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Long-term immersion corrosion of steels in seawaters with elevated nutrient concentration

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Abstract

Data from a variety of field exposure programs is used to quantify the effect of concentration of dissolved inorganic nitrogen (DIN) on long-term seawater immersion corrosion loss of structural steels. A linear correlation model that asymptotes the long-term part of the previously proposed bi-modal corrosion loss model is used. It allows for average seawater temperature. Model parameters and their variability are determined and reported. The model permits prediction of long-term corrosion loss in nutrient polluted waters of known average temperature. An example shows that anthropological pollution of seawater potentially is a major hazard for corrosion of steel infrastructure.

Keywords: A: Steel; B: Modelling studies; B: Weight loss; C: Microbiological corrosion.

Introduction

A previous paper [1] considered the ratio of the corrosion loss of steel piling immediately below the low tide level relative to the corrosion loss in the immersion zone. It, and a subsequent paper [2], showed that this ratio is positively correlated with the annual average concentration of dissolved inorganic nitrogen (DIN) in the local bulk seawater. However, the actual magnitude of corrosion loss was not established. The present paper deals with estimating the magnitude of the corrosion loss in immersion conditions under elevated DIN concentrations. Specifically, a quantified relationship is developed between immersion corrosion loss and the average DIN in the seawater local to the steel of interest. Such a relationship has not been developed previously.

Structural steel is used widely for major infrastructure in or around seawater harbours, for shipping and for offshore structures. Protection using coatings or cathodic protection systems or both can be effective if properly maintained. However, some infrastructure is unsuited to such protective measures and reliance usually is then placed on a sacrificial corrosion allowance. For example,

corrosion allowances in ships [3] typically are given in terms of a corrosion rate, such as 0.1-0.5 mm/y, implying that corrosion loss is a linear function of time, commencing at the origin. However, a variety of data show that corrosion loss for steel in marine exposure conditions is not a simple linear function of time [4,5]. It also is a function of water temperature and may be subject to the additional effect of microbiologically influenced corrosion (MIC). The latter is known to be a function of the nutrients, and in particular DIN, present in seawater [6]. This has been demonstrated in laboratory experiments [7] and, more recently in both short term and long-term field observations [8,9]. These works did not, however, develop quantitative relationships between immersion corrosion loss and the seawater DIN concentration in the immediate vicinity of the corroding steel.

Considerable research effort has focussed on identification and understanding the behaviour of the many microorganisms potentially involved in the microbiologically influenced corrosion (MIC) of steel in seawater [6]. In brief, the species traditionally associated with corrosion of steel in seawater are the obligatory anaerobic sulfate reducing bacteria (SRB) for which the causative agent for MIC has been considered the metabolic product H_2S [10]. However, many other species, including archaea, have been implicated in causing MIC [11] and the list continues to grow [12,13].

Irrespective of the precise species involved, microbiological activity can influence corrosion only if the microorganisms are in appropriate environmental conditions and have sufficiently high rates of supply of energy and of necessary nutrients [6]. In the corrosion process energy is available directly from the electron flow associated with electrochemical and chemical reaction kinetics. In natural seawater most nutrients, such as organic carbon, sulfates and phosphates are readily available and in steel corrosion the nutrient usually limiting microbiological activity, iron, is provided by the corrosion process as Fe^{2+} [6].

Rather than focussing directly on the microorganisms and their interaction with and influence on the corrosion processes, a more practical approach is to consider the relationship between the availability of DIN for microbiological activity and the severity of the resulting corrosion. This approach by-passes detailed consideration of the complex issues associated with microbiology. Instead it considers input-output correlation between nutrient concentration and corrosion loss or corrosion behaviour. This approach has been applied successfully for estimating the effect of DIN concentration on the accelerated low water corrosion (ALWC) of steel piling in seawater harbours [1,2]. It is applied also for the analysis described below. It is noted in passing that even in heavily polluted waters the concentration of DIN is much too low to have a direct effect on the purely electro-chemical corrosion processes, that is through changing the properties of the electrolyte (seawater).

In principle, a relationship between the long-term marine immersion corrosion loss of steel, the DIN concentration in the bulk seawater, the average water temperature and the length of the exposure period could be developed empirically using only field observations. However, a more rational approach is to employ also knowledge gained from earlier studies about the expected progression of corrosion with exposure time. The next section outlines this earlier work, including the basic corrosion loss – exposure time model and its linearised simplification. This is then used to interpret available data and to evaluate the parameters for the model as functions both of average DIN and of annual mean water temperature.

Corrosion loss function

A non-linear model for the progression of uniform or general corrosion through a series of sequential phases was proposed earlier and calibrated to available long-term data that took into account the significant influence of seawater temperature [4]. The theoretical basis for the main parts of the model, and the associated mathematical expressions, has been described [14]. The model has been refined and extended to deal with dissolved oxygen concentration, seawater velocity and the influence of steel composition and it has been shown to apply also to tidal and marine coastal atmospheric exposures [15]. A schematic summary of the principal parts of the model is shown in Fig. 1. The solid line shows the bi-modal corrosion trend under abiotic conditions and the broken line the effect of MIC on longer-term corrosion loss.

Figure 1 here

It is well-known MIC can contribute to corrosion from the beginning of exposure as shown both in laboratory and field studies [7,8] but for the present purposes only the effect on longer-term corrosion (phases 3 and 4) is of interest. The mechanism most likely to be rate-controlling for longer-term corrosion is diffusion of nutrients through the rust layers [14]. As a first approximation this may be modelled as Fickian diffusion, governed by diffusivity of the rusts and by the concentration of nutrients in the bulk water assuming they are fully consumed within the rusts. As a result of the enhanced rate of microbiological processes a greater rate of rust production can be expected (i.e. due to MIC) and overall thicker, more developed rusts can be expected. These can be assumed to provide, as corrosion progresses, increasing resistance to diffusion of nutrients as well as other species and consequentially produce a gradually declining rate both of microbiologically influenced and abiotic corrosion. The result is the polarization of the corrosion rate, as seen in phase 3 (Fig. 1).

Phase 4 of the model is based on compendium of empirical observations [4], including those reported by Forgeson et al. [16] and by Southwell et al. [17] for exposures of steels up to 16 years in tropical seawaters. These data show that after about 1-1.5 years exposure, which corresponds in these cases to the end of phase 3, the corrosion loss as a function of time can be modelled as a linear function [4]. The relatively low value of the long-term rate of corrosion in phase 4 has been attributed to the effect of accumulated corrosion products reducing diffusion, counteracted to some degree by losses of outer rusts caused by slow erosion and by occasional shedding of rusts. Some empirical evidence exists for these mechanisms [18]. On the basis of these observations, it will be assumed for the present purposes that the model of Fig. 1 can be simplified to the linear functional relationship shown in Fig. 2 for long-term exposures. It consists primarily of the linear function B-C representing long-term progression of corrosion (phase 4 in Fig.1) but extended back to A at $t = 0$. A model similar to A-B-C was first suggested by Southwell et al. [19]. It was based only on empirical corrosion loss data from the Panama Canal Zone. A refinement is to approximate also the rate of early corrosion loss, modelled as linear function 0-D. Herein only the linear function A-B-C is considered.

Figure 2 here'

Unlike the conventional average 'corrosion rate' the linear function A-B-C does not pass through the origin. It may be parameterized by c_s and r_s that describe the intercept of the linear function on the corrosion loss axis and the slope of the linear function respectively. Both parameters c_s and r_s are functions of mean seawater temperature, at least for unpolluted and aerated coastal seawaters with low water velocity and wave action typical for such waters [4,14]. The neglect of phases 0-3 in the simplified model is appropriate for exposure durations in excess of about $2.t_a$ (see Fig. 1) where t_a was defined earlier as a function of seawater temperature [4]. *In tropical waters t_a typically is less than one year and it is about 3 years in temperate waters such as in the North Sea.* In the following, data recently available in the literature are used to evaluate c_s and r_s as functions of both average seawater temperature and the DIN concentration in the bulk seawater adjacent to the steel.

Data

Table 1 summarizes data for corrosion losses in the immersion zone measured at 8 different exposure sites on the East coast of Australia, for exposures longer than 12 months [1]. Also shown is the annual average concentration of dissolved inorganic nitrogen (DIN), measured at each site several times each year over a period of at least one year. The second set of data in Table 1 is for immersion corrosion losses reported for sheet piling at 8 different US Navy bases obtained from

coupons cut from the piles after many years continuous exposure [20]. Data are included also for some other US sites at which experimental exposure tests were conducted over 5-year exposure periods on H and other steel piles [21]. For each of these sites the annual average DIN concentrations were estimated from US EPA and other records [2]. These are shown in Table 1.

The third set of data in Table 1 is for corrosion losses of steel coupons [22]. These data can be used here since it has been shown [23,24] that under relatively shallow immersion conditions the corrosion loss for an individual coupon is very similar to that for a vertical steel strip and is almost independent of depth of immersion. The immersion corrosion data for strips and for coupons are therefore directly comparable and may be used together in the data-base. DIN concentration estimates for these sites were reported earlier [22]. For each of the 24 different sites in Table 1, column (3) shows the net period of exposure (t_e), column (5) the corresponding estimated annual average DIN concentration and column (7) the corresponding corrosion loss $c_P(t_e)$.

Table 1 here

Analysis

The effect of nutrient concentration on corrosion loss can be quantified only by comparing corrosion losses $c_P()$ under elevated concentrations of DIN with corrosion losses $c()$ under negligible or background concentrations of DIN. The sites shown in Table 1 had elevated concentrations of DIN and typically the value of corrosion losses that could be expected to occur at these locations under negligible or background concentrations of DIN are not available. The only possibility in these cases is to estimate the corrosion expected to occur under negligible or background concentrations of DIN. This was done using the bi-linear model of Fig. 2 using parameters c_s and r_s as applicable to normal (unpolluted) coastal seawaters. Both parameters depend on mean seawater temperature and for mild steel in unpolluted seawater were previously derived from field data [14]. Their values are shown in Table 1, columns (8) and (9) respectively, for each site.

Table 1 also shows the total exposure periods t_e (column 3). This is taken as the recorded total period of exposure, unless there is evidence of protective (paint) coatings or cathodic protection having been applied. For protective coatings under continuously immersed conditions an effective life of 12 years was assumed and only the subsequent, unprotected, exposure period is considered in the analysis. For piles with cathodic protection, a similar approach is applied.

For each site the corrosion loss expected at t_e for natural coastal seawater at the temperature shown in Table 1 is given by $c(t_e) = c_s + t_e \cdot r_s$ and is shown in column (10). These values may be compared with the corrosion losses $c_p(t_e)$ under elevated DIN conditions (column 7) to obtain the ratio $R_p = c_p(t_e) / c(t_e)$, shown in column (11). Fig. 3 shows the values of the ratio R_p plotted against the values N for the average DIN concentration given in Table 1. It is clear that the data fall into two groups – short-term exposures, mainly up to 2 years and some up to 5 years, and much longer exposures, around 20 years on average. A linear trend line has been fitted through each data set using a least squares fitting routine to give two mean trends of the data.

Figure 3 here

Estimates of the uncertainty in the ratio R_p can be made by considering it as a random variable denoted $R_p = Y \cdot R_{pnom}$ where R_{pnom} is the nominal value of R_p as given by the relevant trend line in Fig. 3 and Y is a random variable used as bias function, with a theoretical mean of unity and with standard deviation determined by the spread of the data about the trend line at a given time N . A similar approach applies for each of the two lines shown in Fig. 3. The statistical properties of Y for each trend line are determined as follows. The value of each data point of DIN concentration N is divided by value of $R_p = R_{pnom}$ at that value N . The mean and standard deviation are then determined using all the data points relevant to that trend line. The results are shown in Table 2. They show that the mean of the bias, even with as few as 10 data points, is close to the theoretical bias mean value of unity. The standard deviations reflect the spread of the data points about each of the two trend lines shown in Fig. 3.

Table 2 here

Estimates can be made of the changes in c_s and r_s with increase in average water temperature T . This was done using the mean trends in Fig. 3 and the annual average temperature data in Table 1 as well as the value of c_s and r_s previously obtained for nominally unpolluted seawater [14]. For any given average seawater temperature T_i say, this would give parameters c_{s0} and r_{s0} say. These are used to construct a corrosion loss plot c - t for DIN = 0. From Fig. 3 for DIN = 0 the ratio R_p is unity and thus $c(0) = c_s$ and the slope of the corrosion loss plot $r = r_s$ are equal to c_{s0} and r_{s0} respectively. For a different value of nutrient pollution, DIN = 0.2 mg/L, say, Fig. 3 provides the multiplier R_p for short and long term exposures respectively. This allows the corrosion loss c_p at time $t = 0$ to be estimated from $c_p(0) = R_p \cdot c(0)$. Similarly, at some long exposure time, $t_j = 20$ years, say, the corrosion loss is then $c_p(t_i) = R_p \cdot c_0(t_i) + r_s \cdot t_i$ with $t_i = 20$. The slope between $c_p(0)$ and $c_p(20)$ is then equal to r_s for the current value of DIN at temperature T_i . The results are shown in Figs. 4 and

5 for mean values of c_s and r_s . Both Figures also show the trends that are ($\pm$) one standard deviation away from the trend of the means. These were derived directly from R_P and the values in Table 2. Scatter bounds are not shown for the trends $DIN = 0$ since these do not involve R_P . This does not mean that there is no scatter in these trends but only that scatter bounds were not quoted in the original sources. [Scatter in the data and in the trends is inevitable in any approach that uses uncontrolled observations such as obtained from field data \[25\]. The scatter is the result of imperfect observation and imperfect characterization of local conditions such as the nutrient concentration immediately adjacent to the steel surface.](#)

By working through the effect of R_P for short and for long-term exposures (taken here as 20 years), the trends for ($\pm$) one standard deviation for r_s correspond to approximately $\pm 10\%$ of the mean value. [For clarity only one](#) set of such trends is shown in Fig. 5, for the case $N = 0.4$ mgN/L. Generally similar trends apply for other values of N .

Figure 4 here

Figure 5 here

Discussion

Despite the scatter in the data in each set, the trends shown in Fig. 3 in each case are as expected. The trend for short-term corrosion is broadly consistent with early rate of corrosion shown schematically as 0-D in Fig. 2. This corresponds to the period in which there is a relatively thin and immature build-up of rusts so that the diffusion of nutrients from the bulk water to the corroding surface can be expected to be at a higher rate than for the later thicker, denser and more mature corrosion products. The latter are likely to be associated with the trend A-B-C for long-term exposures (Fig. 2) and with a lower rate of nutrient diffusion.

Fig. 4 shows that DIN concentration has a considerable influence on c_s and that this is the case for all values of seawater temperature T . The rate of increase in c_s is about 100% per 0.1 mg N/L at 25°C and about 130% at 5°C. The long-term corrosion rate r_s (Fig. 2) also changes with DIN concentration, increasing about 10% per 0.1 mg N/L at 25°C, but showing only negligible change at 5°C. These observations can be interpreted as showing that increased DIN concentration has the greatest effect during phase 3 of the bi-modal model (Fig. 1). Both in the bi-modal model and in its simplification (Fig. 2) an increasing value of the parameter c_s causes the long-term trend to be shifted upwards. In contrast, DIN concentration has a much smaller effect on the long-term

corrosion rate parameter r_s . Further, higher water temperatures cause t_a (Fig. 1) to be of shorter duration [4]. This results in both the magnitude of c_s and changes in c_s to be relatively less important as the value of T increases. In contrast, the long-term corrosion rate r_s increases with T , consistent with expectations that the rate of corrosion, and also microbiological activity, are functions of temperature. The rate of increase suggests that the governing corrosion process lies between kinetic control and diffusion control [26].

The application of the functions for c_s and r_s in Figs. 4 and 5 is illustrated as follows. For simplicity only the mean values are used here. Consider a site with a bare, unprotected steel structure required for an exposure period of $t_e = 20$ years. The mean annual seawater temperature is $T = 10^\circ\text{C}$. Let the concentration of DIN expected to occur over this period be denoted N . The corrosion loss at time t_e is given by:

$$c(T, N, t_e) = c_s(T, N) + t_e r_s(T, N) \quad (1)$$

The values of c_s and r_s can be read from Figs. 4 and 5 for $T = 10^\circ\text{C}$. The simplified corrosion loss plots, similar to Fig. 2, are then obtained for $0 < t_e < 20$ and $N = 0, 0.2$ and 0.4 mgN/L, as shown in Fig. 6.

Figure 6 here

Fig. 6 illustrates the marked increase in longer-term corrosion resulting from DIN for $T = 10^\circ\text{C}$. As expected from the exposition above, Fig. 6 shows that compared to Fig. 2 the parameter c_s has the most influence on the corrosion loss trend, causing an upwards shift, whereas the actual slope of the corrosion trend, given by r_s , changes only slightly. The direct implication of this observation is that the effect of nutrient pollution on corrosion should be detectable relatively early – that is, within only a few years of first exposure. This can be seen in the present case by comparing the simplified linear model with the full bi-modal model, shown schematically at lower left, scaled for time and for seawater at 10°C . It shows that the long-term corrosion trend at this temperature is developed after about 5 years exposure. This means that the full effect of elevated nutrient levels should be detectable well within this time period.

Generally similar trends are shown in Fig. 7 for seawater with an annual average temperature of $T = 25^\circ\text{C}$. Compared with Fig. 6, in this case the increase in the long-term corrosion rate r_s with DIN is somewhat larger, as expected for the higher average water temperature. However, the values for c_s are slightly lower, consistent with Fig. 4.

Figure 7 here

As noted, for seawater DIN is the nutrient usually considered rate controlling for microbiologically influenced corrosion. DIN also is known to be largely the result of anthropological water pollution. For harbours and near-shore locations, predominately it is the result of agricultural fertilizer runoff, feedlot waste runoff and sewage plant effluents. Conventional secondary sewage treatment does not remove nitrogenous matter, with the result that in certain geographic locations sewage plant effluent may be the most significant contributor to elevated nitrate concentrations in receiving waters. Discharges from various industries such as abattoirs, intensive animal husbandry and fish processing [27] also may be involved. Away from the coast, local water nutrient pollution can result from uncontrolled discharges from offshore oil production and storage facilities [28].

Apart from nitrates, other nitrogenous pollutants such as ammonia and nitrite often are recorded in fresh pollutants. However, both usually oxidize relatively quickly to nitrate [once exposed to natural, aerated seawater](#) [29]. As a result nitrate usually is the major component of DIN [in seawater](#). In most cases seasonal variation in nutrient concentration in seawaters is typical. It also may vary with geography and depend on the location of polluting sources and their rates of discharge into receiving waters. A well-documented example is the North Sea and adjacent Atlantic Ocean seawaters for which anthropological and other pollution has been extensively and intensively studied [29]. The results shown in Fig. 6 are directly relevant for the North Sea. Depending on location, DIN in the North Sea ranges from 0-0.1 mgN/L in summer and up to 0.5 mgN/L along the coast in winter. Fig. 6 shows that the latter will increase corrosion loss by more than 50% after 20 years exposure compared to that expected in unpolluted waters. For shorter periods of exposure Fig. 6 shows a greater percentage increase.

Taken together, the above indicates that when protective measures such as protective coatings and cathodic protection are ineffective or impractical, the corrosion of steel infrastructure in immersion conditions can be much increased by anthropological water pollution and in particular by nitrogenous nutrients. Conversely, corrosion of steel infrastructure located in nutrient polluted waters can be reduced considerably by reduction of anthropological water pollution and in particular of nitrogenous nutrients. In practice reduction of DIN into receiving waters may not be politically or technically feasible or may be not cost effective. However, understanding the implications that nutrient pollution may have on the long-term life of steel infrastructure potentially is important in decisions about the economic balance between the life of marine infrastructure and

protective measures on the one hand and the cost of environmental and pollution controls on the other. This is undoubtedly a matter for further investigation.

Finally, herein only long-term corrosion effects were considered and seasonal variations were ignored. It is considered unlikely that these will have an effect on longer-term corrosion in nutrient polluted waters but it remains a topic for further research.

Conclusion

1. Corrosion loss of steel in seawater immersion conditions can be modelled, for longer-term exposures, as a bi-linear function of time. Herein the relationship has been quantified, for the first time, both as a function of the average seawater temperature and the average local concentration of dissolved inorganic nitrogen in the bulk seawater.
2. For long-term exposures the bi-linear function asymptotes the previously developed bi-modal model for corrosion loss.
3. The model parameters were obtained by calibration to long-term corrosion loss field data drawn from a variety of sources and are reported herein. Estimates for uncertainties in model parameters are reported also.
4. The model predicts that under elevated nutrient concentrations corrosion losses are considerably higher than usually experienced in unpolluted seawaters. An example for the North Sea shows corrosion losses more than 50% higher than otherwise expected. It illustrates that anthropological pollution of seawater and the consequent increase in corrosion potentially is a major hazard for long-term durability of steel infrastructure.

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FIGURE TITLES

Figure 1. Schematic non-linear (bi-modal) model (solid trend line) for the progression of (uniform) corrosion loss with time showing the influence of some of the major parameters involved, including the influence of nutrients (shown as microbiological effect, broken line) on long-term corrosion. On the horizontal time scale t_a is about 1 year for waters at 20°C average and about 3 years for waters at 10°C average. Phases 0-4 have been described in the literature [4,15].

Figure 2. Schematic simplification of the model in Fig. 1 for long-term corrosion as a long-term linear function parameterised by c_s and r_s . This simplification is valid for $t > B$. Also shown is that the initial corrosion rate r_0 is an approximation to Fig. 1 for only for only a short time.

Figure 3. Data and trends for the ratio R_p between corrosion loss with and without the influence of microbiological activity as a function of Dissolved Inorganic Nitrogen (DIN), for both short-term periods of exposure and for long-term exposures (see text).

Figure 4. Parameter c_s (defined in Fig. 2) as a function of average annual seawater temperature T and Dissolved Inorganic Nitrogen (DIN). Also shown are the uncertainty estimates for c_s defined by plus and minus one standard deviation. There is no uncertainty shown for DIN = 0 (see text).

Figure 5. Parameter r_s (defined in Fig. 2) as a function of average annual seawater temperature T and Dissolved Inorganic Nitrogen (DIN). Also shown, for DIN = 0.4 mgN/L) are the uncertainty estimates for r_s defined by plus and minus one standard deviation. The others are not shown for clarity.

Figure 6. Estimated corrosion loss trends as a function of exposure period for 10°C average seawater temperature and two levels of elevated average seawater bulk DIN concentration. The bi-modal model (Fig. 1) is sketched to scale in the lower left corner for this water temperature.

Figure 7. Estimated corrosion loss trends as a function of exposure period for 25°C average seawater temperature and two levels of elevated average seawater bulk DIN concentration. The bi-modal model (Fig. 1) is sketched to scale in the lower left corner for this water temperature.

FIGURES

A model for long-term marine corrosion of structural steel and the effect of seawater nutrient pollution

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Table 1. Data for corrosion of immersed structural steel and local dissolved inorganic nitrogen (DIN).

Site	Source Ref.	Net Exposure Period t_e Years	Annual Average Temp. °C	Av. DIN ^a mgN/L	Average Corrosion Rate mm/y	Observed Corrosion $c_P(t_e)$ mm (O)	Unpolluted c_s mm	Unpolluted r_s mm/y	Unpolluted Predicted Corrosion $c(t_e)$ mm (P)	Ratio R_P (O/P)
Column Number	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Thames Estuary	8	5	10	0.3 (-0.5)		0.57 (est)	0.135	0.05	0.385	1.48
North Sea (I4, H1)	8	7.2	10	0.15		1.11	0.135	0.05	0.495	2.24
Moreton Bay	8	2	21	0.05		0.46	0.105	0.07	0.245	1.88
Newcastle Harbour	8	2.2	20	0.02		0.27	0.105	0.07	0.259	1.04
Taylors Beach	8	3	20	0.05		0.25-0.3	0.105	0.07	0.315	1.0
Coffs Harbour	8	2	21	0.005		0.30	0.105	0.07	0.245	1.22
Townsville	1	2	26.5	0.02		0.48	0.105	0.09	0.275	1.75
Taylors Beach	1	2	20	0.065		0.41	0.11	0.07	0.25	1.64
Williamstown	1	1.5	16	0.125		0.35	0.125	0.058	0.212	1.64
Queenscliff	1	2	16	0.095		0.45	0.125	0.058	0.241	1.87
Queenscliff	1	3.2	16	0.095		0.55	0.125	0.058	0.31	1.77
Hobart	1	2	15	0.09		0.46	0.125	0.06	0.205	1.88
Hobart	1	3	15	0.09		0.70	0.125	0.06	0.305	2.30
Port Arthur	1	2.1	15	0.10		0.40	0.125	0.06	0.251	1.80
Boston MA	2	18	10	0.2	0.064	1.15	0.135	0.05	1.035	1.11
Norfolk VA ^b	2	15 (27)	16	0.4	0.070	1.47	0.125	0.06	1.025	1.43
Key West FL	2	22	21	0.03 - 0.04	0.075	1.65	0.105	0.07	1.645	1.03
Coco Solo PCZ	2	24	27	0.03	0.120	3.24	0.105	0.09	2.54	1.27
San Diego CA	2	18	17	0.2	0.100	1.8	0.122	0.062	1.238	1.45
Alameda CA ^c	2	21	16	0.28	0.075 ^f	1.58	0.125	0.058	1.343	1.18
Puget Sound WA ^d	2	9 (14)	11	0.07	0.085	0.77	0.13	0.052	0.59	1.288
Pearl Harbor HI ^{b,e}	2	2 (14)	25	0.11	0.090	0.72	0.105	0.082	2.69	-
Buzzard Bay MA ^c	2	5	9	0.28		0.1	0.13	0.048	0.37	-
La Costa Island FL	2	10	24	Negligible			0.11	0.08		1.0
Kure Beach NC	2	5	15	Negligible	-		0.125	0.06		1.0
Harbor Island NC	2	5	15	0.06-0.12		1.2	0.125	0.06	0.43	2.79

Trondheim, N	2	26	4	0.75		2-2.4	0.14	0.04	1.14	2.12
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Notes:

^a Assumes DIN is primarily NO_3^- and NH_4^+ is ignored (see text).

^b Protective coating - assume coating life 12 years before failure.

^c DO likely to have been low.

^d Cathodic protection applied at year 9.

^e High concentration of biocides etc. noted in seawater.

^f Rate changed from 0.055 to 0.075 mm/y after review.

Table 2. Statistics of the (bias) random variable Y in $R_p = Y \cdot R_{pnom}$

Trend line	No. of samples	Mean	Standard Deviation	Variance
Short term	10	1.042	0.154	0.024
Long term	15	1.046	0.257	0.066
Theoretical		1.000		