Examples of mathematical modelling of long term general corrosion of structural steels in sea water

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Recent progress has been made in developing a mathematical and probabilistic model for general corrosion of structural steels exposed to sea water immersion corrosion. It is based on corrosion science principles, with early corrosion controlled by oxygen concentration limitations that eventually evolve to anaerobic bacterial controlled corrosion behaviour. The model has been calibrated to extensive literature data and original field tests. Herein, three different sets of corrosion field data, for Halong Bay in Vietnam, for an offshore oil platform site and for three coastal sites along the China coast are examined for compatibility with the model. It is shown that all the data are consistent with the model provided allowance is made for the season of the first immersion, the effect of sea water velocity and the possibility of nutrient pollution. In its most general form, the model is probabilistic to allow for natural variability owing to unrecorded (and perhaps unrecordable) influences. The data considered herein are sufficient for comparing with the expected value of the model but not for considering statistical variability. Finally, the model provides plausible explanations for differences in observed corrosion at different sites, considered by others to be due to the action of hard marine fouling.

Keywords: Structural steel, Corrosion, Sea water, Temperature, Oxygen, Models, Data

Introduction

Estimation of the likely general corrosion loss for structural grade steels in marine immersion environments is important for the design and evaluation of marine infrastructure, including sheet piling, bridges, jetties, pipelines, offshore structures and ships. This is despite the extensive use of protective coatings (paints), sacrificial coatings (galvanising) and impressed current cathodic protection, because such systems are not always effective, particularly under less than ideal operational or maintenance conditions. While the corrosion literature contains a wealth of information derived from laboratory observations, mainly electrochemical, there is only limited controlled (rather than anecdotal) information for field conditions. After an extensive review and re-examination of data sources, probabilistic models for general (and for pitting) corrosion as a function of time of exposure were introduced recently.¹⁻⁴ The model for general corrosion is reviewed briefly in the next section. It has previously been calibrated to data for immersion conditions from a variety of sites world wide judged to have conditions similar to the 'at sea' base line assumed for the model. Average sea water temperature was found

to be the main influencing variable. However, there are many other possible influencing factors, such as season of the first immersion, water velocity, nutrient pollution, dissolved oxygen levels, water depth, pH and calcium carbonate levels and salinity, etc. As described in a little more detail below, explanations for the effect of the first four have been given in the literature recently.

The purpose of the present paper is to examine the applicability of the model and its extensions to corrosion data reported for the following locations:

- (i) Halong Bay, Vietnam⁵
- (ii) in an oil field in the Chengdao Sea, China⁶
- (iii) along the China coast at Qingdao, Xiamen and Yulin.⁷

Various explanations have been offered for the observations at each site. Herein different explanations are offered based on the model proposed in Refs. 1 and 2. As can be seen, the data for the first suggest evidence of nutrient pollution, whereas the others are consistent with a significant influence of sea water velocity. They were also exposed at the beginning of winter, thereby delaying somewhat the early development of corrosion owing to a period of lower sea water temperature.

Phenomenological model for corrosion loss

Detailed field investigations and a very extensive review of field observations reported in the literature have

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1 Immersion corrosion loss as function of exposure time showing changing phases of corrosion process and parameterisation

shown that general corrosion is not a simple function of time, such as a linear function (a 'corrosion rate') or one represented by the commonly used expression for corrosion loss $c = At^B$ where t is the exposure time and A and B are constants, most commonly obtained by an empirical fit to a data set. Consideration of basic theoretical corrosion principles indicated that the early corrosion behaviour should be governed by oxygen concentration and diffusion limitations and that anaerobic mechanisms govern later. This led to the model shown schematically in idealised form in Fig. 1.¹

The model consists of a number of sequential phases, corresponding to the different processes controlling the (instantaneous) rate of corrosion. For 'at sea' conditions, the phases of the model may be summarised as:¹

- (i) phase 0 – a very short time period during which corrosion is under 'activation' or kinetic control and is governed by the rate at which local chemical reactions can occur unhindered by external diffusion or transportation limitations
- (ii) phase 1 – a period of 'oxygen concentration' control, with the corrosion rate governed by the rate of arrival of oxygen through the water and the corrosion product layer to the corroding surface.^{8,9} It has been shown that this phase can be modelled, to a first approximation, as a linear relationship between depth of corrosion and time of rate r_0 (Ref. 10)
- (iii) phase 2 – in this phase the corrosion rate is controlled by the rate of oxygen diffusion to the corroding surface through the increasing thickness of corrosion product. This is, therefore, a non-linear function of time. A theoretical description for it has been developed.⁹ As the corrosion products build up, the oxygen flux will decline and eventually anaerobic conditions will be established in the zone between the corrosion product and the corroding metal (see point AP in Fig. 1). This is, of course, an idealisation of the variable conditions that will actually exist over a surface
- (iv) phase 3 – in this phase corrosion is controlled by the metabolic rate of sulphate reducing bacteria (SRB) under anaerobic conditions.^{11–13} Often phase 3 is a period of rapid growth of SRB resulting from the conditions now being suitable for their increased metabolism and from the plentiful supply of nutrients. The

2 Initial corrosion rate r_0 as function of average sea water temperature

high rate of metabolite production initially produces a high rate of corrosion, but this reduces to a quasi-steady state situation in equilibrium with the rate of supply of nutrients and energy sources from the bulk water

- (v) phase 4 – this represents the quasi-steady state situation reached at the end of phase 3 and presumed to continue indefinitely. At the present time there is insufficient understanding of the precise mechanisms involved in this phase, but long term data¹¹ suggest that it is closely linear with time. These observations for a variety of steels also suggest that the corrosion rate is largely independent of the actual activity levels of SRB and of the type of steel.

The function for the expected corrosion loss as a function of time can be constructed initially from the parameters describing the model (Fig. 1). This provides the key features of the function, with the curves either sketched in by hand or, for phase 2, constructed from the mathematical relationships that have been derived for this part of the model.⁹ Mathematical descriptions for phases 3 and 4 are under development.

The model parameters shown in Fig. 1 were calibrated to a wide selection of data reported in the literature for what were judged to be sites with conditions similar to 'at sea' exposure and mixing conditions.^{1,2} This tends to ensure that the waters are fully aerated relative to the water temperature and that wave and velocity conditions and chemical composition (including pH, salinity and calcium carbonate) were comparable, because it is known that large areas of the world's oceans and seas have very similar physical and chemical characteristics.¹⁴

An example of calibration is shown in Fig. 2 for the initial corrosion rate r_0 . It shows that r_0 is primarily a function of sea water temperature, as expected from theoretical corrosion science concepts^{8,15} but not previously demonstrated for field observations. It was found also to be related to temperature through an Arrhenius equation, as would be expected from theoretical considerations but not previously demonstrated for field data.¹ Figure 3 shows the manner in which the time t_a that separates aerobic corrosion from anaerobic corrosion depends on sea water temperature.

3 Time to anaerobic activity t_a as function of average sea water temperature

Although field observations should be consistent with theoretical corrosion science principles, in practice field observations are obtained under imperfect conditions. Therefore some variability between model and observations is to be expected and this is evident in the scatter of points about the trend lines shown in Figs. 2 and 3. Moreover, some influencing parameters were ignored in model development and this also will add a degree of uncertainty to the relationship between model and reality. To cater for this the model in Fig. 1 should be seen as the mean valued function $fn(t, E)$ in the relationship

$$c(t, E) = b(t, E) \cdot fn(t, E) + \varepsilon(t, E) \quad (1)$$

where $c(t, E)$ is the weight loss of material, $b(t, E)$ is a bias function, $\varepsilon(t, E)$ is a zero mean error function, and E is a vector of environmental (and material) parameters. Here $\varepsilon(t, E)$ represents the 'scatter' in the data about the mean value function. In the case of 'at sea' conditions, the vector E has been considered to reduce to the average sea water temperature T (Ref. 1). Empirical relationships for $b(t, E)$ and $\varepsilon(t, E)$ have been reported² but are not reviewed here.

Other influences

The effect of season of the first immersion refers to the fact that many corrosion studies, particularly those used in model calibration, have been timed such that the steels were first exposed during the spring season. Typically this exposes the steel to warmer waters for the first six months or so, followed by colder waters, the effect being more marked where there are large seasonal variations in water temperature. Where the coupons were first exposed at the start of winter or in the autumn, a period of about six months of somewhat lower corrosion is usually observed.^{16,17} Typically, the effect is to translate the main part of the corrosion-time curve 'side ways' in time.

Levels of dissolved oxygen (DO) less than fully aerated become an issue at depth and in coastal and harbour waters.¹⁸ Typically, low DO levels will depress the amount of corrosion in phases 1 and 2 and reduce t_a .

It will not directly affect anaerobic corrosion in the later phases, although these would be expected to mirror the lower levels of earlier corrosion. It may also lower the energy sources available to the SRB. Dissolved oxygen is not considered for the data discussed herein.

Water velocity is known to increase the 'rate' of corrosion. A recent study¹⁹ has shown that the widely accepted classical work in this area,²⁰ based on only 36 days of testing in a recirculating system is not definitive. Field observations¹⁹ show that for the lower velocities relevant for infrastructure applications, water velocity has the distinct effect of increasing corrosion only during the early period of exposure (about 1–2 months), with longer exposures simply reflecting the higher level of earlier corrosion. In essence, the corrosion-time curve is translated 'upward' by a constant amount after the initial period of corrosion, with the amount of translation depending on the water velocity. Detailed observations are available currently only for sea water at an average temperature of 20°C. Also, there are as yet no estimates of the uncertainties involved.

Nutrients such as those resulting from sewage discharges, fertilizer run-off from agriculture or connected with offshore oil production fields have been associated with elevated levels of corrosion, attributed to the increased level of SRB metabolism.²¹ For a number of field observations this effect has been demonstrated to offer an explanation for what appeared to be previously unexplained elevated levels of later corrosion, that is, particularly in phase 3 of the model.²² Thus, in the presence of nutrient pollution, marine corrosion in phase 3 tends to be much greater than would be the case under normal coastal conditions. Qualitatively it can be seen that phase 3 corrosion increases with higher nutrient levels, but at this time the mathematical functional relationship(s) between the level of nutrients in the waters (however measured) and the level of increased corrosion has not been quantified. However, appropriate studies are under way. One of the difficulties in this regard is the poor reporting in the past of local environmental conditions at corrosion testing sites.

Application to observations at Halong Bay, Vietnam

Cuong *et al.*⁵ reported equivalent one sided average corrosion rates obtained from weight losses of 200 × 100 × 3 mm coupons of steel type St3 (Table 1) exposed for 2 years at 1–2 m depth at an undefined location in sea water in Halong Bay, North Vietnam. These results have been converted to corrosion losses and are shown as a function of time in Fig. 4. The chemical composition of the sea water is shown in Table 2. Although specific data were not given, the data do suggest pollution problems (see below). Standard corrosion testing and coupon cleaning techniques were employed.

Biofouling appeared in the first weeks of exposure, and this was noted to change in character with increased exposure. It was claimed that initially marine growth reduced the corrosion rate, but only 'until the growth begins to separate from the metal surface. After that the corrosion rate ... increased until a second marine growth layer appeared (second peak appearance)', at up to 12 months exposure for steel St3.⁵ However, as now will be

4 Corrosion loss as function of exposure period for St3 type steel exposed at Halong Bay, Vietnam under elevated N/P nutrient levels: also shown is curve predicted by corrosion model for 23°C average sea water temperature

immediately evident, this behaviour characteristic corresponds directly with the onset of phase 3 of the model.

Some localised corrosion was observed, with pits of 1–20 mm diameter and up to 0.3 mm depth after 24 months exposure. Although not mentioned by the authors, pits with these characteristics are consistent with corrosion influenced by SRB.¹² This is reflected also in the observed corrosion product after 12–24 months, being noted as mainly $\alpha\text{-Fe}_2\text{O}_3\cdot\text{H}_2\text{O}(\text{FeOOH})$ and some $\gamma\text{-Fe}_2\text{O}_3\cdot\text{H}_2\text{O} + \text{Fe}_3\text{O}_4$.

There are no direct observations reported by Cuong *et al.*⁵ of water pollution for Halong Bay, but in the context of water quality for aquaculture and fishery problems have been noted with oil pollution and a ‘red tide’ occurred in 1984.²³ Also, the estuary is ‘characterised by N/P ratios which are likely due to fertilizer applications and sewage discharges in the drainage

area’.²⁴ These observations are consistent with the higher than expected long term corrosion noted by Cuong *et al.*⁵ More specifically, Fig. 4 shows that the corrosion is higher than expected from the corrosion model for an average water temperature of 23°C once corrosion enters phase 3 (anaerobic corrosion). As noted above, the effect of such nutrients is to supply energy donors to SRB activity, leading directly to higher corrosion levels in phase 3 as a result of the associated increased production of metabolites responsible for corrosion (principally hydrogen sulphide).

Taken together, these observations support the qualitative modification of the corrosion–time curve in phases 3 and 4 of the model, as shown in Fig. 4. However, there is still insufficient information available in the literature to develop definitive relationships between corrosion, SRB metabolism and nutrient supply sources and supply rates, as functions of local environmental parameters (such as water temperature).

Application to observations at Chengdao offshore oil exploration area

The Chengdao sea area is located in the west Bohai Gulf, off the north coast of China and under the influence of the Yellow River with its high silt content and elevated water velocities. Corrosion weight loss measurements on three steels (Table 1) were made using 200 × 100 mm coupons, some 2 mm and others 3 mm thick. All coupons were cleaned and degreased before exposure and cleaned using conventional techniques on recovery. Coupons were exposed at various elevations – only the fully immersed coupons fully electrically insulated from each other are considered here. The average corrosion rates reported by Li *et al.*⁶ were converted to total corrosion values and are plotted as one sided loss in Fig. 5. This also shows the corrosion model curve for the estimated annual average sea water temperature of 12.5°C.¹ This value was estimated from global sea surface water temperature charts,²⁵ because water temperatures were not reported. Other sea water characteristics are shown in Table 2.

Table 1 Composition of steels, %

Ref.	Grade	C	Si	Mn	P	S	Cu	Ni	Mo	Cr
5	St3	0.22	0.14	0.55	0.037	0.41		0.072		0.039
6	A3	0.3–0.35	0.6–0.9	0.8–1.3	≤0.045	≤0.05	≤0.35	≤0.3		≤0.35
6	16Mn	0.12–0.20	0.20–0.55	1.2–1.6	≤0.035	≤0.035	≤0.25	≤0.25		≤0.25
6	20#	0.17–0.24	0.17–0.37	0.35–0.65	≤0.35	≤0.035	≤0.25	≤0.25		≤0.25
7*	A3	0.20	0.25	0.55	0.015	0.25	≤0.05		≤0.05	≤0.10
7*	3C	0.14	0.35	0.92	0.035	0.35	≤0.03		≤0.05	≤0.10

*Al ≤ 0.03, Ti ≤ 0.03, V ≤ 0.03.

Table 2 Characteristics of sea water in study areas

Parameter	Halong Bay (Ref. 5)*	Chengdao OOE (Ref. 6)	Qingdao (Ref. 7)	Xiamen (Ref. 7)	Yulin (Ref. 7)
pH	7.8–8.65	8.05–8.21			
Dissolved oxygen, mL L ⁻¹	5.0–7.25				
Salinity, ‰	18–38.4	30.1–31.0		24.8–32.9	23.3–34.4
Temperature, °C	10.0–34.9	12.5 (est)	10–13	12.7–27.9	21.1–29.9
Water velocity, m s ⁻¹		<1.5	†	2.5–3.0 (tidal)	
Depth of translucence, m				0.86–1.08	1.6–4.7

*Authors also reported: chloride ion, 9.95–21.27 g L⁻¹; sulphate ion, 1.45–4.9 g L⁻¹; free CO₂, 3.52–45.76 mg L⁻¹; HCO₃⁻, 109.8–207 mg L⁻¹; H₂S, 0–1.68 mg L⁻¹; Ca²⁺, 0.22–0.45 g L⁻¹; Mg²⁺, 0.58–1.25 g L⁻¹; conductivity, 21.5–41.6 Ω cm.

†heavily impacted by tides.

5 Corrosion loss as function of exposure period for three steel types exposed at Chengdao OOE, north China: also shown is curve predicted by corrosion model for (estimated) 12.5°C average sea water temperature

It is evident from Fig. 5 that the precise steel composition has little effect on the metal corrosion loss, with the data points being closely grouped at all exposure times. This is as would be expected for steels that are closely similar in composition. Moreover, the rate of corrosion in phases 1 and 2 is controlled by the rate of oxygen diffusion to the corroding surface and this is not strongly dependent on metal composition (although the composition and characteristics of rust layers and the oxygen consumption and generation of marine growth may have a slight influence).

Rather than simply joining the sparse data points, the data were interpreted using the corrosion model and the characteristics noted above for season of the first exposure, water velocity and the influence of nutrients. The season (or date) of the first immersion was not reported. Enquiries with the authors failed to elucidate the necessary information. Nevertheless, it is clear from the trend in the data that the first immersion would have occurred in autumn or winter. The maximum water velocity was assumed to be tidal and is likely to correspond to an average velocity of $\sim 1 \text{ m s}^{-1}$. The experiments of Melchers and Jeffrey¹⁹ suggest that this would cause a vertical upward shift of the model curve after about 2 months of exposure by about 0.10–0.15 mm. This is not inconsistent with the vertical differential shown for velocity in Fig. 5. Finally, the increased corrosion after about 2 years of exposure is generally consistent with the increased corrosion observed in other studies for waters with elevated nutrient levels.²² As noted earlier, unfortunately at this time there is insufficient understanding of the phenomenological relationships involved to estimate the expected increase in corrosion in this phase as a function of nutrient levels.

Application to observations at three sites off coast of China

Observations of corrosion losses over 8 years of exposure at three different sites 'off (the) China coast' were reported by Sun *et al.*⁷ for two structural steels (A3 and 3C, see Table 1). Precise details of the immersion

6 Data for general corrosion loss for A3 and 3C steels as extracted from Sun *et al.*⁷ for 10°C Qingdao: also shown are trend lines fitted to data using corrosion-time model as guide, and standard corrosion model, adjusted to allow for season of first immersion and effect of water velocity

sites and in particular their locations in relation to local sources of fresh water and pollutants are not available, and water quality data are limited (Table 2). The coupons were first exposed in November 1984.²⁶

In interpreting their data the authors note that the general corrosion losses (as measured by weight loss) are counter intuitive compared with the observed sea water temperatures and the effect these would be expected to have on corrosion. They attribute this to the presence of hard scale marine fouling and its (assumed) retarding effect on oxygen transport. Although they acknowledged the possibility of anaerobic activity, it was not made clear how this might have influenced the observed corrosion losses.

Figures 6–8 show, for each of the three corrosion sites, the data points for general corrosion loss extracted from the bar charts and corrosion rate plots reported in Sun *et al.*⁷ Each shows also the corrosion loss-time model curve corresponding to the average sea water temperature at that site. The corrections proposed for the first immersion season and for estimated sea water velocities are shown as appropriate for each site. Unfortunately, the reported information about water velocities is sketchy. This means that the corrections proposed in Figs. 6 and 7 must be seen as interpretations. There is no report of significant water velocity at the Yulin site (Table 2) and this is consistent with the corrosion data relative to the corrosion loss curves (Fig. 8).

Overall, the correlation between the observed corrosion losses given by the discrete data points and the model adjusted for the first immersion season and for estimated effect of water velocity (Figs. 6 and 7), shown as the 'adjusted model curve', is remarkably good in each case, assuming the interpretations made are reasonable. There are some variations between the data and the 'adjusted' model curve. These might be attributed to 'natural variability' and the inevitable errors in weight loss measurements.

7 Data for general corrosion loss for A3 and 3C steels as extracted from Sun *et al.* (2003) for 20°C Xiamen: also shown are trend lines fitted to data using corrosion-time model as guide, and standard corrosion model, adjusted to allow for season of first immersion and effect of water velocity

There is little difference in the corrosion losses in phases 1 and 2 for the two steels, as expected from the fact that the cathodic reaction controls corrosion in these phases, but a bigger difference is evident later, with steel A3 corroding more than steel 3C at 20°C but less for the lower and higher water temperatures. This appears to be inconsistent. It is known²⁷ that higher carbon contents slightly increase corrosion in phases 3 and 4 and that Mn can affect the early part of phase 3.²⁸ However, the most obvious candidates for influencing phase 3 and 4 behaviour, Cr, Cu and Ni are nominally the same and in any case limited to very low levels in the generic compositions shown in Table 1. The inconsistency cannot be a function of sea water temperature as all coupons were nominally subjected to the same exposure conditions. Nevertheless, the annual mean sea water temperature is an important parameter, as shown by way of example in Fig. 8 in which the standard corrosion model is shown for two slightly different water temperatures.

Discussion

An important observation for all figures is that the finer details of the changing phases and their timing are unlikely to be reflected in a sparse set of data points (such as those conventionally reported in the literature and of which the present three data sources are examples). This means that efforts to try to develop understanding of the corrosion processes from such field data alone almost certainly will fail. Much closer observation is required to develop more detailed understanding in conjunction with theory developed from fundamental principles.^{8–10} It also means that fitting simple curvilinear trends (such as the commonly employed relationship $c(t)=At^B$) through such data are almost certainly not correct theoretically and, importantly, can be quite misleading. Relationships of this type suggest long term trends that are inconsistent with trends in observed data and are also inconsistent

8 Data for general corrosion loss for A3 and 3C steels as extracted from Sun *et al.* (2003) for 25°C Yulin: also shown are trend lines fitted to data using corrosion-time model as guide

with the corrosion mechanics from which they are derived.⁹

The above analysis allows for the input of special effects such as water velocity, nutrient pollution and season of the first exposure. These are not the only possible inputs, with salinity, pH, calcium carbonate concentration and DO levels, etc. known to have potential effects on corrosion. The effective prediction of likely corrosion requires information about these parameters and models for connecting the influences to the resulting corrosion. While understanding of these matters is reasonably good, mathematical relationships are not yet fully developed. Such relationships require data for their calibration to field conditions and this highlights the importance of complete and extensive recording of relevant site and environmental data. Evidently, this must include detailed local geographical location of test site and details of microclimatic influences. The availability of such information will reduce the variability between the output of the corrosion model and the recorded data. In terms of model (1), it simply means that $a(t,E)$ will be sufficiently small.

Nevertheless, there is still insufficient information available in the literature to develop definitive relationships between corrosion, SRB metabolism and nutrient supply sources and supply rates, as functions of local environmental parameters (such as water temperature). For older, more significantly deteriorated structures such information is helpful and for this reason should receive research attention.

The reported data for the China Sea show, within the limitations of the available environmental data, a high level of consistency with the time and temperature dependent model for general corrosion described earlier,¹ given that there is always some variability in expected corrosion losses owing to local conditions.² Moreover, it is evident that there is a clear explanation for the temperature effect for general corrosion loss, arising from the changing nature of the corrosion process with time. Failure to account for this can lead to erroneous conclusions about other effects. In particular, Sun *et al.*⁷ observed that the ordering of

general corrosion loss as Qingdao>Xiamen>Yulin was in contrast the ordering of the average sea water temperatures and used this to justify the conclusion that hard marine fouling was responsible for impeding the supply of oxygen to the corroding surface. They appear to ignore the critical role of corrosion product, widely regarded, and observed in field trials, eventually to be very protective of the corroding surface. The rate of corrosion product deposition is temperature dependent and leads eventually to anaerobic conditions. This has an important influence on long term corrosion, more important for higher water temperatures. It also has an influence on the distribution and development of marine growth and marine bacteria.²⁹

These various considerations cast doubt on the possibility that hard marine fouling is the direct causal factor in corrosion behaviour. Rather it indicates that marine growth is a function of sea water temperature. This influences corrosion product characteristics and these have an influence on the marine growth observed at any one time. Undoubtedly variability in marine growth fouling for given conditions has some influence such as through the well known observation of serious localised attack under individual and usually isolated barnacles, as observed already many years ago by LaQue.¹⁶ However, overall the evidence is that model (1) above together with the effects caused by water velocity, nutrients and the first immersion timing is consistent with the observed data. The data analyses herein, for Halong Bay and for sites along the coast of China, interpreted as proposed and within the limitations of natural variability between sites and allowing for reasonable interpretations for unrecorded influences, provide further support for the model.

Conclusions

1. Data for general corrosion in Halong Bay, Vietnam, at an offshore oil platform and at three sites on the China seacoast were re-examined in terms of the previously proposed corrosion model for general corrosion, already calibrated to data from various sources. It was found that the data reviewed herein have an acceptable degree of consistency with the model after its adjustment for season of the first immersion, sea water velocity and nutrient pollution. The data are considered to be closely consistent with the adjusted model when allowance is made for natural variability and reasonable interpretations for unrecorded influences.

2. The apparent contradiction that the three sites off the coast of China show higher long term average general corrosion (rates) as the average sea water temperature decreases follows as a natural consequence of the phenomenological model for general corrosion, which distinguishes between different corrosion phases as the corrosion process evolves with time. It is not necessary to attribute this behaviour to the development of oxygen impervious hard fouling as has been proposed by others.

3. The analysis of reported data showed (again) the importance of complete and extensive recording of relevant site data including the detailed geographical location of, and the local environmental conditions at, test sites. Without such information important clues to peculiarities of the site are lost and this adds to the variability in estimating corrosion losses.

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