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Long-term prediction of metal corrosion losses in atmosphere using a power-linear function

Yu.M. Panchenko*, A.I. Marshakov

A.N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, 119071 Moscow, Russia

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ABSTRACT

A technique for calculation of coefficients in the power-linear function for long-term prediction of corrosion losses of structural metals is presented. The formula consists of a power function at the initial corrosion stage and a linear function at the stationary stage. Conditions for application of the power and power-linear functions for long-term prediction of corrosion losses of technically important metals in various regions of the world are shown. A comparative estimate of predicted corrosion losses of metals based on the equations provided in this study and in ISO CORRAG 9224:2012(E) standard is given.

1. Introduction

Long-term predictions of metal corrosion losses (C) are performed using the power function [1]:

$$C = C_1 \tau^n \quad (1)$$

and/or the equation in logarithmic form [2–7]:

$$\log C = \log C_1 + n \log \tau \quad (2)$$

where C_1 is the corrosion loss over the first year, n is a coefficient that characterizes the protective properties of the corrosion products, and τ is the test duration.

Eqs. (1) and (2) were widely used to describe the corrosion effects obtained in tests with various durations, even up to 20 years, in various regions of the world [1–24]. For each test location, experimental data were processed using Eq. (2) to calculate the n coefficient over the entire test period (logarithmic law), or for the initial and final periods (bilogarithmic law) in case of long-term tests. In some cases, the A value determined from linear relationship Eq. (2) at $\tau = 1$ was used instead of C_1. The use of the calculated n and A values in Eq. (1) and/or Eq. (2) gives the best match with experimental data. A review on application of these functions is presented in [24].

Eqs. (1) and (2) are attractive because the description of the corrosion behavior of metals is based on just two parameters C_1 (A) and n, hence it is unnecessary to study the dependence of C on the meteorological and aerochemical parameters of atmosphere corrosivity. However, these functions with specific C_1 (A) and n for a certain location cannot be used to make predictions in other locations.

Eq. (1) was suggested in a GOST (USSR State Standard) for accelerated determination of corrosion loss of metals, with indication of possible n range in various types of atmospheres [25]. It was first used to predict the corrosion losses of metals for up to 20–25 years in various regions of the world [26]. Experimental C_1 values as well as n values calculated from a stochastic relationship with C_1, $n = f(C_1)$, were used [26]. The metal corrosion loss over the first year of exposure is an integral parameter of atmosphere corrosivity. Taking into account that experimental data of short-term tests or tests without intermediate specimen withdrawals were available at that time, the relationships obtained had to be revised subsequently.

Based on an analysis of results obtained in long-term tests, it was found that the kinetics of metal corrosion loss under atmospheric conditions obeys a power-linear function [27]: a power law at the initial stage assuming a parabolic increase in metal corrosion loss during the first ten years of exposure, and a linear law for exposures longer than 10 years, as it is specified in standards [28,29].

It has been shown [30] that the linear increase in corrosion loss at the stationary stage can be represented as:

$$C = C_0 + \alpha\tau \quad (3)$$

* Corresponding author. Tel.: +7 495 3349805; fax: +7 495 3349805.
E-mail address: panchenkoyum@mail.ru (Yu.M. Panchenko).

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where α is the annual increase in corrosion loss, C_0 is corrosion obtained by extrapolation of the linear plot to $\tau = 0$. During the stationary stage, α is a constant. Based on expression equation (3), the corrosion rate during the stationary stage can be expressed as:

$$\sigma = \frac{C_0}{\tau} + \alpha \tag{4}$$

At $\tau \to \infty$, $\sigma \to \alpha$. Hence, the α value represents not only the annual increase in corrosion loss during the stationary stage but also the limiting corrosion rate for prolonged periods. When the stationary stage has been reached, the corrosion rate is not a constant value but monotonic approaches a limiting α value due to a decrease in C_0/τ.

To date, there are no clear criteria for the stabilization time (τ_{sb}) of the layer of corrosion products. Morcillo et al. [24] believe that a stationary state is attained when the yearly decrease in corrosion rate is ≤10%, and the yearly variation of corrosion rate is also ≤10% for the stationary stage. Based on this, τ_{sb} for weathering steels ranges from 6 to 8 years in less corrosive media to 4–6 years in more corrosive media.

An indicator for the start of the stationary stage was suggested in [30]. According to it, the yearly variation in corrosion rate after the start of the stationary stage obeys Eq. (5):

$$\frac{\sigma_i - \sigma_{i+1}}{\sigma_{i+1} - \sigma_{i+2}} = \frac{i+2}{i} \tag{5}$$

where σ_i, σ_{i+1} and σ_{i+2} are corrosion rates in the year of the beginning of the stationary stage and in the next years, respectively.

Assuming that τ_{sb} is 4, 5, 6, 7 and 8 years, the $\frac{\sigma_i - \sigma_{i+1}}{\sigma_{i+1} - \sigma_{i+2}}$ values should be 1.50, 1.40, 1.33, 1.29 and 1.25, respectively. According to the study reported in [31], the stationary stage for carbon steel, zinc, copper and aluminum begins after 6 years, which corresponds to the value of 1.33 according to Eq. (5). This value was confirmed by the results obtained under ISOCORRAG international program [32]. Considering that C_6 and C_8 correspond to the linear stage, the α value can be determined from them [30]:

$$\alpha = \frac{C_8 - C_6}{2} \tag{6}$$

Using Eqs. (3)–(6), a prediction of corrosion losses of metals has been given for the period from 8 to 50 years based on data of 8-year tests with intermediate specimen withdrawals within ISOCORRAG international program [32]. It can be believed that the long-term prediction taking the onset of the stationary stage matches the actual corrosion losses most exactly.

The method for C evaluation by extrapolation using Eq. (3) is rather accurate and simple. However, application of this method requires test data for at least 8 years with intermediate specimen withdrawals. It is hardly feasible to perform such environmental tests in each region of interest. However, the importance of data on long-term corrosion losses is that it became possible to compare the results of long-term predictions of C using various functions with those actually observed in periods of up to 8 years and extrapolated using a linear relationship at the stationary stage.

If experimental data from long-term tests with intermediate specimen withdrawals are missing, long-term corrosion losses can be estimated using Eq. (1). In order to use Eq. (1) in any regions of the world, taking the dependence of n on atmosphere corrosivity into account, a stochastic relationship for each type of atmosphere was obtained in the form $n = f(C_1)$, which is a square-law function [33]:

$$n = A(BC_1 - G)^2 + D \tag{7}$$

where A, B, G and D are constants and C_1 is used as an integral parameter of atmosphere corrosivity [26,33]. The numerical values of A, B, G and D for n calculation ensuring a C prediction for up to 50 years are reported in [30,33]. Calculations based on Eqs. (1) and (7) result in an insignificant overestimation of C in the period of up to ~25 years and an underestimation of C in subsequent years, which gives an insignificant total prediction error over the entire period. A prediction of metal corrosion losses over 10, 20, 30 and 50 years was given using the power-law function for the test locations within ISOCORRAG international program [30].

The power-linear model is convenient for practical use. However, its application in any arbitrary region of the world requires the knowledge of not only C_1 but also n and α values in order to provide a reliable prediction of mass losses at the initial and stationary stages. It should also be noted that the prediction accuracy considerably depends on correct determination of C_1.

The purposes of this paper were to show the significance of C_1 values used in Eq. (1); to elaborate formulas for calculation of n and α values to be applied in the power-linear model; and to compare the C predictions made using the power-linear function with those based on the relationships recommended by the ISOCORRAG standard [29].

2. Experimental procedure

2.1. Exposure programs

The study was based on the results of 10–17 year tests within the Russian program [31] and 8-year tests within the ISOCORRAG international program [32]. The results obtained on flat specimens of carbon steel, zinc, copper and aluminum under ISOCORRAG program were used. Information about the elementary composition of metals, specimen sizes, exposure program, as well as the corrosion losses of metals and environmental data at the test locations are given in Ref. [32].

Under the Russian program [31], flat specimens (150 mm × 100 mm × 2 mm) made of zinc (98.5%) and aluminum (99.5%) were used. Upon conclusion of each exposure, the specimens were retrieved and cleaned according to the procedures shown in ISO 9226 [34]. Sulfur dioxide deposition was measured by the lead dioxide sulfation plate according to ISO 9225 [34]. Chloride deposition was determined by the wet candle method described in ISO 9225 [35]. Detailed environmental data in Murmansk and Vladivostok are presented in [32].

2.2. Estimation of the significance of C_1 values in Eq. (1)

For a reliable prediction, the C_1 values in Eq. (1) should match the average long-term corrosivity parameters of the atmospheres in the test locations. In the present work, it was confirmed by studies on the kinetics of corrosion losses and corrosion rates of zinc and aluminum. Results of tests on zinc and aluminum coupons carried out in Murmansk and Vladivostok under a Russian program [31] and ISOCORRAG program [32] were used. The long-term tests in Murmansk were carried out for 8 years (ISOCORRAG program, intermediate coupon withdrawals after 1, 2 and 6 years) and 17 years (Russian program, intermediate coupon withdrawals after 1, 2, 5 and 14 years). The long-term tests in Vladivostok were carried out for 7 years (ISOCORRAG program, intermediate coupon withdrawals after 1, 2 and 5 years) and 10 years (Russian program, intermediate coupon withdrawals after 1, 2 and 5 years). Moreover, under these program, 13 and 15 one-year tests starting in different months of different years were performed in Murmansk and Vladivostok, respectively. Based on the results obtained, an analysis of the kinetics of corrosion losses (C) and corrosion rate (σ) of these metals was given. The corrosion losses over the first year (C_1) in long-term tests were compared to C_1 for 13 and 15 one-year tests.