with RH>80% for T>0" is attractive. The issue of solar gain by surfaces, reducing the relative humidity in the air layer immediately adjacent to the surface, appears to warrant some careful consideration. Some reduction below an initially expected corrosivity value might be explained because even though the surface is in an environment where there is likely to be seasalt deposition, there is likely to be regular rainwashing (which is true of many tropical and temperate marine climates). Under these conditions, the rain-exposed surfaces may have relatively low chloride concentration, pushing them (even if they

were in S zones) into effectively $S_0 S_1$. But the ISO 9223[2] categories would still assign these surfaces to a C3 classification because of the TOW, which is in contradiction to the experimental evidence.

It is a regular occurrence for panels to be warm to the touch on a sunny day in Australia or New Zealand, even if the RH is at 90%. The water content of air required to create a bulk air RH of 90% at 18℃ is however only sufficient to generate a RH of 45% at 30℃. Panel temperatures can frequently get higher (by up to 20℃[32]) than this during sunny periods.

FAILURE OF THE ISO TOW CRITERION AT LOW TEMPERATURES

There is no doubt that the criterion fails in Antarctica where, despite the persistent myth that there is no corrosion because of the "dry cold", corrosion is significant in coastal areas. Corrosivity measurements were made at two sites in the New Zealand Ross Dependency in Antarctica by King et al.[33] Coupons of a standard low-alloy copper steel were exposed at Cape Evans (the site of Scott's hut which is very close to the sea) and at Vanda Station in the Dry Valleys (ice-free areas fed by cold air from the polar plateau where no rain has fallen in over a million years). Results were 10.83 and 0.87 μm/year respectively. The result from Cape Evans shows corrosivity comparable with suburban areas in temperate regions of Australia, and is certainly much higher than expected since the site is 77℃S and is surrounded by sea ice for 10 months of the year, with air temperatures rarely above 0℃. At the nearby McMurdo station (77℃51'S 166℃40'E) the mean temperature of the hottest month (January) for the years 1957–89 was –3.0℃.[34] In 1995 a mobile meteorological recording station (Pegasus South) was located very close to McMurdo (and Cape Evans) at 77.99℃S 166.58℃E. Readings of temperature were taken at three-hourly intervals.[34] In the hottest month (Decem-

ber, with an average maximum of 3.5℃ and average minimum of –9.4℃) the temperature exceeded 0℃ only about 17% of the time (i.e. 1.4% on the annual basis). Similar unexpectedly high corrosion rates, inconsistent with the nominal 30% TOW at the site, have been found elsewhere in Antarctica by South American workers.[35]

At Mawson, Australia's main Antarctic base (67℃36'S), corrosivity of the standard copper steel was measured at 3.4 μm/y.[36] There is only one month of the year (January) where the average temperature is above 0℃ (0.25℃) based on the mean daily maxima and minima.

These results are incompatible with the ISO definition of TOW being the "length of time when the relative humidity is greater than 80% at a temperature greater than 0℃". Salt deposition is significant in coastal regions of Antarctica. Rain is very rare and wind-driven salt deposits are not washed off surfaces. The phenomenon of depression of freezing point by salt solutions is well established.[37] With appropriate relative salt composition involving chlorides of calcium and sodium, the freezing point could be depressed to as low as –50℃. Given the salt deposition regime, and the absence of rainwashing, a scenario of a saturated salt solution at the surface is definitely feasible in
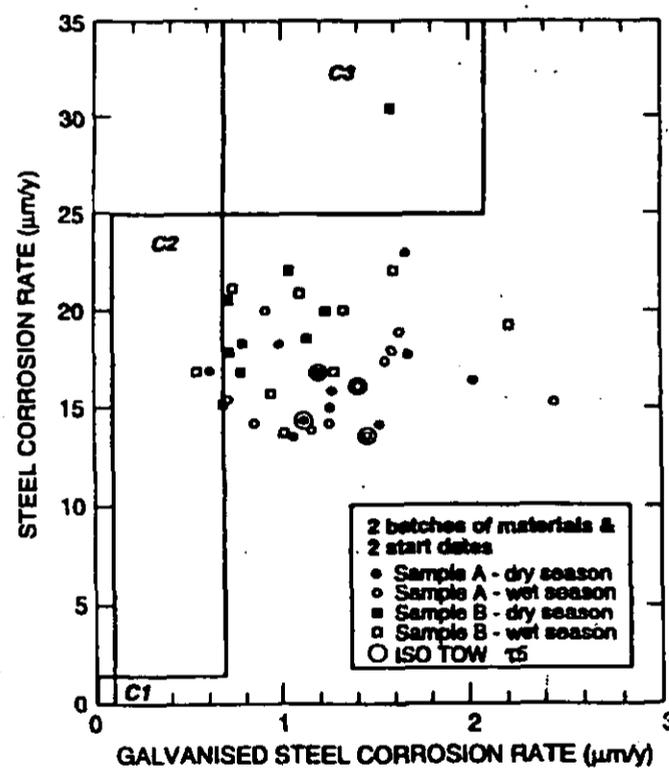

Figure 7. Plot of one-year corrosion rates for steel versus zinc for sites in the Philippines (ref. 15), together with ISO corrosivity categories.
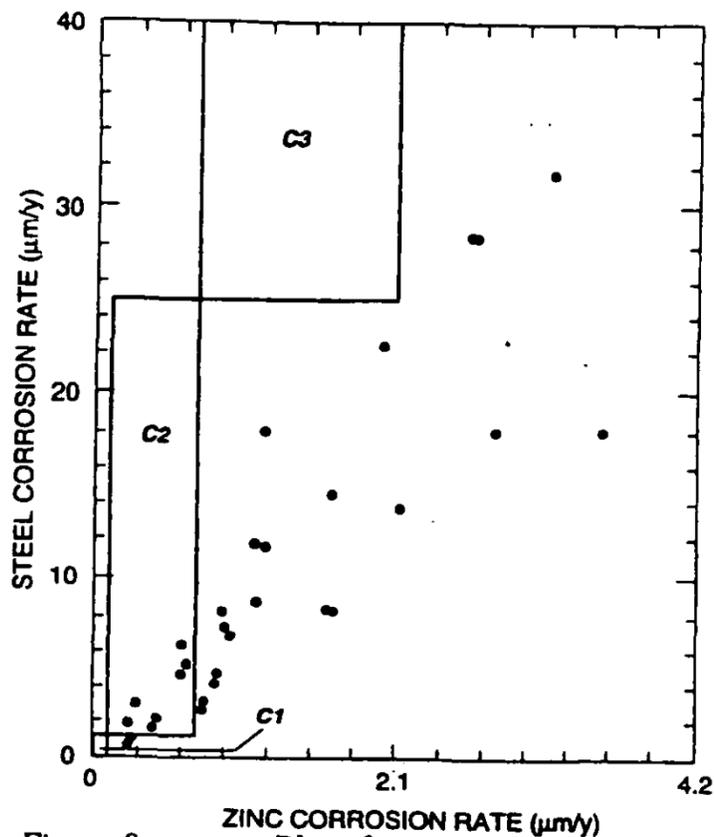
Figure 8. Plot of one-year corrosion rates for steel versus zinc for sites in the far eastern former Soviet Union (refs 16, 17), together with ISO corrosivity categories.

such environments.

It is possible also that the long hours of sunlight in the Antarctic summer can raise the surface temperature of dark objects considerably above the surrounding air temperature, as suggested above as a factor in temperate/tropical climates, but that the temperature rise is inadequate to totally volatilise the electrolyte layer. A confounding observation is that when the historic huts at Cape Evans were cleared of ice, the artefacts inside them (which had corroded very little in the preceding 60 years) started to corrode at significant rates, yet would not be subject to heating by direct solar gain.

INADEQUACIES IN THE NUMBER AND BREADTH OF THE CORROSIVITY CATEGORIES

Three of the studies referred to in Table 1[4,6,12] have sites for which the corrosivity of both steel and zinc exceed the limits of the C5 category, and there are a number of sites where the corrosivity of one of these metals exceeds the C5 limit, including two sites in Spain. Measurements in South Africa using mild steel and galvanised steel or zinc have shown very high levels of corrosivity at marine sites: e.g. Skulpfontein[42] – steel 458 μm/y, zinc 5.1 μm/

y; Koeberg – steel 597 μm/y, zinc 13.0 μm/y. A recent study in three Caribbean countries[38] had sites with corrosivity of steel up to more than four times the upper limit of category C5, and recommended a new category "be added to allow the inclusion of coastal zones in tropical areas".

The balance in the existing categories is also inadequate. For category C2, the range of corrosivity for steel is from 1.3 to 25 μm/y and for zinc from 0.1 to 0.7 μm/y, factors of 19 and 7 respectively. The rates for steel at the bottom of the range can be found in deserts or some Antarctic sites (though not coastal Antarctic regions, where corrosion rates can be substantial), and at the top are typical of temperate climates. A range of corrosion protection systems for steel would be required in such diverse environments. Ideally corrosivity categories should be able to be well identified and levels of corrosion protection matched to each category to ensure adequate life for service without overspecification.

The present ISO C2 and C3 categories combined would represent the majority of populated locations, and span a range of steel corrosivity of about 40. The authors therefore do not agree with the statement[6] that this number of classes is sufficient to cover the range of design and corrosion protection measures that may be required for practical purposes. It would be desirable for three categories of similar comparative range to cover this, but they might better be arranged in a geometric progression of limits (with ratios of the upper to lower limits approximately comparable), rather than an arithmetic progression as at present. Based on this, possible alternative ranges of corrosivity for steel for the categories could be:

C1	Minimal	up to 2 μm/y
C2	Mild	from 2–6 μm/y
C3	Moderate	from 6–20 μm/y
C4	Severe	from 20–50 μm/y
C5	Very severe	from 50–150 μm/y
C6	Extreme	greater than 150 μm/y

FINAL DISCUSSION AND CONCLUSIONS

It may be argued by some that the classifications provided by the ISO boxes are "good enough"—that after all, as shown in Table 1, the relationship between steel and zinc corrosion rates is adequately predicted for 70% of sites in the ISO CORRAG,[6] Spain,[10] and southeast Melbourne[16] cases (leaving aside the inaccurate predictions in New Zealand, the Philippines, and Peru). But this surely indicates that we have extensive further understanding and development of the Standard to do. If the assertion by Barton[1] is correct, and we have it wrong just 10% of the time, the cost of inaccuracy in this standard to the world economy is perhaps of the order of 0.1–0.2% of GDP.

The authors do not pretend to have all the answers. They are however concerned that in their dealings with their industries there is a perception that Standards are "right", and the evidence presented in this paper raises five especially important points:

- that the steel composition defined in ISO 9226 may be too broadbanded to provide reliable results for comparison with the meteorological predictor method;
- that ISO 9223 is in any case a poor predictor of corrosion rates (of zinc especially) in tropical and temperate marine environments, which seems related to inadequate estimation of the "time of wetness";
- that, in contradiction of ISO 9223, in the presence of chloride, corrosion continues at temperatures below 0°C;
- that consequently ISO 9223 is not a good guide for use by designers to the likely corrosivity of atmospheric environments; and
- that, even if the above defects can be addressed, there needs to be redefinition of the boundaries between corrosion rate zones, especially addressing segmentation of the C2 zone.

We look forward to constructive debate in progressing this standard further.
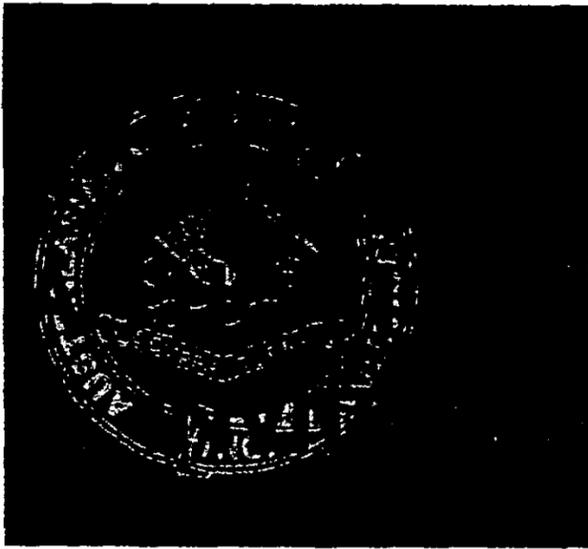
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