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# Exact calculation of corrosion rates by the weight-loss method

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## Abstract

Corrosion is an important problem that engineers and scientists must overcome to avoid the collapse of structures, chemical processing plants, and metallic objects, which can lead to not only economic loss but also environmental and human losses. One of the simplest and most widely used methods to quantify corrosion rates (CRs) is the immersion test. The usual approach that has been used to date, to quantify the CR by this method, is to assume that the initial surface area of the corroding object remains constant over time. It is shown that such approximations underestimate the true CR and that they may lead to significant errors. A formula to calculate the CR considering changes in the area is presented in this work. The formula herein can be used to accurately quantify the CR by the immersion test and improve the quality of experimental data and the analysis and modeling of corrosion phenomena.

**Keywords:** corrosion rate quantification; immersion test; modeling studies; weight loss

## Objectives

The main objective of this work is to establish the errors of assuming constant surface area in the calculation of corrosion rates through the weight-loss method (immersion test) and to derive a mathematical expression to perform such calculations in a more accurate manner.

## Introduction

Corrosion is a natural process by which materials (usually metals) gradually degrade by chemical and/or electrochemical reactions with their environment, which generally result in the loss of their useful properties (such as strength). Corrosion processes are complex in nature and studies thereof have become an interdisciplinary research field, combining fundamental sciences and engineering (Malaret, 2021, pp. 73–74).

Corrosion can lead to structural and equipment failures in domestic, civil, and industrial settings (such as oil, gas, and chemical industries), which might have catastrophic consequences (Kreysa & Schütze, 2007). To avoid these situations, globally, billions of dollars are spent each year to fight corrosion. In a 2-year study (1999–2001) to determine the economic impact of corrosion, it was estimated that the total annual direct cost of corrosion in the USA was 276 billion \$US, approximately

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3.1% of the nation's Gross Domestic Product (Koch et al., 2002; Kutz, 2005, p. 47, chapter 3; NACE SP01690, 2013).

The main approaches to study corrosion are gravimetric (weight-loss method) and electrochemical methods, which are not discussed in this work. The former technique is one of the most common methods to quantify corrosion rates (CRs), as it is a simple technique that does not involve measurements of currents or voltages (Kutz, 2005, p. 49, chapter 3). As immersion tests are so prevalent both in academic and industrial research, there are a large number of standardized procedures that have been developed and published (summary in Supplementary Table S1).

There are national and international regulations for the handling of dangerous chemicals derived from the "United Nations Recommendations on the Transport of Dangerous Goods, Model Regulations" (Model Regulations) and the "Globally Harmonized System of Classification and Labelling of Chemicals (GHS)". The "Manual of Test and Criteria" (UN ECE, 2019) contains criteria test methods and procedures to be used for (1) the classification of dangerous goods according to the provisions of the Model Regulations, as well as (2) chemicals presenting physical hazards according to the GHS. According to the Manual, a substance is considered corrosive when the CR, measured through the immersion test for at least 1 week (168 hr), exceeds 6.25 mm per year at a test temperature of 55°C on either steel or aluminum surfaces.

To quantify the CRs by the weight-loss method, also referred to as the immersion tests, the mass loss of the specimen under study (of known surface area) is determined by the difference in weight before and after it is immersed in a corrosive medium for a specified amount of time (ASTM, 2012). This is a simple and well-established method to study corrosion; however, it presents some important limitations:

- It only provides the average CR over the immersion test duration, not allowing for differences in the oxidation kinetics to be determined.
- It can lead to inaccuracies in CR determination as a consequence of poor or excessive corrosion product removal post-immersion.
- It does not provide information about the corrosion mechanisms.
- It can underestimate the true CR if localized corrosion is the dominant corrosion mechanism (Kutz, 2005, p. 49, chapter 3).

Standard guidelines to study corrosion, such as ISO, ASTM, or NACE TM0169/G31–12a "Standard Guide for Laboratory Immersion Corrosion Testing of Metals" (ASTM, 2012), are broadly used by industry and academics. They describe the methodology to quantify the CRs by immersion test experiments (summary in Supplementary Table S1). The formula presented in these standards to quantify the CR, which is also broadly used in the academic literature, is given below:

$$\text{CR} = \frac{k \cdot m_{\text{loss}}}{A \cdot t \cdot \rho}, \quad (1)$$

where  $k$  is a constant  $8.76 \cdot 10^4$  so that CR is in [mm/y],  $m_{\text{loss}}$  is the mass loss [g] of the metal ( $m_0 - m_t$ ) in time  $t$  [hours],  $A$  is the surface area of the material exposed [cm<sup>2</sup>], and  $\rho$  is the density of the material [g/cm<sup>3</sup>] (ASTM, 2012; Kreysa & Schütze, 2007; Kutz, 2005).

In this formula (Eq. (1)), it is assumed that the surface area remains constant throughout the corrosion process, but this is clearly not the case, as the surface area of the material will change as a function of time as the object dissolves in the corrosion medium.

Detailed dissolution profiles and the influence of shape factors on the dissolution kinetics for crystals, polymers, and drugs have been discussed in the literature for both spherical and nonspherical objects (Hixson & Crowell 1931b; Veng Pedersen & Brown, 1976). However, these concepts applied to corrosion problems have not been discussed in detail in the scientific literature or in industrial standards.

As the quantification of the CRs by immersion tests is centered on the measurement of the mass change, it is important to have a significant (or measurable) mass change to minimize the relative errors of weighing, which will typically be achieved at long exposure times. However, at long exposure times,

there might be significant area changes. It has been highlighted in the ASTM standard that tests run for long periods are considerably more realistic than those conducted for short durations (ASTM, 2012). In addition, it has been highlighted that corrosion should not proceed to the point where the original specimen size or the exposed area is drastically reduced or where the metal is perforated. However, no detailed guidelines are available regarding the extent to which area changes impact the accuracy of CR calculations by Eq. (1). Thus, a detailed formula to quantify CRs considering changes in the surface area was developed based on the isotropic dissolution of a 3D prismatic object. The impact of assuming constant area on the CR calculations (Eq. (1)) was also investigated.

**Materials and methods**

*Mathematical description of the dissolution process*

If the anodic dissolution of a metallic material occurs isotropically, that is, the rate of dissolution per unit surface area, known as the CR (or penetration rate) [length/time], is constant, then the mass loss rate can be expressed as:

$$\frac{\partial m}{\partial t} = -CR \cdot A \cdot \rho, \tag{2}$$

where  $m$  is the amount undissolved [mass], and  $A$  is the surface area [length<sup>2</sup>]. This equation implies that the boundary of a plane interface retreats with a constant speed during the dissolution process such that:

$$\frac{\partial r}{\partial t} = -CR, \tag{3}$$

where  $r$  is the distance perpendicular to the interface from some fixed reference point in the dissolving solid (length). Equation (3) integrates to:

$$r = r_0 - CR \cdot t, \tag{4}$$

where  $r_0$  is the initial ( $t = 0$ ) distance to the reference point (for a regular  $n$ -gonal polygon,  $r$  represents the apothem and for a circle, it represents the radius). When Eq. (4) is applied to the isotropic dissolution of a prismatic object having a regular  $n$ -gonal cross-section with an initial side of length  $s_0$  and initial height  $h_0$  (Supplementary Figure S1), the following equation arises to describe the volume change of the object as a function of time (derivation provided in Supplementary Material):

$$\begin{aligned} &(-2n \cdot \tan(\pi/n)) \cdot CR^3 \cdot t^3 + ((2n \cdot s_0 + n \cdot \tan(\pi/n) \cdot h_0)) \cdot CR^2 \cdot t^2 \\ &- \left(\frac{1}{2} \cdot n \cdot s_0^2 \cdot \cot(\pi/n) + n \cdot s_0 \cdot h_0\right) \cdot CR \cdot t - \frac{\Delta m}{\rho} \\ &= 0. \end{aligned} \tag{5}$$

Disks (cylinders) and rectangular prisms (Supplementary Figure S1) are the most common geometries used in the quantification of the CR by the weight-loss method. When Eq. (5) is applied to these geometries, the following equation arises: For cylinders and disks ( $n \rightarrow \infty, s_0 \rightarrow 0, ns_0 \rightarrow 2\pi r_0$  and  $n \tan(\pi/n) \rightarrow \pi$ ) Eq. (6) and for rectangular prisms and sheets ( $n = 4$ , and  $s_0$  equals to  $x_0$  if  $x_0 = y_0$  or  $\sqrt{x_0 y_0}$  if  $x \neq y$ ) Eq. (7):

Cylinders and disks:

$$-2\pi \cdot CR^3 \cdot t^3 + \pi(2D_0 + h_0) \cdot CR^2 \cdot t^2 - \pi/2(D_0^2 + 2D_0 \cdot h_0) \cdot CR \cdot t - \frac{\Delta m}{\rho} = 0, \tag{6}$$

Rectangular prisms and sheets:

$$-8 \cdot CR^3 \cdot t^3 + 4(2x_0 + z_0) \cdot CR^2 \cdot t^2 - 2(x_0^2 + 2x_0 \cdot z_0) \cdot CR \cdot t - \frac{\Delta m}{\rho} = 0, \tag{7}$$

where  $D_0$  and  $h_0$  are the initial diameter and height of a cylinder (or disk) and  $X_0$ ,  $Y_0$ , and  $Z_0$  are the initial dimensions for rectangular prisms and sheets.

### Error analysis

The CR error was calculated using the following equation:

$$\text{CR error} = 100\% \cdot \frac{\text{CR}_{\text{true}} - \text{CR}_{\text{cal}}}{\text{CR}_{\text{true}}}, \quad (8)$$

where  $\text{CR}_{\text{true}}$  is the CR value used to compute detailed dissolution profiles in accordance with Eqs. (5)–(7) and  $\text{CR}_{\text{cal}}$  is the CR calculated with Eq. (1). The plots were constructed using a Python 3 script.

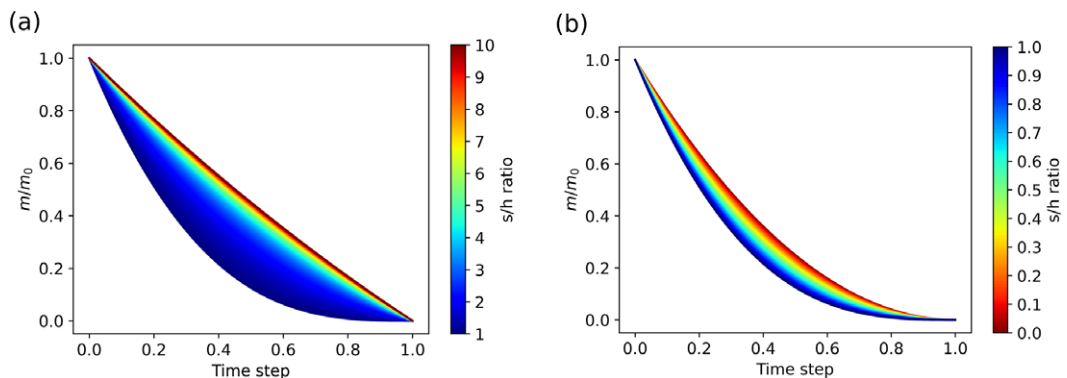
## Results

### Dissolution profiles

From Eqs. (5)–(7), it can be seen that the change in volume (or mass) of an isotropic solid dissolving in a corrosive medium without the deposition of corrosion products over its surface, or passivation, is a cubic function of time. Examples of this behavior include most of the active metals exposed to aqueous solutions of strong mineral acids, such as hydrochloric acid and sulfuric acid with the evolution of hydrogen gas, or dissolution of noble metals in aqua regia or sodium cyanide, in the presence of oxygen gas (Li & Binnemans, 2021). This cubic dependence is true for the dissolution of 3D objects (Veng Pedersen & Brown, 1976). For example, when a spherical object dissolves isotropically, it obeys the Hixson and Crowell cube root law, that is, a plot of  $(m/m_0)^{1/3}$  versus time is linear. It can also be seen that the volume change is not only a function of the CR but also a function of the initial dimensions of the object.

The dissolution profiles of a square prism as a function of the time step for different initial shapes are shown in Figure 1.

The values to compute the dissolution profiles (given in the figure caption) were chosen arbitrarily; however, as the values in the plot are relative/normalized, the choice of such values will not affect the results. The time step is defined as the fraction of the time required to completely dissolve the solid ( $t/t_{\text{max}}$ ), that is, a time step of 1 corresponds to the complete dissolution of the solid. The time to completely dissolve the solid ( $t_{\text{max}}$ ) can be calculated as the minimum between the time to dissolve in the direction of  $r$  (cross-section, setting  $r$  equals to zero in Eq. (4) and solving for  $t$ ) and  $h$  (height).



**Figure 1.** Calculated dissolution profile of a regular square prism (4-egon) as a function of the time step for arbitrary values: initial area of  $1 \text{ cm}^2$ ,  $\rho = 7.05 \text{ g/cm}^3$  and CR of  $0.1 \text{ cm/y}$ . (a)  $r/h < 1$ . (b)  $r/h > 1$ . Nota bene: initial surface area, density, and corrosion rate do not affect the results, as the values in the plot are relatives.

$$t_{\max} = \min \left( \frac{S_0 \cdot \cot(\pi/n)}{2 \cdot \text{CR}} \text{ and } \frac{h_0}{2 \cdot \text{CR}} \right), \quad (9)$$

which reduces to Eq. (10) and Eq. (11) for cylindrical and rectangular geometries, respectively.

$$t_{\max} = \min \left( \frac{D_0}{2 \cdot \text{CR}} \text{ and } \frac{h_0}{2 \cdot \text{CR}} \right), \quad (10)$$

$$t_{\max} = \min \left( \frac{x_0}{2 \cdot \text{CR}} \text{ and } \frac{y_0}{2 \cdot \text{CR}} \text{ and } \frac{z_0}{2 \cdot \text{CR}} \right). \quad (11)$$

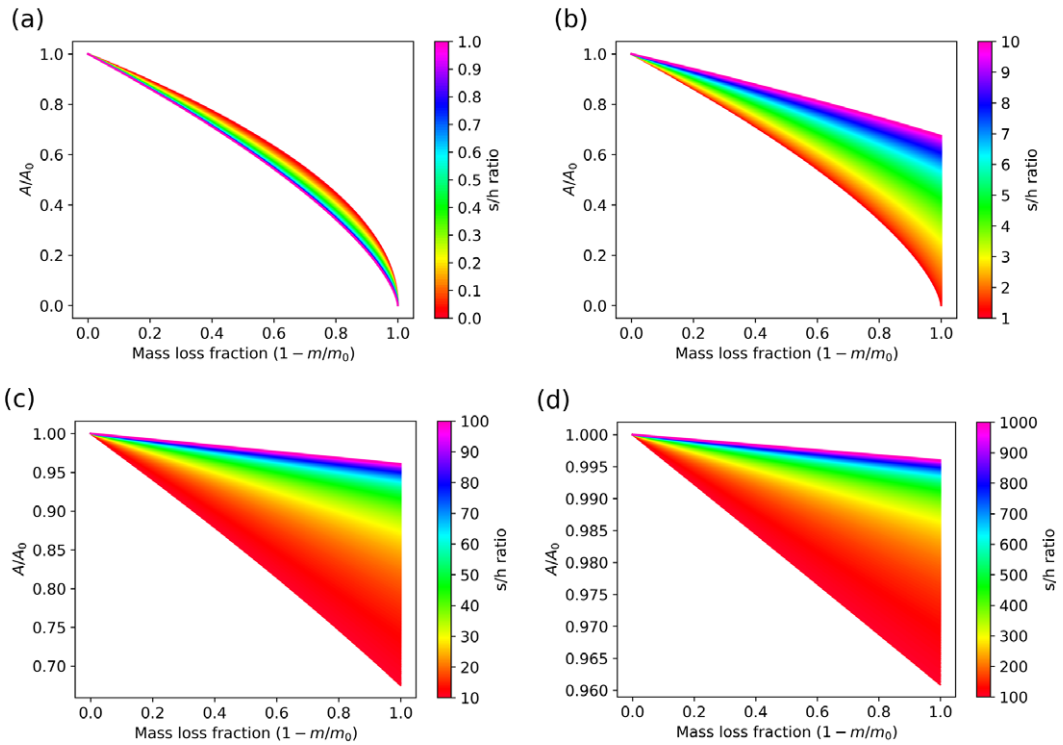
From Figure 1(a), it can be seen that for rod-like objects ( $r/h < 1$ ), the dissolution profile is a convex function in the whole range of the time step regardless of the  $s/h$  ratio, even in the limit value when  $s/h \rightarrow 0$ , which corresponds to an infinite 1D wire. For illustration purposes of this mathematical limit, values of  $s/h$  equal to  $10^{-6}$  and/or  $10^{-10}$  were used in this work. From Figure 1(b), it can be seen that the function is also convex for the entire range of the time step but tends to a straight line when  $s/h \rightarrow \infty$ , which corresponds to an infinite 2D plane. For illustration purposes of this mathematical limit, an  $s/h$  value of  $10^{10}$  was used in this work. The maximum curvature occurs when  $s/h = 1$  for square prisms and  $D/h = 1$  for cylinders. For reference, typical metal coupons used in corrosion testing have an edge dimension (or diameter for disks) between 1 and 3 inches (2.54–7.62 cm) and a thickness between 1/16 and 1/8 of an inch (0.16–0.32 cm), resulting in  $s/h$  (or  $D/h$ ) ratios between 8 and 48. The dimensions of the standard specimen according to the “Manual of Tests and Criteria” (UN ECE, 2019) are  $50 \times 20$  mm and 2 mm thickness ( $s/h = 15.8$ ). Some suppliers can provide thin metallic sheets. Some examples include disks of 18 mm diameter and 0.125 mm thickness ( $D/h = 144$ ) supplied by Goodfellow Cambridge Limited, which also provide coupons with thickness ranging from 0.0004 to 25 mm (Malaret et al., 2020). Sigma-Aldrich includes foils of 0.001 mm thickness in their catalogue ( $s/h = 50,000$  for a  $50 \times 50$  mm sheet).

It is noteworthy that there are other parameters affecting the corrosion process that will influence the accuracy of quantifying the CRs using both methods, that is, the simplified approach presented in the ASTM standard (Eq. (1)) and the exact calculations presented in this work (Eqs. (5)–(7)). For example, the CR might not be constant during an immersion test, due to changes in the corrosion medium linked to the accumulation of cations or reduction of reactive species. In these situations, the mass loss is the integral result of the CR with time. Obstruction of the exposed surface of the corrosion medium by deposition of corrosion products or gas bubbles attached to the surface will induce errors in the quantification of CR by the ASTM standard (Eq. (1)) and the exact calculations presented in this work (Eqs. (5)–(7)). Another factor not considered either in Eqs. (1) or Eqs. (5)–(7) is the surface morphology (roughness). Geometrically speaking, surface roughness means that the actual exposed surface of the object to the corrosive medium is larger than an equivalent smooth object with the same macroscopic dimensions. Therefore, Eqs. (1) or Eqs. (5)–(7) both slightly overestimate the true CRs of rough surfaces. In some situations, surface irregularities may induce localized corrosion, such as pitting corrosion, in which Eqs. (5) or Eqs. (5)–(7) cannot be used to quantify the CRs. Pitting testing is discussed in ASTM Guide G46, ASTM Test Methods G48, and ISO 8993, ISO 8994, and ISO 11463.

### Changes in area

The relative changes in the surface area ( $A/A_0$ ) as a function of the relative mass loss ( $1 - m/m_0$ ) (or volume loss) for a dissolving square prismatic object are shown in Figure 2. The values to compute the data shown in Figure 2 (given in the figure caption) were chosen arbitrarily; however, as the values in the plot are relative/normalized, the choice of such values will not affect the results.

From Figure 2(a) ( $r/h < 1$ ), it can be seen that the relative area changes as a function of the remaining mass fraction (or volume) for rod-like objects is significant. The maximum deviation occurs when



**Figure 2.** Relative area changes ( $A/A_0$ ) as a function of the mass loss fraction ( $1 - m/m_0$ ) (or volume loss fraction) for a dissolving square prism for different  $s/h$  ratios calculated with arbitrary values: initial area of  $1 \text{ cm}^2$ ,  $\rho = 7.05 \text{ g/cm}^3$ , CR of  $0.1 \text{ cm/y}$ . (a)  $s/h < 1$ . (b)  $1 < s/h < 10$ . (c)  $10 < s/h < 100$ . (d)  $s/h > 100$ . Nota bene: initial surface area, density, and corrosion rate do not affect the results, as the values in the plot are relative.

$r/h = 1$ , which corresponds to a cube (or when  $D/h = 1$  for cylinders), consistent with the observations from the dissolution profiles shown in Figure 1. The reason for this is that the area to volume ratio is minimum for a cube or a cylinder ( $D/h = 1$ ); therefore, small changes in the volume will result in maximum relative area changes. For rod-like objects ( $s/h = 10^{-6}$ ), 1% reduction of the area is achieved at 1.8% mass loss ( $1 - m/m_0$ ), 5% area reduction at 9.8% mass loss, and 10% area reduction at 19% mass loss. For  $r/h = 1$ , 1% reduction occurs at 1.5% mass loss, 5% area reduction at 7.3% mass loss, and 10% area reduction at 14.5% mass loss. When  $r/h$  equals 10, 1% area reduction is achieved at 3.3% mass loss, 5% area reduction at 17%, and 10% at 33.3% mass loss. For  $s/h$  equal to 100, 1% area reduction is achieved at 25.8% mass loss. These results show that for geometries with a  $r/h$  ratio equal to 1, smaller mass loss will lead to important area changes. This effect becomes less significant when  $r/h$  is large. For  $r/h$  equal to 100, the relative area changes are always less than 4% for the entire dissolution process. It should be pointed out that Figure 2 is a normalized plot, therefore the initial surface area, density, and CR values do not affect the results. This shows that the magnitude of the area changes of a corroding object (at constant CR and without deposition of corrosion products over the surface) depends on the initial geometry of the object and, as expected, increases with time. The errors induced in the CR calculation by area changes are quantified and discussed in section “Changes in area”.

When the initial gradients for the relative area changes as a function of the mass loss (or volume loss), which corresponds to the slope of the functions shown in Figure 2 at  $(1 - m/m_0) = 0$ , are plotted versus  $s/h$  in for square geometries, the relative changes in the area to changes in volume are maximum at  $s/h = 1$ . In the limit  $s/h \rightarrow 0$ , the function numerically tends to 0.50025, while when  $s/h \rightarrow \infty$ , the function tends to zero. Interestingly, the function has an inflexion point at  $r/h$  equal to 2.506 (Supplementary Figure S2).

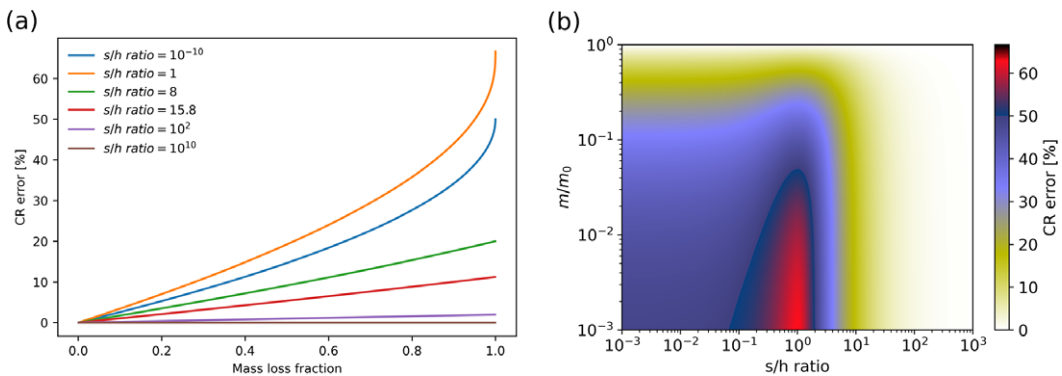
## Discussion

The usual formula to quantify the CR by the immersion test is Eq. (1) that does not include the quadratic and cubic terms of the true expression shown in Eqs. (5)–(7). It is of interest to evaluate the errors in such approximation, which arise from the assumption that the initial surface area of the dissolving object does not change as a function of time.

The relative errors of using Eq. (1) as a function of the remaining mass fraction for different  $s/h$  ratios are shown in Figure 3. The values to compute the data shown in Figure 3 (given in the figure caption) were chosen arbitrarily; however, as the values in the plot are relative/normalized, the choice of such values will not affect the results. Numerical values are given in Supplementary Table S2.

It can be seen from Figure 3(a) that the maximum error for square geometries corresponds to an  $s/h$  ratio of 1. For  $s/h$  ratio  $< 1$ , the errors of assuming constant area are significant through the entire dissolution process, even in the limit of  $s/h \rightarrow 0$ . The ASTM standard recommends a maximum ratio of edge area to total area of less than 20%, which corresponds to a  $D/h$  or  $x/z$  ( $\sqrt{xy}/z$ ) of 8 for prismatic objects (ASTM, 2012). From Figure 3(a), it can be seen that the errors in the CR can be significant for  $s/h = 8$  at high mass loss fraction (which corresponds to long exposure times). The relative error for a positive corrosion test as described in the “Manual of Tests and Criteria” (UN ECE, 2019) is 1.4% minimum ( $s/h = 15.8$  and a mass loss fraction of 0.135), which is not significant. These results suggest that the standard dimensions of the specimen proposed in the “Manual of Tests and Criteria” (UN ECE, 2019) for corrosion testing are adequate for a 7-day exposure test. It can be seen that sheet-like objects, with  $s/h$  ratio  $> 100$ , behave as a 2D plane, minimizing the errors of assuming a constant initial area for the calculation of the CR by Eq. (1). In the limit of  $s/h \rightarrow \infty$ , the errors tend to zero as the area changes become negligible as the material dissolves.

A contour plot showing the relative error of the calculated CR using Eq. (1) as a function of the  $s/h$  ratio and the remaining mass fraction is presented in Figure 3(b), where it can be seen that the errors of ignoring the area changes can be significant, especially for rod-like objects. The values to compute the data shown in Figure 3(b) (given in the figure caption) were chosen arbitrarily; however, as the values in the plot are relative/normalized, the choice of such values will not affect the results. This suggests that Eq. (1) is only valid at very short exposure times or for sheet-like objects ( $s/h > 100$ ). As mentioned previously, short exposure times in the immersion test will maximize relative errors in the weighing process and might lead to an inaccurate description of the corrosion process. Figure 3(b) can be used to estimate the magnitude of the error of assuming constant area. For more accurate results, the CR can be calculated by solving the cubic equations presented in Eqs. (5)–(7).



**Figure 3.** (a) Relative errors in the corrosion rate as a function of the mass loss fraction if Eq. (1) is used (constant area), calculated with arbitrary values. Numerical values in Supplementary Table S2. (b) Relative errors in the corrosion rate as a function of the mass fraction and the  $s/h$  ratio if Eq. (1) is used for a square prismatic object calculated with arbitrary values: initial area of  $1 \text{ cm}^2$ ,  $\rho = 7.05 \text{ g/cm}^3$ , CR of  $0.1 \text{ cm/y}$ . Nota bene: initial surface area, density, and corrosion rate do not affect the results, as the values in the plot are relatives.



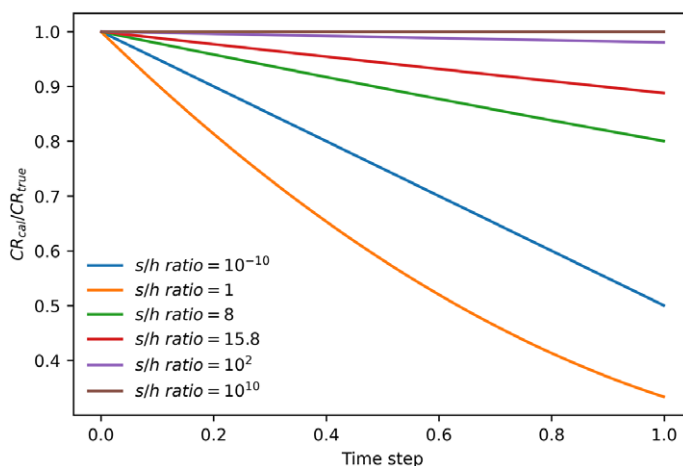
The determinant ( $\Delta$ ) for a cubic equation  $ax^3 + bx^2 + cx + d = 0$  is  $18abd - 4b^3d + b^2c^2 - 4ac^3 - 27a^2d^2$ . A detailed analysis of Eqs. (5)–(7) shows that  $a < 0$ ,  $b > 0$ ,  $c < 0$  and  $d > 0$ , leading to  $\Delta < 0$ . Cubic equations with a negative discriminant have one real root and two nonreal complex conjugate roots. Even though cubic equations have exact algebraic solutions which are discussed in the scientific literature (Nickalls, 1993), they are not simple and are not shown here. However, they can be readily solved using numerical methods or mathematical solvers. An Excel spreadsheet is provided in the Supplementary Material to calculate the CRs with the formulae presented in this work.

As in some corrosion studies it is of interest to establish the CR dependency over time, an analysis of the impact of assuming constant area on the CR profile over time is presented in Figure 4. The values to compute the data shown in Figure 4 (given in the figure caption) were chosen arbitrarily; however, as the values in the plot are relative/normalized, the choice of such values will not affect the results.

Despite the fact that the CR used to construct the plots shown in Figure 4 is constant ( $CR_{\text{true}}$ ), it can be seen that the calculation of the CR using the initial area and ignoring changes in the area over time (Eq. (1)) ( $CR_{\text{cal}}$ ) can have a significant effect when establishing the CR profiles over time. Firstly, Eq. (1) underestimates the true CR in the entire range of the time step ( $CR_{\text{cal}} < CR_{\text{true}}$ ). The errors depend on the  $s/h$  (or  $D/h$ ) ratio and are maximum when the ratio  $s/h$  (or  $D/h$ ) = 1, as mentioned previously. Secondly, from Figure 4, it would appear that the CRs are a function of time for ratios  $s/h$  (or  $D/h$ ) < 100. Moreover, for ratios  $s/h$  (or  $D/h$ ) close to 1, it would appear that the CR is slowing down with time, which could be attributed to a corrosion process that is being inhibited. These results indicate that it is essential to consider the potential effects on the CR profiles over time calculated using Eq. (1).

## Conclusions

The CR quantification by the weight-loss method (immersion test) is typically calculated assuming constant initial area of the test specimen. It has been shown in this work that this assumption underestimates the true CR and that significant errors can arise if area changes are not considered, specifically for 3D and rod-like objects. Errors in the CR calculation could potentially lead to premature failure of metallic structures designed with erroneous data. The CR can be accurately determined by solving a cubic equation that takes into account changes in the area (Eqs. (5)–(7)). The errors of assuming constant area for sheet-like objects ( $s/h > 100$ ) are minimum and Eq. (1) can be used. However, performing corrosion testing on thin films can be experimentally challenging, as metal foils are not rigid and can easily break. Moreover, it has been highlighted in the ASTM standard that thin specimens



**Figure 4.** Relative corrosion rate (CR) profiles calculated assuming constant area (Eq. (1)) and arbitrary values:  $CR = 0.1 \text{ cm/y}$ ,  $\rho = 7.05 \text{ g/cm}^3$ , and  $A = 1 \text{ cm}^2$ . Nota bene: initial surface area, density, and CR do not affect the results, as the values in the plot are relatives.



such as shims of some materials produced by heavy machining or cold rolling may have different CRs from materials not subjected to these processes (ASTM, 2012). Researchers quantifying CRs over time using the immersion test should consider the effects of changing area on the CR calculations by Eq. (1), as this assumption can lead to significant variations that might be mistaken by physical phenomena retarding or inhibiting the corrosion process. For accurate work, the CR should be calculated using (Eqs. (5)–(7)). It is noteworthy that the error analysis presented in this work only considers errors in the CR calculation due to area changes and does not discuss other experimental error sources encountered in CR quantification by the weight-loss method. Eqs. (5)–(7), as the standard approach (Eq. (1)), describe corrosion processes of objects with smooth surfaces, dissolving isotropically at a constant CR without passivation (or corrosion products deposition over the surface). Errors in the quantification of CRs if these conditions are not met, will affect the accuracy of the calculation by the standard approach as well as by the equations presented in this work. However, from a mathematical standpoint, Eqs. (5)–(7) will provide a better estimate than Eq. (1).

An Excel spreadsheet is provided in Supplementary Material to calculate the CRs with the formulae presented in this work.

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**Conflict of interest.** The author declares no conflict of interest.

**Data availability statement.** The data presented in this study are available on request from the corresponding author.

**Supplementary information.** Detailed derivation of the cubic formula given in Eq. (5). Plot of initial gradients as a function of  $s/h$ , list of standards for corrosion testing by immersion, and numerical values of the relative errors in the CR by assuming constant area. Excel spreadsheet to calculate the corrosion rates with the formulae presented in this work.

**Supplementary Materials.** To view supplementary material for this article, please visit <http://doi.org/10.1017/exp.2022.5>.

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# Peer Reviews

Reviewing editor: Dr. Xin-She Yang

Minor revisions requested

doi:10.1017/exp.2022.5.pr1

## Review 1: Exact calculation of corrosion rates by the weight-loss method

Reviewer: Dr. Marta Terrados-Cristos 

University of Oviedo, Oviedo, Spain, 33003

Date of review: 06 December 2021

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**Conflict of interest statement.** Reviewer declares none.

### Comment

*Comments to the Author:* This interesting study presents a formula to calculate CR considering changes in area, to accurately quantify CR with immersion test. The proposed concept and the overall result is very good and relevant. The objective of the experiment is defined, and the problem is clearly stated but I recommend adding and citing more relevant studies that support certain information and statements made in the introduction, as well as authors or studies that represent case examples when it is indicated that the techniques are broadly used.

The methodology, calculus and equations were comprehensively explained, and the analyses performed are adequately described and well supported by the figures. However, on section 3 (3.2 page 8) it may be interesting to present the results of the percentage of reduction and mass loss in the form of a table to easier analyse them. This would make this part of the paper much more valuable for the scientific and technical community. Regarding the appendix, it is clear and easy to use (just review spelling on parameter 'height').

Overall, congratulations to the authors for their good work, I encourage them to make those minor changes to make the presentation of their study even better.

### Score Card

Presentation



Is the article written in clear and proper English? (30%)

5/5

Is the data presented in the most useful manner? (40%)

5/5

Does the paper cite relevant and related articles appropriately? (30%)

4/5

## Context



Does the title suitably represent the article? (25%)

5/5

Does the abstract correctly embody the content of the article? (25%)

5/5

Does the introduction give appropriate context? (25%)

4/5

Is the objective of the experiment clearly defined? (25%)

5/5

## Analysis



Does the discussion adequately interpret the results presented? (40%)

5/5


Is the conclusion consistent with the results and discussion? (40%)

5/5

Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)

5/5

## Review 2: Exact calculation of corrosion rates by the weight-loss method

Reviewer: Dr. M. A. Fazal 

Date of review: 03 March 2022

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**Conflict of interest statement.** None.

### Comment

*Comments to the Author:* Please confirm the followings:

- 1) Experimental validation
- 2) Both formula and derivation should be clear and brief.

### Score Card

#### Presentation



Is the article written in clear and proper English? (30%)

4/5

Is the data presented in the most useful manner? (40%)

3/5

Does the paper cite relevant and related articles appropriately? (30%)

3/5

#### Context



Does the title suitably represent the article? (25%)

5/5

Does the abstract correctly embody the content of the article? (25%)

4/5

Does the introduction give appropriate context? (25%)

2/5

Is the objective of the experiment clearly defined? (25%)

4/5

#### Analysis



Does the discussion adequately interpret the results presented? (40%)

4/5

Is the conclusion consistent with the results and discussion? (40%)

4/5

Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)

3/5