
**Corrosion of metals and alloys —
Corrosivity of atmospheres —
Mapping areas of increased risk of
corrosion**

*Corrosion des métaux et alliages — Corrosivité des atmosphères —
Cartographie des zones présentant un risque accru de corrosion*

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Contents

	Page
Foreword.....	iv
Introduction.....	v
1 Scope.....	1
2 Normative references.....	1
3 Terms and definitions.....	1
4 Mapping of corrosivity.....	2
4.1 Dose-response functions.....	2
4.2 Environmental data used as input to dose-response functions.....	2
4.3 Transformation of the environmental data to a common grid system.....	2
4.4 Calculation and presentation of corrosion.....	2
5 Mapping of lifetime.....	3
6 Mapping of corrosion cost.....	3
7 Mapping errors.....	4
Annex A (informative) ISO 9223 dose-response functions.....	5
Annex B (informative) ICP materials functions.....	6
Annex C (informative) Example of environmental data sources.....	8
Annex D (informative) Procedure for calculation of lifetimes.....	9
Bibliography.....	10

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 156, *Corrosion of metals and alloys*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Corrosion maps have become more frequent, and to ensure transparency and ease of comparison of corrosion maps, this work was initiated.

This document describes procedures for calculating corrosivity maps based on arrays of environmental data organised in a grid and using a dose-response function. Corrosivity maps based on dose-response functions can be very useful for illustrating geographical variations, trends in time and the relative importance of different underlying parameters (climate, pollution) and to communicate these results to those not working in the field of corrosion. The result for an individual grid cell of a corrosivity map is, however, very uncertain. If a corrosivity assessment for a single location is needed, it is recommended to also consider direct measurements of corrosion according to ISO 9223.

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Corrosion of metals and alloys — Corrosivity of atmospheres — Mapping areas of increased risk of corrosion

1 Scope

This document gives guidelines for producing corrosivity maps and maps related to increased risk of corrosion in outdoor open atmospheres, but not sheltered or semi-sheltered positions.

The maps are calculated based on environmental data using specific relationships, so-called dose-response functions. Other means of producing corrosivity maps, for example using detailed measurements of corrosion and subsequent interpolation of measured corrosion values, are not within the scope of this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 9223:2012, *Corrosion of metals and alloys — Corrosivity of atmospheres — Classification, determination and estimation*

ISO 9224:2012, *Corrosion of metals and alloys — Corrosivity of atmospheres — Guiding values for the corrosivity categories*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

dose-response function

relationship derived from results of field tests for calculation of corrosion loss from average values of environmental parameters

Note 1 to entry: The term is commonly used for all functions, including those where it is not mathematically correct to denote the combination of time and pollution by the word “dose”.

4 Mapping of corrosivity

4.1 Dose-response functions

For worldwide corrosivity mapping of carbon steel, zinc, copper and aluminium (C1-C5 and CX), dose-response functions given in ISO 9223 should be used. Other functions can also be used for comparison purposes.

NOTE 1 The error associated with estimation of corrosivity categories using dose-response functions is always higher compared to direct measurements and can lead to significant over or under estimation.

For mapping regions, countries or local areas other dose-response functions can be used.

NOTE 2 Several dose-response functions are available, and examples are given in [Annex A](#) and [Annex B](#).

Dose-response functions should be derived from a statistical analysis of field exposure data collected according to the procedures given in ISO 8565.

The dose-response functions used shall be clearly indicated in the map or map legend. If dose-response functions are not derived from a statistical analysis of field exposure data, this shall be mentioned. This is also the case if dose-response functions based on field data are altered or if several functions based on different field exposure data are combined.

NOTE 3 It is permissible to simplify a dose-response function before its use by inserting a constant instead of an environmental parameter if it can be clearly motivated by an error analysis. This can, for example, be done with respect to temperature, if the mapped area is local with a small variation in temperature compared to other parameters.

4.2 Environmental data used as input to dose-response functions

Data used as input to dose-response functions shall be based on annual averages or longer time spans. The respective years(s) for the data shall be clearly indicated in the map or map legend.

It is recommended to use the same time period for all data, but exceptions can be made. One example is if a map series is produced with the purpose of illustrating the effect of a changing pollution situation over time (trends), where it is appropriate to use the same climate data (e.g. 30-year averages) for the meteorological data in all maps in this series.

NOTE Data are generally available from national weather services, European agencies or other worldwide data sources. A list of some common sources for data is given in [Annex C](#).

Data used as input to dose-response functions shall not be outside the intervals for the parameters upon which the dose-response function was derived. An extrapolation outside the boundaries of the equation should be clearly marked in the map or map legend.

4.3 Transformation of the environmental data to a common grid system

To combine data by use of the dose-response function, all environmental data shall be transformed to the same grid system and resolution.

It is recommended to keep the data with highest degree of uncertainty untransformed and transform all remaining data accordingly.

4.4 Calculation and presentation of corrosion

The unit to be used for expressing uniform corrosion is μm . If the corrosion is localised but needs to be expressed as an average, the unit g/m^2 shall be used.

NOTE The relationship between these two units for uniform corrosion [$\text{g}/(\text{m}^2 \cdot \mu\text{m}) = \text{g}/\text{cm}^3$] is equal to the density of the metal.

For carbon steel, zinc, copper and aluminium intervals corresponding to corrosivity categories C1-C5 and CX as defined in ISO 9223 shall be used. Intervals for low-alloyed steels, including weathering steels, shall follow those for carbon steel, zinc alloys and zinc coatings shall follow those for zinc, copper alloys those for copper, and aluminium alloys those for aluminium.

Corrosivity shall be presented in maps with different colours ranging from lighter, corresponding to low values of corrosivity, to darker, corresponding to high values of corrosivity.

It is recommended to use a scale which gives a logical representation of corrosivity (lighter – low; darker – high) when a colour map is printed in black and white.

5 Mapping of lifetime

If the time development is given in the dose-response function, this expression shall be used. Otherwise, the time expression given in ISO 9224 shall be used.

The corrosion rate, D , is given as a function of time according to ISO 9224:

$$D = r_{\text{corr}} t^b \quad (1)$$

where

r_{corr} is the corrosion rate experienced in the first year, which can be mapped and expressed according to the procedures in [Clause 4](#);

t is the exposure time, expressed in years, and $t < 20$ years;

b is the metal-environment-specific time exponent, usually less than 1.

The use of [Formula \(1\)](#) beyond 20 years is probably justified in most cases, especially if the exposure is not much greater than 20 years. However, ISO 9224 also introduces an alternative linear approach of estimating the corrosion rates at longer exposure times (> 20 years). The lifetime, t_1 , can be calculated as given in [Formula \(2\)](#), by assuming a specified limiting corrosion attack at which the material/component shall be replaced or maintained, D_1 .

$$t_1 = (D_1/r_{\text{corr}})^{1/b} \quad (2)$$

When selecting D_1 , the particular application shall be taken into account.

NOTE An example of a typical lifetime calculation is given in [Annex D](#).

6 Mapping of corrosion cost

The corrosion cost can be calculated according to [Formula \(3\)](#):

$$C = c \cdot S/t_1 \quad (3)$$

where

C is the corrosion cost per year;

c is the replacement or maintenance cost per surface area;

S is the total surface area of the material;

t_1 is the lifetime, which can be mapped and expressed according to the procedures in [Clause 5](#).

NOTE 1 The replacement or maintenance cost per surface area, c , is not a constant and can vary substantially between countries.

NOTE 2 The total surface area of the material, S , or the so called “stock of materials at risk” is a geographically dependent parameter that can be very difficult to estimate.

Dose-response functions are particularly suitable for mapping costs related to different scenarios with respect to climate (climate change) or pollution (air quality policy). For such purposes, it is necessary to estimate the difference in cost between two alternative scenarios. It can, for example, express the cost savings associated with air quality policy from a difference between the current situation and a future scenario. The cost difference, ΔC , can then be calculated as given by [Formula \(4\)](#):

$$\Delta C = c \cdot S (t_{1,1}^{-1} - t_{1,2}^{-1}) \quad (4)$$

where

$t_{1,1}$ is the lifetime (scenario 1);

$t_{1,2}$ is the lifetime (scenario 2).

7 Mapping errors

Corrosivity in a certain location can be determined by first year exposure tests in accordance with ISO 9223. The level of uncertainty for this determination is given in ISO 9223:2012, Annex A and is in the range between ± 2 % to ± 5 %, depending on the metal. The uncertainty associated with the estimation of corrosion attack from dose-response functions is much higher and depends on errors in the used environmental data, uncertainty in the dose-response function and error from the chosen geographical scale. For mapping of lifetime, there is an additional extrapolation error while for mapping of corrosion cost, there are all these errors and in addition errors associated with the estimation of costs for replacement or maintenance.

NOTE The natural variation in the environment from year to year resulting in a corresponding variation in corrosivity from year to year can be substantial but is not part of this error analysis. This natural variability will affect both the determination of the corrosion attack by one-year exposure tests as well as the estimation of corrosion attack with dose-response functions.

Environmental data used as input to the dose-response functions are either from models based on physical and chemical transport equations or from interpolation of measurements from weather station data. The errors can be substantial but vary significantly depending on the data source and it is not possible to give a general magnitude of the error. It is recommended to make an estimation of the errors for all the input environmental mapping data.

Dose-response functions are statistical relationships and the statistical error when using a dose-response function, even with perfect input data, is about ± 50 %, depending on the formula (see ISO 9223:2012, Annex A).

Maps are produced at a certain scale represented by the grid size, which is determined by the geographical resolution of the input data. Geographical variations in corrosivity can, however, be substantial. Special care should be taken when interpreting maps where a strong gradient in one or more of the input parameters is expected, for example, variation in SO_2 within an urban area or variation in chloride deposition in coastal areas.

Errors associated with extrapolation in time can be substantial, especially for longer lifetimes. ISO 9224 give uncertainties for the coefficient b in [Formula \(1\)](#), which can be used to estimate uncertainties for estimated lifetimes.

Annex A (informative)

ISO 9223 dose-response functions

Dose-response functions for carbon steel, zinc, copper and aluminium are given in ISO 9223:

$$r_{St} = 1,77 P_d^{0,52} \cdot \exp(0,020RH+f_{St}) + 0,102 S_d^{0,62} \cdot \exp(0,033RH+0,040T)$$

$$r_{Zn} = 0,0129 P_d^{0,44} \cdot \exp(0,046RH+f_{Zn}) + 0,0175 S_d^{0,57} \cdot \exp(0,008RH+0,085T)$$

$$r_{Cu} = 0,0053 P_d^{0,26} \cdot \exp(0,059RH+f_{Cu}) + 0,01025 S_d^{0,27} \cdot \exp(0,036RH+0,049T)$$

$$r_{Al} = 0,0042 P_d^{0,73} \cdot \exp(0,025RH+f_{Al}) + 0,0018 S_d^{0,60} \cdot \exp(0,020RH+0,094T)$$

where

r_{Me} is the first-year corrosion rate of a metal (Me), expressed in micrometres per year ($\mu\text{m/a}$) for the metals carbon steel (St), zinc (Zn), copper (Cu) and aluminium (Al);

RH is the annual average relative humidity, expressed as a percentage (%);

T is the annual average temperature, expressed in degrees Celsius ($^{\circ}\text{C}$);

f_{Me} is a temperature (T) and metal (Me) dependent function, different for the four metals (St, Zn, Cu, Al);

$f_{St} = 0,150(T-10)$ when $T \leq 10^{\circ}\text{C}$; $-0,054(T-10)$ when $T > 10^{\circ}\text{C}$

$f_{Zn} = 0,038(T-10)$ when $T \leq 10^{\circ}\text{C}$; $-0,071(T-10)$ when $T > 10^{\circ}\text{C}$

$f_{Cu} = 0,126(T-10)$ when $T \leq 10^{\circ}\text{C}$; $-0,080(T-10)$ when $T > 10^{\circ}\text{C}$

$f_{Al} = 0,009(T-10)$ when $T \leq 10^{\circ}\text{C}$; $-0,043(T-10)$ when $T > 10^{\circ}\text{C}$

P_d is the SO_2 dry deposition, expressed in annual averages of milligrams SO_2 per square metre per day [$\text{mg}/(\text{m}^2\cdot\text{d})$]. The SO_2 concentration can be used to estimate SO_2 deposition using the formula $P_d = 0,8C_{\text{SO}_2}$, where C_{SO_2} is the SO_2 concentration expressed in annual averages of micrograms SO_2 per cubic metre ($\mu\text{g}/\text{m}^3$);

S_d is the Cl^- dry deposition, expressed in annual averages of milligrams Cl per square metre per day [$\text{mg}/(\text{m}^2\cdot\text{d})$].

Care shall be taken when extrapolating the formulae outside the intervals of environmental parameters for their calculations (e.g. in coastal environments), which are $-17,1^{\circ}\text{C}$ to $28,7^{\circ}\text{C}$ for temperature, 34 % to 93 % for relative humidity, $0,7 \text{ mg}/(\text{m}^2\cdot\text{d})$ to $150,4 \text{ mg}/(\text{m}^2\cdot\text{d})$ for SO_2 deposition and $0,4 \text{ mg}/(\text{m}^2\cdot\text{d})$ to $760,5 \text{ mg}/(\text{m}^2\cdot\text{d})$ for Cl^- deposition.

Annex B (informative)

ICP materials¹⁾ functions

Dose-response functions for carbon steel, weathering steel, zinc, aluminium, copper and bronze are given in the Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads and Levels and Air Pollution Effects, Risks and Trends.^[2] The manual also gives functions for the stone materials limestone and sandstone as well as paint coated steel and galvanised steel but those are not repeated in this annex.

ICP materials dose-response functions are classified as “functions for the SO₂ dominating situation” and “functions for the multi-pollutant situation”.

Functions for the SO₂ dominating situation are as follows:

$$\Delta m_{Ws} = 34C_{SO_2}^{0,13} \cdot \exp(0,020RH+f_{Ws}) \cdot t^{0,33}$$

$$\Delta m_{Zn} = 1,4C_{SO_2}^{0,22} \cdot \exp(0,018RH+f_{Zn}) \cdot t^{0,85} + 0,029[H^+] \cdot d_{aq} \cdot t$$

$$\Delta m_{Al} = 0,002 \cdot 1C_{SO_2}^{0,23} \cdot RH \cdot \exp(f_{Al}) \cdot t^{1,2} + 0,000 \cdot 023[Cl^-] \cdot d_{aq} \cdot t$$

$$\Delta m_{Cu} = 0,002 \cdot 7C_{SO_2}^{0,32} \cdot C_{O_3}^{0,79} \cdot RH \cdot \exp(f_{Cu}) \cdot t^{0,78} + 0,050[H^+] \cdot d_{aq} \cdot t^{0,89}$$

$$\Delta m_{Br} = 0,026C_{SO_2}^{0,44} \cdot RH \cdot \exp(f_{Br}) \cdot t^{0,86} + (0,029[H^+] + 0,000 \cdot 43[Cl^-]) \cdot d_{aq} \cdot t^{0,76}$$

where

Δm_{Me} is the corrosion of a metal (Me), expressed as mass loss in grams per square meter (g/m²) for the metals weathering steel (Ws), zinc (Zn), aluminium (Al), copper (Cu) and bronze (Br);

C_{SO_2} is the SO₂ air concentration, expressed in annual averages of micrograms SO₂ per cubic meter (µg/m³);

C_{O_3} is the O₃ air concentration, expressed in annual averages of micrograms O₃ per cubic meter (µg/m³);

T is the annual average temperature, expressed in degrees Celsius (°C);

f_{Ws} = 0,059(T-10) when $T \leq 10$ °C; -0,036(T-10) when $T > 10$ °C

f_{Zn} = 0,062(T-10) when $T \leq 10$ °C; -0,021(T-10) when $T > 10$ °C

f_{Al} = 0,031(T-10) when $T \leq 10$ °C; -0,061(T-10) when $T > 10$ °C

f_{Cu} = 0,083(T-10) when $T \leq 10$ °C; -0,032(T-10) when $T > 10$ °C

f_{Br} = 0,060(T-11) when $T \leq 11$ °C; -0,067(T-11) when $T > 11$ °C

t is the time of exposure expressed in years (a);

1) International Co-operative Programme on Effects on Materials including Historic and Cultural Monuments (ICP Materials)

- [H⁺] is the H⁺ concentration of precipitation, expressed in annual averages of as milligrams H per litre (mg/l);
- [Cl⁻] is the Cl⁻ concentration of precipitation, expressed in annual averages of as milligrams Cl per litre (mg/l);
- d_{aq} is the precipitation (water and snow) deposition, expressed in annual averages of millimetres water per year (mm/a), which at water density 1 corresponds to kilograms water per square meter per year [(kg/(m²·a))].

The formulae are valid for regions without strong influence of sea salts with total chloride content in precipitation less than 5 mg/l approximately, regardless of the source.

Functions for the multi-pollutant situation are as follows:

$$r_{\text{St}} = 6,5 + 0,178C_{\text{SO}_2}^{0,6} \cdot RH_{60} \cdot \exp(f_{\text{St}}) + 0,076C_{\text{PM}_{10}} + 0,166[\text{H}^+] \cdot d_{\text{aq}}$$

$$r_{\text{Zn}} = 0,49 + 0,066C_{\text{SO}_2}^{0,22} \cdot \exp(0,018RH + f_{\text{Zn}}) + 0,192C_{\text{HNO}_3} + 0,0057[\text{H}^+] \cdot d_{\text{aq}}$$

$$r_{\text{Br}} = 0,15 + 0,000985C_{\text{SO}_2} \cdot RH_{60} \cdot \exp(f_{\text{Br}}) + 0,00432C_{\text{PM}_{10}} + 0,00465[\text{H}^+] \cdot d_{\text{aq}}$$

where, complementing those above in this annex

r_{Me} is the first-year corrosion rate of a metal (Me), expressed in micrometres per year (µm/a) for the metals carbon steel (St), zinc (Zn) and bronze (Br);

RH_{60} = 0 when $RH \leq 60$; $RH - 60$ when $RH > 60$

f_{St} = 0,150(T-10) when $T \leq 10$ °C; -0,054(T-10) when $T > 10$ °C (as in [Annex A](#))

f_{Zn} = 0,062(T-10) when $T \leq 10$ °C; -0,021(T-10) when $T > 10$ °C (as above)

f_{Br} = 0,060(T-11) when $T \leq 11$ °C; -0,067(T-11) when $T > 11$ °C (as above)

C_{HNO_3} is the HNO₃ air concentration, expressed in annual averages of micrograms HNO₃ per cubic metre (µg/m³);

$C_{\text{PM}_{10}}$ is the air concentration of particles of size less than 10 µm, expressed in annual averages of micrograms per cubic meter (µg/m³).

Annex C (informative)

Example of environmental data sources

When using multiple environmental data sources as input values, it should be recognized that environmental factors differ not only in horizontal but also in vertical locations. In particular, the Cl⁻ or SO₂ dry deposition value can vary greatly depending on the height to be measured. As a result, if the measurement heights are different in multiple environmental data sources, the results can be different from the actual ones.

The World Meteorological Organization (WMO) has a catalogue for climate data assessed through an internationally agreed maturity evaluation process (<https://climatedata-catalogue.wmo.int/>).

The climate research unit, University of East Anglia (www.cru.uea.ac.uk) provides data on temperature, precipitation, relative humidity and many other climatic parameters. It should be noted that the so-called “climate normals”, corresponding to 30-year averages during the period 1961 to 1990, can only be useful when illustrating past decreasing corrosion trends due to pollution. However, for prediction of future corrosion, climate change needs to be considered and it is suitable to use average values only for the intended period, preferably at least 3 to 5 years average.

The Data Distribution Centre (DDC) of the Intergovernmental Panel on Climate Change (IPCC) provides climate, socio-economic and environmental data, both from the past and also in scenarios projected into the future (www.ipcc-data.org).

The European Environment Agency (EEA) provides information on the environment to the European countries (www.eea.europa.eu).

The co-operative programme for monitoring and evaluation of the long-range transmissions of air pollutants in Europe (EMEP) provides both modelled and measured data over the so-called EMEP region (www.emep.int).

National data centres are available in most countries, for example:

- CSIRO in Australia has a data access portal (<https://data.csiro.au/>) where, among other data sets, the chloride deposition rate is available.
- Thai Meteorological department (<https://www.tmd.go.th/en/>).
- Japan Meteorological Agency (<https://www.jma.go.jp/jma/indexe.html>).
- Swedish Meteorological and Hydrological Institute (<https://www.smhi.se/en/>).

These examples are not complete and often knowledge/language skill is required to access all available data at a local level.