Corrosion Monitoring in Atmospheric Conditions

Subjects: Materials Science, Characterization & Testing | Meteorology & Atmospheric Sciences

Contributor: Tomas Prosek

A variety of techniques are available for monitoring metal corrosion in electrolytes. However, only some of them can be applied in the atmosphere, in which case a thin discontinuous electrolyte film forms on a surface. Traditional and state-of-the-art real-time corrosion monitoring techniques include atmospheric corrosion monitor (ACM), electrochemical impedance spectroscopy (EIS), electrochemical noise (EN), electrical resistance (ER) probes, quartz crystal microbalance (QCM), radio-frequency identification sensors (RFID), fibre optic corrosion sensors (FOCS) and respirometry.

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real-time corrosion monitoring
atmospheric corrosion monitor
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1. Introduction

The atmospheric corrosion of metallic materials has huge financial, environmental and cultural implications. In 2016, the Association for Material Protection and Performance (AMPP) published the International Measures of Prevention, Application, and Economics of Corrosion Technologies (IMPACT) report, which estimated the global cost of corrosion to be equivalent to 3.4% of the global Gross Domestic Product. They calculated that by using the available corrosion control techniques, it would be possible to save between 15 and 35% of the total corrosion cost [1]. Alongside financial losses, undetected corrosion can cause sudden industrial and transport failures that may result in environmental catastrophes and hazards that endanger health and lives. Furthermore, corrosion is known to induce irreversible damage in, or even destruction of, unique cultural artefacts.

Atmospheric corrosion is a complex process of interaction between materials and the environment. Environmental corrosivity is dependent on various parameters, including relative humidity (RH), temperature (T) and air pollutant concentrations. Thus, understanding the corrosion of metallic materials requires detailed knowledge of these parameters and their effect on the underlying corrosion processes [2]. The main tools used to assess environmental corrosiveness, corrosion progression, material corrosion behaviour and the effects of coatings and inhibitors, involve cumulative or real-time monitoring of corrosion rates and environmental parameters, and frequent equipment inspections. This review is focused on real-time corrosion monitoring, which we define as a long-term instantaneous measuring of parameters directly linked to corrosion loss.

Many real-time corrosion monitoring techniques have been developed for monitoring of metal corrosion in electrolytes. However, their applicability is limited under atmospheric conditions, under which a thin electrolyte layer is formed on a metallic surface. This limitation particularly relates to electrochemical methods that require a conductive connection between the electrodes. Modified electrochemical and non-electrochemical real-time corrosion monitoring techniques have been developed for use in both indoor and outdoor atmospheres. Such techniques are designed to meet the requirements of easy measurement and data interpretation, direct corrosion rate determination, rapid responses to changes in corrosivity and wide applicability in environments with different influences on corrosivity [3]. In the last decade, these techniques have evolved, but no paper summarizing the developments has been published.

2. Comparison of Atmospheric Corrosion Monitoring Techniques

Studies applying the real-time atmospheric corrosion monitoring techniques described in the previous sections are summarised in **Table 1** in terms of environments, sensing materials, ranges of detected corrosion rates and suitability for localised corrosion detection.

Table 1. Summary of studies applying real-time atmospheric corrosion monitoring.

Technique	Environment *	Sensing Metal **	Range of Measured Corrosion Rates ***, [$\mu m \cdot a^{-1}$]	References	Localised Corrosion Detection
ACM [1]	Outdoor exposures	Fe	1×10^{-1}–1×10^{2}	[4][5][6][7][8][9][10][11][12]	–
		Zn	Not calculated	[13]	
	ACTs	Fe	1×10^{2}	[14]	
	Laboratory tests	Fe	1×10^{1}–1×10^{3}	[15][16]	
		Zn	1×10^{1}–1×10^{3}	[15][16]	
		Cu	1×10^{1}–1×10^{3}	[15]	
		Al	1×10^{1}–1×10^{3}	[15]	
ER	Outdoor exposures	Fe	1×10^{-1}–1×10^{3}	[17][18][19]	[3][20][21]
		Zn	1×10^{-1}–1×10^{1}	[18]	
		Cu	1×10^{-1}–1×10^{0}	[22]	
	ACTs	Fe	1×10^{1}–1×10^{3}	[2][23][24][18][25]	

Technique	Environment *	Sensing Metal **	Range of Measured Corrosion Rates ***, $[\mu m \cdot a^{-1}]$	References	Localised Corrosion Detection
				[26][27]	
		Zn	1×10^{0}–1×10^{3}	[2][23][24]	
		Cu	1×10^{3}	[2]	
		Al	1×10^{-1}–1×10^{1}	[20]	
		Fe	1×10^{-3}–1×10^{1}	[2][3][28]	
		Cu	1×10^{-3}–1×10^{-1}	[2][29][30][28]	
	Laboratory tests	Ag	1×10^{-3}–1×10^{1}	[29][30][31]	
		Zn	1×10^{0}–1×10^{2}	[2]	
		Pb	1×10^{-3}–1×10^{2}	[32][33][34]	
	Indoor exposures	Cu	1×10^{-3}–1×10^{-1}	[29][35][36][37][38][39]	
		Ag	1×10^{-3}–1×10^{-1}	[29][35][36][38][40]	
		Pb	1×10^{-2}–1×10^{1}	[36][38][41]	
	Outdoor exposures	Fe	1×10^{-1}–1×10^{1}	[42][43]	
		Cu	1×10^{2}–1×10^{3}	[22]	
EIS [2]	ACTs	Fe	1×10^{2}–1×10^{3}	[46]	[44][45]
		Fe	1×10^{-1}–1×10^{4}	[47][48][49][50][51]	
	Laboratory tests	Zn-coated steel	1×10^{0}–1×10^{3}	[52][53][54][55]	
	Outdoor exposures	Zn	1×10^{1}	[56]	
		Cu	1×10^{-1}–1×10^{1}	[57][58][22]	
EN [3]		Fe	1×10^{-1}–1×10^{1}	[44][59]	[44][59][45][60]
		Cu	1×10^{-2}–1×10^{2}	[61][60]	

Technique	Environment *	Sensing Metal **	Range of Measured Corrosion Rates ***, [μm·a^{-1}]	References	Localised Corrosion Detection
QCM [4]	Laboratory tests	Cu	1 × 10^{-1}–1 × 10^{0}	[62]	–
		Ag	1 × 10^{-3}–1 × 10^{-2}	[63][64][65][66][67][68]	
	Indoor exposures	Cu	1 × 10^{-3}–1 × 10^{-1}	[36][69]	
		Ag	1 × 10^{-2}–1 × 10^{-1}	[36][40][69]	
		Co	1 × 10^{-2}–1 × 10^{-1}	[69]	
RFID	ACTs	Fe	1 × 10^{2}–1 × 10^{3}	[70][71]	[72][73]
	Laboratory tests	Zn	1 × 10^{1}	[72][74][73]	
FOCS		Fe	No data for atmospheric corrosion		–
Respirometry [5]	Laboratory tests	Fe	1 × 10^{-1}–1 × 10^{2}	[75][76]	[77][78]
		Cu	1 × 10^{-2}–1 × 10^{-1}	[75]	
		Al	1 × 10^{-1}–1 × 10^{0}	[77]	
		Mg	1 × 10^{1}–1 × 10^{3}	[77][78]	

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Table 2. Comparison of atmospheric corrosion monitoring techniques.

* Outdoor exposures–field exposures outdoors; ACTs–standardised accelerated corrosion tests; Laboratory tests–

Technique	Current Applications	Potential Fields of Application	Sensitivity *	Commercial Suppliers	Main Advantages	Main Drawbacks
Coupons	Indoor and outdoor corrosivity classification according to standards Verification of other techniques	Applicable in any environment	High at long exposure times, otherwise medium	Several	Standardised technique Easy data interpretation	No real-time data Time-consuming
ACM	Outdoor monitoring TOW assessment	Outdoor and indoor at higher RH	Medium	1	Not sensitive to temperature fluctuations Suitable for harsh outdoor environments	Corrosion acceleration due to galvanic coupling Unclear data interpretation

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Technique	Current Applications	Potential Fields of Application	Sensitivity *	Commercial Suppliers	Main Advantages	Main Drawbacks
						during rainfall Electrolyte presence required
EIS	Laboratory tests at higher RH and under thin electrolyte layers Assessment of protective coatings	Outdoor and indoor at higher RH	Medium	0	Information about corrosion mechanism Non-destructive assessment of coatings	Knowledge about investigated system needed for correct data interpretation Electrolyte presence required Unclear results under very thin electrolyte layers and in presence of thick corrosion products
EN	Outdoor corrosion monitoring	Outdoor and indoor at higher RH	Medium	0	Localised corrosion detection Corrosion mechanism determination	Complex and unclear interpretation Electrolyte presence required
ER	Indoor and outdoor corrosion monitoring, laboratory studies Corrosivity classification	Applicable in any environment	High	4	Universal technique High sensitivity Easy operation and data interpretation Optimal for uniform corrosion monitoring	Sensitive to temperature fluctuations Limited possibilities in monitoring of non-uniform corrosion
QCM	Indoor corrosivity classification Laboratory tests	Indoor at lower corrosivity	High	2	High sensitivity and short response time	Sensitive to temperature fluctuations, moisture and pollutants

Technique	Current Applications	Potential Fields of Application	Sensitivity *	Commercial Suppliers	Main Advantages	Main Drawbacks
					Electrolyte presence not required	presence Not suitable for harsh environments
RFID	Laboratory tests	Outdoor and indoor at higher corrosivity	Low	0	Compact and wireless Electrolyte presence not required	Further development needed
FOCS	None for atmospheric corrosion	Not clear yet, as the technique is at the development stage	Not available	0	Not known for atmospheric corrosion yet	
Respirometry	Laboratory tests	Not clear yet, as the technique is at the development stage	High	0	High sensitivity Information about corrosion mechanism Electrolyte presence not required	Sensitivity to RH, temperature and pressure fluctuations Further development needed

* Low sensitivity–corrosion detection in high-corrosive outdoor environments. Medium sensitivity–detection of corrosion rate in an order of 10 μm·a^{-1} and higher corresponding to outdoor corrosivity. High sensitivity–detection of corrosion rate in an order of 1×10^{-3} μm·a^{-1} and higher corresponding to indoor corrosivity.

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ave been d showed necessity for the electrolyte presence to provide connection between electrodes, corrosion acceleration of the less noble metal caused by galvanic coupling and unclear data interpretation during rainfall and condensation, when the current output increases steeply. Future development of the technique should aim at the improvement of data interpretation algorithms, particularly for the rainfall effect correction.

Similarly to ACM, EIS and EN techniques require a continuous layer of electrolyte to connect the electrodes to be present on the surface. EIS proved to be able to generate useful laboratory or short-term outdoor data in atmospheric exposure conditions. However, it is not considered to be fit for long-term monitoring due to the complex signal interpretation and insufficient stability. EN has been tested outdoors. The main advantage of this method is its potential for localised corrosion detection and corrosion mechanism assessment, but the interpretation of its data is complex, and there is no generally valid data treatment method allowing for a direct corrosion rate calculation from the measured EN signal. The further development of the EN data processing procedure is thus of great importance.

ER is a universal technique that can be recommended for both indoor and outdoor measurements, as a compromise between sensitivity and lifetime can be found by a correct choice of sensor thickness. Sensors made of a wide range of metals and alloys are available. The method is suitable for long-term monitoring of uniform corrosion, providing direct and easy-to-interpret corrosion loss data. The measurement sensitivity to rapid temperature fluctuations which cannot be fully compensated by the reference part may, however, require additional data processing. Along with thermal noise elimination and filtering, the ability of the technique to detect localized corrosion should be considered as beneficial rather than disadvantageous and quantified in future studies.

QCM is an extremely sensitive technique used for corrosivity classification indoors and for laboratory studies of corrosion mechanisms. Due to its sensitivity to moisture, pollutants' presence and temperature fluctuations, it is not suitable for exposures in harsh environments.

RFID is a state-of-the-art technique currently under development. It is probable to be applicable for corrosion monitoring in service in the future, especially under conditions which require compact wireless solutions. However, there is no ready-to-use solution available yet, as a number of technical obstacles need to be solved first.

FOCS is a technique potentially feasible for monitoring of atmospheric corrosion, but so far it has been developed and applied only for corrosion monitoring in concrete.

Respirometry is a highly-sensitive method which can provide information about corrosion rate and mechanisms. For these purposes, it has been used within laboratory investigations. The technique was tested as an indicator of historical artefacts' degradation. It can be difficult to use it for real-time corrosion monitoring due to its sensitivity to RH, temperature and pressure variations, and the necessity of placing the monitored object into a sealed box, or to attach a sealed container to the surface.

3. Conclusions

Techniques used for real-time corrosion monitoring of metallic materials have been reviewed and compared focusing on their use in atmospheric conditions. Based on their key characteristics, such as sensitivity, lifetime, availability and data interpretation complexity, the following conclusions can be drawn.

- Electrochemical EIS, EN and ACM methods can be recommended for the use under outdoor conditions and in laboratory tests at higher RH when stable electric connection between electrodes in ensured.
- QCM is a powerful technique for extremely low corrosion rate detection in indoor environments.
- The ER technique is the most universal corrosion monitoring tool, which can be applied both in high and weakly corrosive environments, depending on the sensor's thickness.
- Further development of the state-of-the art RFID, FOCS and respirometric techniques in the field of atmospheric corrosion is expected. At the current stage, it is too early to evaluate their application potential.

References

1. Koch, G.; Varney, J.; Thompson, N.; Moghissi, O.; Gould, M.; Payer, J. International Measures of Prevention, Application, and Economics of Corrosion Technologies Study; NACE International: Houston, TX, USA, 2016.
2. Prosek, T.; Kouril, M.; Hilbert, L.R.; Degres, Y.; Blazek, V.; Thierry, D.; Hansen, M. Real time corrosion monitoring in atmosphere using automated battery driven corrosion loggers. Corros. Eng. Sci. Technol. 2008, 43, 129–133.
3. Li, S.; Kim, Y.G.; Jung, S.; Song, H.S.; Lee, S.M. Application of steel thin film electrical resistance sensor for in situ corrosion monitoring. Sens. Actuators B Chem. 2007, 120, 368–377.
4. Shinohara, T.; Motoda, S.; Oshikawa, W. Evaluation of corrosivity in atmospheric environment by ACM (Atmospheric Corrosion Monitor) type corrosion sensor. In Proceedings of the Pricm 5: The Fifth Pacific Rim International Conference on Advanced Materials and Processing, Pts 1–5, Beijing, China, 2–5 November 2004; Volume 475–479, pp. 61–64.
5. Mizuno, D.; Suzuki, S.; Fujita, S.; Hara, N. Corrosion monitoring and materials selection for automotive environments by using Atmospheric Corrosion Monitor (ACM) sensor. Corros. Sci. 2014, 83, 217–225.
6. Zibo Pei, X.C.; Xiaojia, Y.; Qing, L.; Chenhan, X.; Dawei, Z.; Xiaogang, L. Understanding environmental impacts on initial atmospheric corrosion based on corrosion monitoring sensors. J. Mater. Sci. Technol. 2020, 64, 214–221.
7. Pei, Z.B.; Zhang, D.W.; Zhi, Y.J.; Yang, T.; Jin, L.L.; Fu, D.M.; Cheng, X.Q.; Terryn, H.A.; Mol, J.M.C.; Li, X.G. Towards understanding and prediction of atmospheric corrosion of an Fe/Cu corrosion sensor via machine learning. Corros. Sci. 2020, 170, 108697.
8. Fuse, N.; Naganuma, A.; Fukuchi, T.; Tani, J.; Hori, Y. Methodology to Improve Corrosion Rate Estimation Based on Atmospheric Corrosion Monitoring Sensors. Corrosion 2017, 73, 199–209.
9. Kainuma, S.; Yamamoto, Y.; Itoh, Y.; Oshikawa, W. Prediction method for mean corrosion depth of uncoated carbon steel plate subjected to rainfall effect using Fe/Ag galvanic couple ACM-Type corrosion sensor. Zair. Kankyo Corros. Eng. 2011, 60, 497–503.
10. Kainuma, S.; Sugitani, K.; Itoh, Y.; Kim, I.T. Evaluation Method for Time-dependent Corrosion Behavior of Carbon Steel Plate using Atmospheric Corrosion Monitoring Sensor. Adv. Fract. Damage Mech. Viii 2010, 417, 417–420.
11. Cao, X.L.; Xiao, Y.D.; Deng, H.D.; Cao, P.J.; Jia, B. Evaluation of Atmospheric Corrosivity by ACM Technique. In Materials Science Forum; Trans Tech Publications Ltd.: Freienbach, Switzerland, 2009; Volume 610, pp. 3–8.
12. Huang, Y.L.; Yang, D.; Xu, Y.; Lu, D.Z.; Yang, L.H.; Wang, X.T. Field Study of Weather Conditions Affecting Atmospheric Corrosion by an Automobile-Carried Atmospheric Corrosion Monitor Sensor. J. Mater. Eng. Perform. 2020, 29, 5840–5853.

13. Shi, Y.N.; Fu, D.M.; Zhou, X.Y.; Yang, T.; Zhi, Y.J.; Pei, Z.B.; Zhang, D.W.; Shao, L.Z. Data mining to online galvanic current of zinc/copper Internet atmospheric corrosion monitor. Corros. Sci. 2018, 133, 443–450.
14. Ahn, J.H.; Jeong, Y.S.; Kim, I.T.; Jeon, S.H.; Park, C.H. A Method for Estimating Time-Dependent Corrosion Depth of Carbon and Weathering Steel Using an Atmospheric Corrosion Monitor Sensor. Sensors 2019, 19, 1416.
15. To, D.; Shinohara, T.; Umezawa, O. Experimental Investigation on the Corrosivity of Atmosphere through the Atmospheric Corrosion Monitoring (ACM) Sensors. Atmos. Mar. Corros. 2017, 75, 1–10.
16. Dara, T.; Shinohara, T.; Umezawa, O. Effects of Anion on the Corrosion Behaviors of Carbon Steel under Artificial Rainfall. In Proceedings of the 9th Pacific Rim International Conference on Advanced Materials and Processing (PRICM9), Kyoto, Japan, 1–8 August 2016; The Japan Institute of Metals and Materials: Sendai, Japan, 2016.
17. Kouřil, M.; Prošek, T.; Scheffel, B.; Dubois, F. High sensitivity electrical resistance sensors for indoor corrosion monitoring. Corros. Eng. Sci. Technol. 2013, 48, 282–287.
18. Msallamova, S.; Kouril, M.; Strachotova, K.C.; Stoulil, J.; Popova, K.; Dvorakova, P. Historical lead seals and the influence of disinfectants on the lead corrosion rate. Herit. Sci. 2019, 7, 18.
19. Zajec, B.; Bajt Leban, M.; Kosec, T.; Kuhar, V.; Legat, A.; Lenart, S.; Fifer Bizjak, K.; Gavin, K. Corrosion monitoring of steel structure coating degradation. Teh. Vjesn. 2018, 25, 1348–1355.
20. Diler, E.; Peltier, F.; Becker, J.; Thierry, D. Real-time corrosion monitoring of aluminium alloys under chloride-contaminated atmospheric conditions. Mater. Corros. 2021, 72, 1377–1387.
21. Prošek, T.; Le Bozec, N.; Thierry, D. Application of automated corrosion sensors for monitoring the rate of corrosion during accelerated corrosion tests. Mater. Corros. 2014, 65, 448–456.
22. AirCorr: Corrosion. Available online: https://nke-instrumentation.com/produit/aircorr-corrosion/ (accessed on 21 December 2021).
23. Dubus, M.; Kouril, M.; Nguyen, T.P.; Prosek, T.; Saheb, M.; Tate, J. Monitoring Copper and Silver Corrosion in Different Museum Environments by Electrical Resistance Measurement. Stud. Conserv. 2010, 55, 121–133.
24. Kouril, M.; Prosek, T.; Scheffel, B.; Degres, Y. Corrosion monitoring in archives by the electrical resistance technique. J. Cult. Herit. 2014, 15, 99–103.
25. Van den Steen, N.; Simillion, H.; Thierry, D.; Terryn, H.; Deconinck, J. Comparing Modeled and Experimental Accelerated Corrosion Tests on Steel. J. Electrochem. Soc. 2017, 164, C554–C562.
26. Kreislova, K.; Fialova, P.; Bohackova, T. Indoor corrosivity in Klementinum baroque library hall. In Prague Structural Studies, Repairs and Maintenance of Heritage Architecture XVII & Earthquake

Resistant Engineering Structures XIII; WIT Press: Ashurst, UK, 2021; p. 123.

27. Shan, W.; LIAO, B.-k.; DONG, Z.-h.; GUO, X.-p. Comparative investigation on copper atmospheric corrosion by electrochemical impedance and electrical resistance sensors. Trans. Nonferrous Met. Soc. China 2021, 31, 3024–3038.
28. Dubus, M.; Prosek, T. Standardized Assessment of Cultural Heritage Environments by Electrical Resistance Measurements. e-PRESERVATIONScience 2012, 9, 67–71.
29. Prošek, T.; Kouřil, M.; Dubus, M.; Taube, M.; Hubert, V.; Scheffel, B.; Degres, Y.; Jouannic, M.; Thierry, D. Real-Time monitoring of indoor air corrosivity in cultural heritage institutions with metallic electrical resistance sensors. Stud. Conserv. 2013, 58, 117–128.
30. Faifer, M.; Goidanich, S.; Laurano, C.; Petiti, C.; Toscani, S.; Zanoni, M. Measurement Setup for the Development of Pre-Corroded Sensors for Metal Artwork Monitoring. In Proceedings of the 2019 IMEKO TC-4, Florence, Italy, 4–6 December 2019; pp. 1–6.
31. Kosec, T.; Kuhar, V.; Kranjc, A.; Malnaric, V.; Belingar, B.; Legat, A. Development of an Electrical Resistance Sensor from High Strength Steel for Automotive Applications. Sensors 2019, 19, 1956.
32. Msallamova, S.; Kouril, M.; Strachotova, K.C.; Stoulil, J.; Popova, K.; Dvorakova, P.; Lhotka, M. Protection of lead in an environment containing acetic acid vapour by using adsorbents and their characterization. Herit. Sci. 2019, 7, 76.
33. Strachotova, K.C.; Kuchtakova, K.; Kouril, M.; Msallamova, S. Protection of Lead in Acetic Acid Containing Air by Means of Corrosion Inhibitors. In Proceedings of the 27th International Conference on Metallurgy and Materials (Metal 2018), Brno, Czech Republic, 23–25 May 2018; pp. 1045–1050.
34. Van den Steen, N.; Simillion, H.; Thierry, D.; Deconinck, J. Modeling Film Thicknesses and Estimating Corrosion Depths Under Climate Control. In Proceedings of the ECS Meeting Abstracts, PRiME 2016/230th ECS Meeting, Honolulu, HI, USA, 2–7 October 2016; p. 1319.
35. Yasri, M.; Lescop, B.; Diler, E.; Gallee, F.; Thierry, D.; Rioual, S. Fundamental basis of electromagnetic wave propagation in a zinc microstrip lines during its corrosion. Sens. Actuators B Chem. 2016, 223, 352–358.
36. Prosek, T.; Taube, M.; Dubois, F.; Thierry, D. Application of automated electrical resistance sensors for measurement of corrosion rate of copper, bronze and iron in model indoor atmospheres containing short-chain volatile carboxylic acids. Corros. Sci. 2014, 87, 376–382.
37. Kouřil, M.; Prošek, T.; Dubus, M.; Taube, M.; Hubert, V.; Scheffel, B.; Degres, Y.; Jouannic, M.; Thierry, D. Korozní monitoring v rukách restaurátorů a konzervátorů/Corrosion monitoring in the hands of restorers and conservators. Koroze Ochr. Mater. 2012, 56, 67–75.

38. Bailey, G.; Brian, J.; Champion, C. An investigation into the impact of sealed wooden and acrylic showcases and storage cases on the corrosion of lead objects during long term storage and display. AICCM Bull. 2017, 38, 43–50.
39. Morcillo, M.; Otero, E.; Chico, B.; de la Fuente, D. Atmospheric corrosion studies in a decommissioned nuclear power plant. In Nuclear Power; InTech: Rijeka, Croatia, 2010; pp. 243–265.
40. SURVEYOR PLUS™. Available online: https://circul-aire.com/corrosion-monitoring/surveyor-plus/ (accessed on 21 December 2021).
41. Svadlena, J.; Voracova, E.; Stoulil, J. Corrosion of silver in environment containing halides, pseudohalides, or thiourea. Mater. Corros. Werkst. Und Korros. 2020, 71, 1721–1728.
42. Nishikata, A.; Suzuki, F.; Tsuru, T. Corrosion monitoring of nickel-containing steels in marine atmospheric environment. Corros. Sci. 2005, 47, 2578–2588.
43. Nishikata, A.; Zhu, Q.J.; Tada, E. Long-term monitoring of atmospheric corrosion at weathering steel bridges by an electrochemical impedance method. Corros. Sci. 2014, 87, 80–88.
44. Xia, D.H.; Song, S.Z.; Jin, W.X.; Li, J.; Gao, Z.M.; Wang, J.H.; Hu, W.B. Atmospheric Corrosion Monitoring of Field-exposed Q235B and T91 Steels in Zhoushan Offshore Environment Using Electrochemical Probes. J. Wuhan Univ. Technol. Mater. Sci. Ed. 2017, 32, 1433–1440.
45. ASTM G96-90(2008)Standard Guide for Online Monitoring of Corrosion in Plant Equipment (Electrical and Electrochemical Methods), ASTM: West Conshohocken, PA, USA, 2008.
46. Li, C.L.; Ma, Y.T.; Li, Y.; Wang, F.H. EIS monitoring study of atmospheric corrosion under variable relative humidity. Corros. Sci. 2010, 52, 3677–3686.
47. Nishikata, A.; Yamashita, Y.; Katayama, H.; Tsuru, T.; Usami, A.; Tanabe, K.; Mabuchi, H. An Electrochemical Impedance Study on Atmospheric Corrosion of Steels in a Cyclic Wet-Dry Condition. Corros. Sci. 1995, 37, 2059–2069.
48. Shi, Y.; Tada, E.; Nishikata, A. A method for determining the corrosion rate of a metal under a thin electrolyte film. J. Electrochem. Soc. 2015, 162, C135–C139.
49. Nishikata, A.; Ichihara, Y.; Hayashi, Y.; Tsuru, T. Influence of electrolyte layer thickness and pH on the initial stage of the atmospheric corrosion of iron. J. Electrochem. Soc. 1997, 144, 1244.
50. Thee, C.; Hao, L.; Dong, J.H.; Mu, X.; Ke, W. Numerical Approach for Atmospheric Corrosion Monitoring Based on EIS of a Weathering Steel. Acta Met. Sin. Engl. 2015, 28, 261–271.
51. Angelini, E.; Grassini, S.; Corbellini, S.; Ingo, G.M.; De Caro, T.; Plescia, P.; Riccucci, C.; Bianco, A.; Agostini, S. Potentialities of XRF and EIS portable instruments for the characterisation of ancient artefacts. Appl. Phys. A Mater 2006, 83, 643–649.

52. Katayama, H.; Tay, Y.-C.; AS, V.; Nishikata, A.; Tsuru, T. Corrosion monitoring of Zn and Zn–Al coated steels under wet-dry cyclic conditions using AC impedance method. Mater. Trans. JIM 1997, 38, 1089–1094.
53. El-Mahdy, G.A.; Nishikata, A.; Tsuru, T. AC impedance study on corrosion of 555%Al-Zn alloy-coated steel under thin electrolyte layers. Corros. Sci. 2000, 42, 1509–1521.
54. El-Mahdy, G.A.; Nishikata, A.; Tsuru, T. Electrochemical corrosion monitoring of galvanized steel under cyclic wet-dry conditions. Corros. Sci. 2000, 42, 183–194.
55. Yadav, A.; Nishikata, A.; Tsuru, T. Electrochemical impedance study on galvanized steel corrosion under cyclic wet–dry conditions—influence of time of wetness. Corros. Sci. 2004, 46, 169–181.
56. Ma, X.M.; Cheng, Q.L.; Zheng, M.; Cui, F.Y.; Hou, B.R. Monitoring Marine Atmospheric Corrosion by Electrochemical Impedance Spectroscopy under Various Relative Humidities. Int. J. Electrochem. Sci. 2015, 10, 10402–10421.
57. Pan, C.; Lv, W.; Wang, Z.; Su, W.; Wang, C.; Liu, S. Atmospheric corrosion of copper exposed in a simulated coastal-industrial atmosphere. J. Mater. Sci. Technol. 2017, 33, 587–595.
58. Wan, S.; Hou, J.; Zhang, Z.F.; Zhang, X.X.; Dong, Z.H. Monitoring of atmospheric corrosion and dewing process by interlacing copper electrode sensor. Corros. Sci. 2019, 150, 246–257.
59. Xia, D.-H.; Ma, C.; Song, S.; Xu, L. Detection of atmospheric corrosion of aluminum alloys by electrochemical probes: Theoretical analysis and experimental tests. J. Electrochem. Soc. 2019, 166, B1000.
60. Garcia-Ochoa, E.; Gonzalez-Sanchez, J.; Corvo, F.; Usagawa, Z.; Dzib-Peerez, L.; Castaneda, A. Application of electrochemical noise to evaluate outdoor atmospheric corrosion of copper after relatively short exposure periods. J. Appl. Electrochem. 2008, 38, 1363–1368.
61. Li, J.; Kong, W.K.; Shi, J.B.; Wang, K.; Wang, W.K.; Zhao, W.P.; Zeng, Z.M. Determination of Corrosion Types from Electrochemical Noise by Artificial Neural Networks. Int. J. Electrochem. Sci. 2013, 8, 2365–2377.
62. Schwind, M.; Langhammer, C.; Kasemo, B.; Zoric, I. Nanoplasmonic sensing and QCM-D as ultrasensitive complementary techniques for kinetic corrosion studies of aluminum nanoparticles. Appl. Surf. Sci. 2011, 257, 5679–5687.
63. Kleber, C.; Wiesinger, R.; Schnoller, J.; Hilfrich, U.; Hutter, H.; Schreiner, M. Initial oxidation of silver surfaces by S2- and S4+ species. Corros. Sci. 2008, 50, 1112–1121.
64. Wiesinger, R.; Kleber, C.; Frank, J.; Schreiner, M. A New Experimental Setup for in Situ Infrared Reflection Absorption Spectroscopy Studies of Atmospheric Corrosion on Metal Surfaces Considering the Influence of Ultraviolet Light. Appl. Spectrosc. 2009, 63, 465–470.

65. Wiesinger, R.; Schreiner, M.; Kleber, C. Investigations of the interactions of CO2, O3 and UV light with silver surfaces by in situ IRRAS/QCM and ex situ TOF-SIMS. Appl. Surf. Sci. 2010, 256, 2735–2741.
66. Wiesinger, R.; Schade, U.; Kleber, C.; Schreiner, M. An experimental set-up to apply polarization modulation to infrared reflection absorption spectroscopy for improved in situ studies of atmospheric corrosion processes. Rev. Sci. Instrum. 2014, 85, 064102.
67. Wiesinger, R.; Martina, I.; Kleber, C.; Schreiner, M. Influence of relative humidity and ozone on atmospheric silver corrosion. Corros. Sci. 2013, 77, 69–76.
68. Wan, S.; Ma, X.Z.; Miao, C.H.; Zhang, X.X.; Dong, Z.H. Inhibition of 2-phenyl imidazoline on chloride-induced initial atmospheric corrosion of copper by quartz crystal microbalance and electrochemical impedance. Corros. Sci. 2020, 170, 108692.
69. Hosseinpour, S.; Schwind, M.; Kasemo, B.; Leygraf, C.; Johnson, C.M. Integration of Quartz Crystal Microbalance with Vibrational Sum Frequency Spectroscopy-Quantification of the Initial Oxidation of Alkanethiol-Covered Copper. J. Phys. Chem. C 2012, 116, 24549–24557.
70. Alamin, M.; Tian, G.Y.; Andrews, A.; Jackson, P. Corrosion detection using low-frequency RFID technology. Insight 2012, 54, 72–75.
71. Yasri, M.; Gallee, F.; Leseop, B.; Diler, E.; Thierry, D.; Rioual, S. Passive Wireless Sensor for Atmospheric Corrosion Monitoring. In Proceedings of the 8th European Conference on Antennas and Propagation (EuCAP 2014), The Hague, The Netherlands, 6–11 April 2014; pp. 2945–2949.
72. Dyos, G. The Handbook of Electrical Resistivity: New materials and pressure effects; The Institution of Engineering and Technology: London, UK, 2012.
73. Alamin, M. Passive Low Frequencey RFID for Detection and Monitoring of Corrosion under Paint and Insulation; Newcastle University: Newcastle upon Tyne, UK, 2014.
74. Yasri, M.; Lescop, B.; Diler, E.; Gallee, F.; Thierry, D.; Rioual, S. Monitoring uniform and localised corrosion by a radiofrequency sensing method. Sens. Actuators B Chem. 2018, 257, 988–992.
75. Watkinson, D.; Rimmer, M. Quantifying Effectiveness of Chloride Desalination Treatments for Archaeological Iron Using Oxygen Measurement. In Proceedings of the Metal 2013: Interim Meeting of the ICOM-CC Metal Working Group, Edinburg, Schotland, 16–20 September 2013; pp. 95–102.
76. Emmerson, N.; Seifert, J.; Watkinson, D. Refining the use of oxygen consumption as a proxy corrosion rate measure for archaeological and historic iron. Eur. Phys. J. Plus 2021, 136, 546.
77. Strebl, M.; Virtanen, S. Real-Time Monitoring of Atmospheric Magnesium Alloy Corrosion. J. Electrochem. Soc. 2018, 166, C3001–C3009.

78. Matthiesen, H. A novel method to determine oxidation rates of heritage materials in vitro and in situ. Stud. Conserv. 2007, 52, 271–280.
79. Nishikata, A.; Ichihara, Y.; Tsuru, T. Electrochemical impedance spectroscopy of metals covered with a thin electrolyte layer. Electrochim. Acta 1996, 41, 1057–1062.
80. Thee, C.; Hao, L.; Dong, J.H.; Mu, X.; Wei, X.; Li, X.F.; Ke, W. Atmospheric corrosion monitoring of a weathering steel under an electrolyte film in cyclic wet-dry condition. Corros. Sci. 2014, 78, 130–137.
81. Thee, C.; Dong, J.; Ke, W. Corrosion monitoring of weathering steel in a simulated coastal-industrial environment. Int. J. Environ. Ecol. Eng. 2015, 9, 587–593.
82. Cruz, R.V.; Nishikata, A.; Tsuru, T. AC impedance monitoring of pitting corrosion of stainless steel under a wet-dry cyclic condition in chloride-containing environment. Corros. Sci. 1996, 38, 1397–1406.
83. Cruz, R.V.; Nishikata, A.; Tsuru, T. Pitting corrosion mechanism of stainless steels under wet-dry exposure in chloride-containing environments. Corros. Sci. 1998, 40, 125–139.
84. Yadav, A.P.; Nishikata, A.; Tsuru, T. Degradation mechanism of galvanized steel in wet–dry cyclic environment containing chloride ions. Corros. Sci. 2004, 46, 361–376.
85. Somphotch, C.; Hayashibara, H.; Ooi, A.; Tada, E.; Nishikata, A. Corrosion behavior of zinc under thin solution films of different thicknesses. J. Electrochem. Soc. 2018, 165, C590.
86. Liao, X.-N.; Cao, F.-H.; Chen, A.-N.; Liu, W.-J.; Zhang, J.-Q.; Cao, C.-N. In-situ investigation of atmospheric corrosion behavior of bronze under thin electrolyte layers using electrochemical technique. Trans. Nonferrous Met. Soc. China 2012, 22, 1239–1249.
87. Liao, X.; Cao, F.; Zheng, L.; Liu, W.; Chen, A.; Zhang, J.; Cao, C. Corrosion behaviour of copper under chloride-containing thin electrolyte layer. Corros. Sci. 2011, 53, 3289–3298.
88. El-Mahdy, G.; Kim, K.B. AC impedance study on the atmospheric corrosion of aluminum under periodic wet-dry conditions. Electrochim. Acta 2004, 49, 1937–1948.
89. Van Tran, N.; Ooi, A.; Tada, E.; Nishikata, A. EIS Characteristics of Galvanic Couple of Aluminum Alloy and High-strength Steel under Thin Solution Films. J. Electrochem. Soc. 2020, 167, 131507.
90. Ma, C.; Song, S.Z.; Gao, Z.M.; Wang, J.H.; Hu, W.B.; Behnamian, Y.; Xia, D.H. Electrochemical noise monitoring of the atmospheric corrosion of steels: Identifying corrosion form using wavelet analysis. Corros. Eng. Sci. Technol. 2017, 52, 432–440.
91. Jamali, S.S.; Zhao, Y.; Gao, Z.M.; Li, H.J.; Hee, A.C. In situ evaluation of corrosion damage using non-destructive electrochemical measurements-A case study. J. Ind. Eng. Chem. 2016, 43, 36–43.

92. Iverson, W.P. Transient Voltage Changes Produced in Corroding Metals and Alloys. J. Electrochem. Soc. 1968, 115, 617.
93. Ehahoun, H.; Gabrielli, C.; Keddam, M.; Perrot, H.; Cetre, Y.; Diguet, L. Electrochemical quartz crystal microbalance corrosion sensor for solid metals and metal alloys—Application to the dissolution of 304 stainless steel. J. Electrochem. Soc. 2001, 148, B333–B336.
94. Odlyha, M.; Jakiela, S.; Bergsten, C.J.; Slater, J.M.; Niklasson, A.; Svensson, J.; Cavicchioli, A.; de Faria, D.; Thickett, D.; Grøntoft, T. Dosimetry for monitoring in organ pipes and in microclimate frames for paintings. In Proceedings of the Metal 2010: Interim Meeting of the ICOM-CC Metal Working Group, Charleston, CA, USA, 11–15 October 2010; 2010; pp. 321–326.
95. OnGuard Smart. Available online: https://www.purafil.com/products/monitoring/active-monitoring/onguard-smart/ (accessed on 21 December 2021).
96. Odlyha, M.; Slater, J.M.; Grøntoft, T.; Jakiela, S.; Obarzanowski, M.; Thickett, D.; Hackney, S.; Andrade, G.; Wadum, J.; Christensen, A.H. A Portable Tool for the Evaluation of Microclimate Conditions within Museum Enclosures, Transit Frames, and Transport Cases. Stud. Conserv. 2018, 63, 407–410.
97. Agbota, H.; Mitchell, J.E.; Odlyha, M.; Strlič, M. Remote assessment of cultural heritage environments with wireless sensor array networks. Sensors 2014, 14, 8779–8793.
98. Matthiesen, H.; Stemann-Petersen, K. A fast and non-destructive method to document and quantify the efficiency of metals conservation. In Proceedings of the Metal 2013: Interim Meeting of the ICOM-CC Metal Working Group, Edinburgh, Scotland, 16–20 September 2013; pp. 16–20.
99. Watkinson, D.; Emmerson, N.; Seifert, J. Matching Display Relative Humidity to Corrosion Rate: Quantitative Evidence for Marine Cast Iron Cannon Balls. In Proceedings of the Metal 2016: Interim Meeting of the ICOM-CC Metals Working Group, New Delhi, India, 26–30 September 2016; pp. 195–202.
100. Watkinson, D.E.; Rimmer, M.B.; Emmerson, N.J. The influence of relative humidity and intrinsic chloride on post-excavation corrosion rates of archaeological wrought iron. Stud. Conserv. 2019, 64, 456–471.
101. Emmerson, N.J.; Watkinson, D.E. Surface preparation of historic wrought iron: Evidencing the requirement for standardisation. Mater. Corros. 2016, 67, 176–189.
102. Watkinson, D.; Emmerson, N. The impact of aqueous washing on the ability of βFeOOH to corrode iron. Environ. Sci. Pollut. Res. 2017, 24, 2138–2149.

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