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OPTIMUM SELECTION OF METAL COATING IN CABLE TRUNKING SYSTEMS FOR ELECTRICAL INSTALLATIONS BASED ON ITS RESISTANCE TO CORROSION

Chenoll Mora, Ernesto; Cloquell Ballester, Vicente-Agustín

Universitat Politècnica de València

The selection in an industrial project of the most suitable type of coating of the electrical trunking systems to guarantee its resistance to atmospheric corrosion, as well as the required cost, is currently based on heuristic calculation procedures, not taking into account the influence of atmospheric conditions. The corrosion-time function is logarithmic and depends on the corrosion of the first year of exposure and on environmental parameters. This investigation is divided into two parts; the first one is focused on the traditional zinc-based coatings, for which ten mathematical models have been selected for the prediction of corrosion in the first year and which have been compared with field tests, in order to select the one that best fits and subsequently, calculate the long-term corrosion function. The second part is focused on the new alloys based on zinc-aluminum-magnesium (ZM), for which field and accelerated corrosion tests have been analyzed, obtaining very clear conclusions, and allowing to make a first approximation of the corrosion-time function. These results show the logarithmic behavior of the corrosion function and the need to take it into account to minimize the impact on the cost of the project.

Keywords: *Corrosion; trunking; coatings; ZM alloys; ZA alloys*

SELECCIÓN ÓPTIMA DEL TIPO DE RECUBRIMIENTO METÁLICO DE LOS SISTEMAS DE CANALIZACIÓN ELÉCTRICA BASADA EN SU RESISTENCIA A LA CORROSIÓN

La selección en un proyecto industrial del tipo de recubrimiento más adecuado de la canalización eléctrica para garantizar su resistencia a la corrosión atmosférica, así como el coste requerido, actualmente se basa en procedimientos de cálculo heurísticos, no teniendo en cuenta la influencia de las condiciones atmosféricas. La función corrosión-tiempo es de tipo logarítmico, dependiendo de la corrosión del primer año de exposición y de parámetros ambientales. Esta investigación se divide en dos partes; la primera centrada en los tradicionales recubrimientos basados en cinc, para los cuales se han seleccionado diez modelos matemáticos para la predicción de la corrosión el primer año y que han sido comparados con ensayos reales, con el fin de seleccionar el que mejor se ajusta y posteriormente, calcular la función de corrosión a largo plazo. La segunda parte se centra en las nuevas aleaciones basadas en cinc-aluminio-magnesio (ZM), para las que se han analizado ensayos de campo y de corrosión acelerada existentes, habiéndose obtenido conclusiones muy evidentes, que han permitido realizar una primera aproximación de la función corrosión-tiempo. Estos resultados muestran el comportamiento logarítmico de la función de corrosión y la necesidad de tenerla en cuenta para minimizar el impacto en el coste del proyecto.

Palabras clave: *Corrosión; canalización; recubrimientos; aleaciones ZM; aleaciones ZA*

Correspondencia: Ernesto Chenoll Mora ernesto.chenoll@icloud.com

1. Introduction and objective

The lack of analytical methods in the field of industrial electrical trunking systems (*Cable tray systems* according to IEC 61537 (International Electrotechnical Commission [IEC], 2006), *Cable trunking and cable ducting systems* according to EN 50085-1 (European Committee for Standardization [CEN], 2005) and *Conduits systems* according to EN 61386-1 (CEN, 2008a)), for determining the effect of corrosion, makes the selection of the optimal coating in this kind of installations difficult, since current methods don´t use any scientific methodology that considers the different environmental parameters that take part in this process, which are both, meteorological (e.g. relative humidity, number of rainy days, temperature, etc.) and pollutants (mainly, chlorine and sulphur ions).

At present, the most used type of coating for such trunking systems are zinc-based coatings, but in the last years, several types of alloy coatings based in zinc-aluminium-magnesium have been developed, designated as ZM (Zn/Al/Mg) or ZA (Zn/Al), according to EN 10346 (CEN, 2015). These alloys aim to improve the performance of traditional zinc-based metallic coatings, so as to have a better corrosion resistance while reducing the cost, thanks to the reduction of the total mass of the coating per unit of surface.

Whatever the type of coating, currently it is selected in a heuristic way and because of that, it usually does not meet the requirements regarding corrosion resistance; thus, the expected life of the trunking system could be drastically reduced or, on the contrary, could be unnecessarily overqualified.

The aim of this research study is to provide a methodology that solves this problem.

2. Quantification of Atmospheric Corrosion

2.1 Logarithmic general expression

As shown in previous studies (CEN, 2012; Feliu Batlle, Morcillo, & Feliu, 1993a; González Fernández, 1984; Pourbaix, 1982b), the corrosion in most of the cases, is estimated by means of bi-logarithmic expressions of the type:

$$C\ (t) = A \cdot t^{n} \qquad (1)$$

Where, $C\ (t)$ is the accumulated corrosion at year *"t"*; A is the corrosion at first year of exposure; n is a constant, which depends on each metal and the particular atmospheric conditions (Morcillo, 1998); and t is the time in years.

2.2 Zinc-based coatings

2.2.1 Corrosion during the first year of exposure (A)

Ten different methods were selected in this study, to determine the best fitting to actual corrosion values. Table 1 shows the different variables and parameters considered.

Table 1: Variables and parameters (V/P) used in the methods to estimate annual corrosion (A)

V/P	Description / Value	Units
A_x	Corrosion at first year of exposure calculated with method *x*	Microns (µm)
RH	Average annual relative humidity	%
T	Average annual temperature	ºC

L	Number of rainy days per year	Days
W	Wetness time, estimated as the hours in one year during which RH ≥ 80% and T > 0°C simultaneously (ISO, 2012)	Hours
M	Corrosion module for 1000 h of wetness of the metal surface in a pure atmosphere	μm
t_w	Wetness time	Hours/1000
f_t	Coefficient of corrosion inhibition with annual wetness time (t_w)	Constant
α	Influence of SO_2 contamination	Constant
ß	Influence of Cl^- contamination	Constant
f_c	Stimulating coefficient of corrosion due to contaminants in the air	Constant
Cl^-	Average annual concentration of chlorides	$mg\cdot(m^{-2}\cdot d^{-1})$
S	Average annual concentration of sulphur dioxide (SO_2)	$mg\cdot(m^{-2}\cdot d^{-1})$
S*	Average annual concentration of SO_2 + Cl^-	$mg\cdot(m^{-2}\cdot d^{-1})$
P_d	Annual average SO_2 deposition	$mg\cdot(m^{-2}\cdot d^{-1})$
f_{Zn}	0,038·(T – 10) when T ≤ 10 °C; otherwise, -0,071·(T – 10)	ºC
S_d	Annual average Cl^- deposition	$mg\cdot(m^{-2}\cdot d^{-1})$
d	Day	-

- Method 1: Applicable in atmospheres exempt from contamination (Chico et al., 2010; Feliu & Morcillo, 1980, 2013; Morcillo & Feliu, 1987)

$$A_1= -0{,}00603\cdot RH+0{,}0038\cdot T+0{,}0093\cdot L+0{,}597 \tag{2}$$

- Method 2: Applicable in atmospheres exempt from contamination. This method is based on the same study from which Method 1 comes from.

$$A_2 = -0{,}000198\cdot W+0{,}015\cdot T+0{,}015\cdot L+0{,}215 \tag{3}$$

- Method 3: Applicable in atmospheres exempt from contamination (Costa et al., 1993)

$$A_3 = 0{,}12\cdot L - 0{,}35 \tag{4}$$

- Method 4: Applicable in any type of atmosphere (Morcillo & Feliu, 1993)

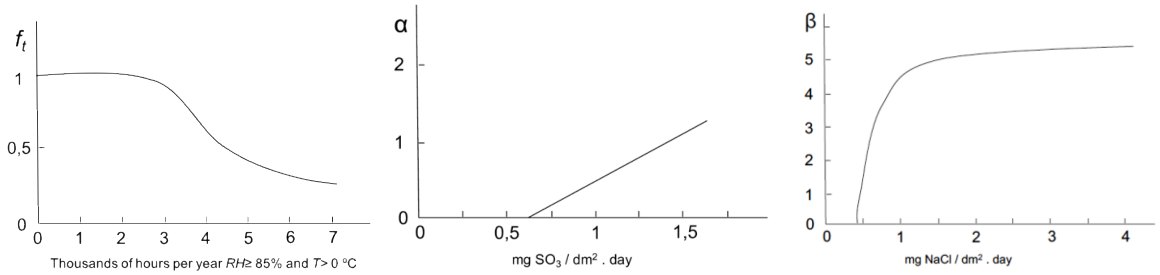
$$A_4 = M\cdot t_w\cdot f_t\cdot f_c \tag{5}$$

Where M corresponds to 0,4 μm for zinc; and f_c is calculated through the following expression:

$$f_c = 1+\alpha+\beta \tag{6}$$

Coefficient f_t and parameters α and β, can be obtained by the graphs in figure 1.

Figure 1: Variation of f_t, α and β versus wetness time, SO_2 and Chlorides respectively. Source: own illustration based on reference (Morcillo & Feliu, 1993)



- Method 5: Applicable in contaminated atmospheres (Morcillo, 1998; Morcillo & Feliu, 1993)

$$A_5 = 0{,}713+0{,}0511 \cdot Cl^- \quad (7)$$

- Method 6: Applicable in any type of atmosphere (Almeida et al., 1999)

$$A_6 = 2{,}52 \cdot W + 0{,}02 \cdot Cl^- - 0{,}05 \quad (8)$$

- Method 7: Applicable in contaminated atmospheres. This method is part of the same study as that referenced in Method 10:

$$A_7 = 0{,}785+0{,}0226 \cdot S+0{,}0501 \cdot Cl^- \quad (9)$$

- Method 8: Applicable in any type of atmosphere (International Organization for Standardization [ISO], 2012)

$$A_8 = 0{,}0219 \cdot P_d^{0{,}44} \cdot e^{0{,}046 \cdot RH + fzn} + 0{,}0175 \cdot S_d^{0{,}57} \cdot e^{0{,}008 \cdot RH+0{,}085 \cdot T} \quad (10)$$

- Method 9: Applicable in any type of atmosphere (Haagenrud, Henriksen & Gram, 1985)

$$A_9 = 12{,}26 \cdot W + 0{,}03 \cdot S - 3{,}05 \quad (11)$$

- Method 10: Applicable in contaminated atmospheres (Benarie & Lipfert, 1986; Feliu Batlle et al., 1993a; Feliu Batlle, Morcillo & Feliu, 1993b; Morcillo, 1998)

$$A_{10} = 0{,}671 + 0{,}0741 \cdot S^* \quad (12)$$

2.2.2 Estimation of the parameter *n*

The following studies to determine the parameter *n* in equation (1) were selected:

- It is commonly accepted (CEN, 2012; Chico et al., 2010; Hernández, Miranda, & Domínguez, 2002) that for the case of zinc, *n*-parameter is usually in the range of 0,8 to 1.
- For his part, M. Pourbaix (Pourbaix, 1982a) facilitates indicative values (table 2):

Table 2: Possible values of n-parameter for different types of atmospheres (Pourbaix, 1982a)

Rural atmosphere	Urban-Industrial atmosphere	Marine atmosphere
0,65	0,9	0,9

- M. Morcillo (Morcillo, 1998) makes the analysis for exposures over 10 years (table 3), the latter based on actual field trials within the ISO CORRAG program (Dean & Reiser, 2002; Knotkova, Boschek, & Kreislova, 1995; Knotkova, Dean, & Kreislova, 2010; Panchenko et al., 2014).

Table 3: n ranges obtained in long-term exposures (10-20 years) (Morcillo, 1998)

Rural-Urban atmosphere away from the sea	Industrial atmospheres away from the sea	Marine atmosphere
0,8 – 1	0,9 – 1	0,7 – 0,9

- The standard EN ISO 9224 (CEN, 2012) gives two values for *n*: *B1* = 0,813 and *B2* = 0,873. For general application, *n* will take the value of *B1*. The use of *B1* or *B2* as parameter *n*, will depend on the degree of accuracy intended for the calculation. In addition, this standard states that for *t* > 20 years or for high concentrations of sulphur dioxide, values between 0,9 and 1 should be chosen, because the zinc corrosion ratio becomes linear.

2.2.3 Comparison between current theoretical methods and actual field tests

This section aimed to verify the adequacy of the current methods seen before, versus actual corrosion values measured in field tests. 15 different test stations, each having distinct atmospheric natures, were used. The corrosion for the first year of exposure for each method (A_x) was calculated and compared with the actual values measured at such test stations.

The results of the analysis are shown in tables 4-6, including actual corrosion values (Morcillo & Feliu, 1993; Panchenko & Marshakov, 2016), the difference between theoretical predicted values and the actual results (methods with the least difference are highlighted in bold letters) and the average of the differences of each method and its standard deviation.

From the results, the following conclusions were obtained:

- Method 1 is the method that best matches the actual values of corrosion: lowest average of differences (0,46 µm) and standard deviation (0,53 µm).
- Method 4 is the one that best fits the actual test values for contaminated atmospheres: lowest average of differences (1,19 µm) and standard deviation (1,78 µm).
- Methods 9 and 10 were discarded (corrosion values very distant to the actual results)

Table 4: Predicted corrosion values (µm) versus actual test values (Part I)

Test station location	Alicante (Spain, 30 m from sea)		Alicante (Spain, 100 m from sea)		El Escorial (Madrid-Spain)		Bilbao (Spain)		Barcelona (Spain)		Cabo Negro (Jávea – Spain)		Zaragoza (Spain)		Avilés (Spain)	
Method	Value	Diff.	Value	Diff.	Value	Diff.	Value	Diff.	Value	Diff.	Value	Diff.	Value	Diff.	Value	Diff.
A_1: Rural	-	-	1,16	0,44	1,26	1,34	-	-	-	-	-	-	1,20	-0,10	2,06	-0,56
A_2: Rural	-	-	1,01	0,59	1,16	1,44	-	-	-	-	-	-	1,42	-0,32	2,58	-1,08
A_3: Rural	-	-	0,74	0,86	0,86	1,74	-	-	-	-	-	-	0,78	0,32	1,97	-0,46
A_4: General	5,68	0,62	0,86	0,74	1,01	1,59	3,56	2,04	3,28	-0,38	4,30	4,90	1,01	**0,09**	1,04	**0,46**
A_5:Contaminated	9,20	-2,90	-	-	-	-	4,14	1,46	3,01	**-0,11**	6,74	2,46	-	-	-	-
A_6: General	14,11	-7.81	11,3	-9,6	9,78	-7,18	8,85	-3,25	8,91	-6,01	13,15	-3,95	5,24	-4,14	9,27	-7,77
A_7:Contaminated	12,60	-6,30	-	-	-	-	6,42	-0,82	4,98	-2,08	7,37	**1,83**	-	-	-	-
A_8: General	4,82	**1,48**	1,80	**-0,2**	0,96	1,64	6,75	-1,15	3,56	-0,66	2,93	6,27	1,64	-0,54	3,33	-1,83
A_9: General	54,3	-48,02	50,3	-48	45,2	-42,6	36,8	-31,2	38,8	-35,9	50,6	-41,4	24,4	-23,3	43,7	-42,3
A_{10}:Contaminated	24,46	-18,16	-	-	-	-	13,1	-7,52	10,4	-7,48	11,6	-2,44	-	-	-	-
Average value	9,28	-2,98	2,81	-1,2	2,51	**0,09**	5,94	**-0,34**	4,75	-1,85	6,90	2,30	1,88	-0,78	3,37	-1,87

(Method 1 to 8)																
Actual value / ISO Corrosivity category	6,3	C5	1,6	C3	2,6	C4	5,6	C5	2,9	C4	9,2	CX	1,1	C3	1,5	C3

Note: Values in “Difference (Diff.)” fields in bold letters, represent the lowest of the values calculated

Table 5: Predicted corrosion values (μm) versus actual test values (Part II)

Test station location	Cádiz (Spain)		Madrid (Spain)		Málaga (Spain)		La Coruña (Spain)		Cáceres (Spain)		Helsinki (Finland)		Ponteau Martigues (France)	
Method	Value	Diff	Value	Diff.	Value	Diff.	Value	Diff.	Value	Diff.	Value	Diff.	Value	Diff.
A_1: Rural	1,09	**0,91**	1,26	0,14	0,57	0,04	1,41	0,64	1,08	0,22	1,25	0,27	-	-
A_2: Rural	1,01	0,99	1,52	**-0,12**	0,64	**-0,03**	1,45	**0,60**	1,10	0,20	1,37	**0,15**	-	-
A_3: Rural	0,71	1,29	0,86	0,54	-0,01	0,62	1,21	0,84	0,75	055	1,03	049	-	-
A_4: General	0,98	1,02	1,01	0,39	0,53	0,08	1,10	0,95	1,18	0,12	1,04	0,48	6,14	-3,94
A_5:Contaminated	-	-	-	-	-	-	-	-	-	-	-	-	13,03	-10,83
A_6: General	11,24	-9,24	5,24	-3,84	3,31	-2,70	11,53	-9,48	8,72	-7,42	8,26	-6,74	14,85	-12,65
A_7:Contamintated	-	-	-	-	-	-	-	-	-	-	-	-	14,83	-12,63
A_8: General	3,24	-1,24	1,88	-0,48	0,00	0,61	0,00	2,05	0,00	1,30	2,77	-1,25	5,20	**-3,00**
A_9: General	48,63	-46,63	24,80	-23,40	13,30	-12,69	53,28	-51,23	39,64	-38,34	37,53	-36,01	48,60	-46,40
A_{10}:Contaminated	-	-	-	-	-	-	-	-	-	-	-	-	24,98	-22,78
Average value (Method 1 to 8)	3,04	-1,04	1,96	-0,56	0,84	-0,23	2,78	-0,73	2,14	-0,84	2,62	-1,10	8,73	-6,53
Actual value / ISO Corrosivity category	2	C3	14	C3	0,61	C1	2,05	C3	1,3	C3	1,52	C3	2,2	C4

Note: values in “Difference (Diff.)” fields in bold letters represent the lowest of the values calculated

Table 6: Average differences and standard deviation of corrosion methods (one year exposure)

Method	Average Diff. (µm)	Standard deviation (µm)
A1: Rural	**0,46**	**0,53**
A2 : Rural	0,55	0,71
A3: Rural	0,77	0,58
A4: General	**1,19**	**1,78**
A5: Contaminated	3,55	5,34
A6: General	6,79	2,83
A7: Contaminated	4,73	5,64
A8: General	1,58	2,20
A9: General	37,87	11,05
A10: Contaminated	8,90	8,45
Average value (Method 1 to 8)	1,50	1,87

Note: the lowest *average difference* and *standard deviation* values are highlighted in bold letters

2.3 ZM/ZA coatings

Since ZM/ZA alloys are relatively new compared to zinc-based coatings, there are no long-term corrosion calculation models as shown before for zinc. That is why, real field tests values have been used in order to provide a methodology for this purpose, in which the corrosion data that have been found are for a maximum of two years.

In this sense, an extensive search of field tests for ZM and ZA alloys has been carried out (Autocoat, 2013; de Rincón et al., 2009; LeBozec et al., 2012, 2013; Nordic Galvanizers, n.d.; Salgueiro Azevedo et al., 2015; Schouller-Guinnet, Allély, & Volovitch, 2011; Thierry et al., 2011; Tomandl & Labrenz, 2016).

Table 7 groups the different corrosion rate results for ZM alloys, by corrosivity category and differentiating values for year 1 and year 2 exposure. An average of these values has been calculated for each category. These will be the values used in the next step for the determination of the long-term corrosion function. Values in bold letters have been considered out of the normal range and they have been discarded for the calculations. Table 8 gives the same information but for ZA alloys.

Table 7: Corrosion values (µm) for ZM alloys in field tests, grouped by corrosivity category

Corrosivity category ISO 9223	Year	Measurement													Average
		1	2	3	4	5	6	7	8	9	10	11	12	13	
C1-Very low	Y1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Y2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C2-Low	Y1	0,20													0,20
	Y2	0,50	**0,90**	**1,20**	0,23										0,36
C3-Medium	Y1	0,70	0,45	1,00	0,20	0,90	1,05	0,45							0,68
	Y2	0,60	0,80	0,50	0,50	0,50	0,40	0,30	0,70	0,50	**1,20**	0,80	0,80	0,30	0,56
C4-High	Y1	1,00	2,00	4,00											2,33
	Y2	1,60	1,10	1,30	1,20	1,50	2,10	2,30							1,59
C5-Very high	Y1	4,80	**2,00**	**3,00**											4,80
	Y2	4,40	4,20	**2,30**	4,00										4,20
CX-Extreme	Y1	6,50	7,40	6,00	5,00										6,23
	Y2	5,80	5,90												5,85

Table 8: Corrosion values (µm) for ZA alloys in field tests, grouped by corrosivity category

Corrosivity category ISO 9223	Year	Measurement				Average
		1	2	3	4	
C1-Very low	Y1					
	Y2					
C2-Low	Y1	0,03				0,03
	Y2		0,40	0,09		0,25
C3-Medium	Y1	0,90	0,30			0,60
	Y2	0,60	0,60	0,30	0,17	0,50
C4-High	Y1					
	Y2	0,80	1,30			1,05
C5-Very high	Y1					
	Y2	3,10				3,10
CX-Extreme	Y1	14,00				14,00
	Y2	9,00				9,00

3. Methodology. Case study

3.1 Zinc-based coatings

The proposed methodology involved eight steps to calculate the maximum coating life based in the location and the optimum zinc-coated trunking. It will be in parallel illustrated with a real case study: the city of Alicante (Spain), in a location separated 30 meters from the sea coast, an area with a high degree of pollution.

1. Determination of customer requirements

The two most important parameters to consider in terms of atmospheric corrosion are the prescribed lifetime of electrical installation (in years) and the maximum cost.

For the case study, a cable tray with these dimensions has been chosen: height 60 mm and width 200 mm. A prescription of 15-years guarantee against corrosion has been considered.

2. Determination of atmospheric data (location)

The environmental parameter wetness time (t_w or estimated as W) and the concentration of sulphur dioxide (SO_2) and chloride contaminants (Cl^-) should be collected.

For the case study, in Alicante we have (Morcillo & Feliu, 1993): W= 4300 h; (S) = 1,55 mg·(dm^{-2}·d^{-1}) and (Cl^-) = 1,66 mg·(dm^{-2}·d^{-1}).

3. Initial calculation of annual corrosion

In order to determine the corrosivity category, a general calculation method (rural or contaminated areas) is primarily needed. Method 4 was selected because it is the general application method with the lowest average of differences and the lowest standard deviation from actual test values (see tables 4-6).

For the case study, the following variables were determined in advance:

- M: As seen before, for zinc it was 0,4 µm.
- t_w: Estimated as W (criterion RH> 80% and T> 0º C). As mentioned in step 2, W = 4300 h.
- f_t: was obtained applying on the graph (figure 1) a t value of 4,3, that gave back a value of f_t = 0,7.

- f_c: This value was calculated from equation (6). The values of α and β were extracted from the graphs in figure 1, by applying the values of S= 1,55 mg·(dm^{-2}·d^{-1}) and Cl^{-} = 1,66 mg·(dm^{-2}·d^{-1}). This generated the value of α = 1,2 and β = 4,4. Thus, f_c = 1 + 1,2 + 4,4 = 6,6.

The annual corrosion was calculated with Method 4, using equation (5), where, A_4 = 0,4·4,3·0,7·6,6 = 7,95 μm.

4. Determination of corrosivity category

The first calculation of corrosion (from step 3), allowed the initial classification of the corrosivity category to be obtained from table 9, according to ISO 9223 (ISO, 2012).

Table 9: Corrosion rates for zinc, r_{corr}, first year exposure, for the different corrosivity categories ISO 9223 (ISO, 2012)

Corrosivity category	r_{corr} (μm·a^{-1})
C1	$r_{corr} \leq 0.1$
C2	$0.1 < r_{corr} \leq 0.7$
C3	$0.7 < r_{corr} \leq 2.1$
C4	$2.1 < r_{corr} \leq 4.2$
C5	$4.2 < r_{corr} \leq 8.4$
CX	$8.4 < r_{corr} \leq 25$

For the case study, according to table 9, the corrosion value (A_4 = 7,95 μm) corresponded to C5 (range of 4,2 to 8,4 μm).

5. Calculation of annual corrosion

- If the corrosivity category is C1, C2 or C3 (rural atmospheres), then Method 1 will be applied, as it is the one that best fits the predicted values (tables 4-6).
- If the corrosivity category is C4, C5 or CX (contaminated atmospheres), then the value of corrosion, A_4, calculated in the previous step, shall be accepted as valid.

For the case study, since the corrosivity category was C5, the corrosion calculated using Method 4, was accepted, i.e., A = A_4 = 7,95 μm.

6. Determination of the parameter *n*

The value was determined to be between 0,65 and 1 (see section 2.2.2).

For the case study, considering the installation in a marine atmosphere, the parameter *n* was set to *n* = 0,90 (tables 2-3).

7. Estimation of maximum coating life

The maximum coating life was estimated clearing *t* in equation (1):

$$t_{max} = 10^{\left(\frac{\log C - \log A}{n}\right)} \qquad (13)$$

Where variable *C,* corresponds to the average thickness of each of the standard coatings. By way of reference, it can be used table 10:

Table 10: Mean thickness of Zn coatings mostly used in electrical trunking systems (IEC, 2006)

Type of coating	Average common thickness (μm)

Electroplated-EN ISO 2081 (CEN, 2008b)	8
Pre-galv sheet-EN 10346. ISO 4998 (CEN, 2015; ISO, 2014)	15
Hot dip galvanized sheet-EN ISO 1461 (CEN, 2009)	60
Hot dip galvanized wire-EN ISO 1461 (CEN, 2009)	100

For the case study, the maximum duration of the coating was calculated, through equation (13), where A = 7,95 µm, n = 0,9 and C is the nominal thickness of the zinc layer, which was obtained from the values in table 10:

- $t_{max\ (ez)}$ = 1,007 years (electroplated)
- $t_{max\ (pg)}$ = 2,025 years (sheet or band pre-galvanized or continuously galvanized)
- $t_{max\ (hdg)}$ = 9,447 years (sheet or band hot dip galvanized)
- $t_{max\ (hdgw)}$ = 16,665 years (hot dip galvanized wire)

8. Representation and analysis of the corrosion function

From the corrosion function, a graphical representation (*C(t)* versus *t*) has to be done. It will helps the user to choose the most suitable finish. This should be done for different *n* values.

3.2 ZM / ZA coatings

Corrosion function will be determined for each corrosivity category, by applying equation (1), as the general expression for corrosion processes. For the case study, the corrosivity category C3 for ZM (data from table 7) will be used.

These are the steps followed for the determination:

- Identify yearly corrosion for the first year of exposure (parameter *A* estimated as the average of the different corrosion values in the tests done). For our case study, this is calculated as the average of the recorded values for Y1. So, A = 0,68 µm.
- Identify corrosion for the second year of exposure (estimated as the average of the different corrosion values for Y2). For our case study, it corresponds to 0,56 µm.
- Calculate the cumulated corrosion for the second year of exposure, *C* (2) by adding the yearly corrosion value first year (*A*) and yearly corrosion value second year. For our case study: $C(2) = 0,68 + 0,56 = 1,24$ µm.
  Substitute *C* (2) and *A* in equation (1) and clear *n* parameter. In the case study: $C(t) = A \cdot t^n$; $C(2) = A \cdot 2^n$; $1,24=0,68 \cdot 2^n$; $2^n = 1,823$; $n = \log 1,823 / \log 2 = 0,866$.
- Determine the long-term corrosion function by substituting *n* and *A* parameters in equation (1). In our case study, ZM for C3 corrosivity class will be:

$$C(t) = 0,68 \cdot t^{0,866} \tag{14}$$

4. Results

4.1 Zinc-based coatings

The corrosion function that followed the present case study was: $C = 7,95 \cdot t^{0,9}$

In table 11, the corrosion function was developed for *n* values of 0,9 and 1 (linear corrosion)

Table 11: Annual corrosion values for logarithmic and linear functions (Alicante, Spain)

Year	Corrosion *C* (µm)	t_{max}	Linear corrosion (µm)
1	7,95	$t_{max(ez)}$ (8 µm)	7,95
2	14,84	$t_{max\ (hdg)}$ (15 µm)	15,90
3	21,37	-	23,85
…			
8	51,66	-	63,60
9	57,44	$t_{max\ (hdg)}$ (60 µm)	71,55
10	63,15	-	79,50
…			
15	90,96	-	119,25
16	96,40	$t_{max\ (hdgw)}$ (100 µm)	127,20

For example, the price of a mesh cable tray (made in wires) considered (60 x 200 mm), resulted in 31·€·m^{-1} (Schneider Electric, 2015). If this price was divided between its average thickness (100 µm), the cost per µm was of 0,31 € (µm·m)$^{-1}$.

If the parameter *n* was not taken into account (linear corrosion), for a 15-year guarantee on corrosion, the cost per meter of the tray was 119,25 µm·0,31 €·(µm·m)$^{-1}$. i.e., 36,96 €·m^{-1}. On the contrary, if the logarithmic factor was taken into account, the cost was 90,96 µm·0,31 €·m^{-1}, i.e. 28.19 €·m^{-1}. In total, there was a difference of 8,76 €·m^{-1} savings, which implied a really important and positive economic impact.

Figure 2, shows the annual evolution of corrosion, with and without logarithmic function.

Figure 2: Annual evolution of corrosion versus linear behaviour (Alicante case study)

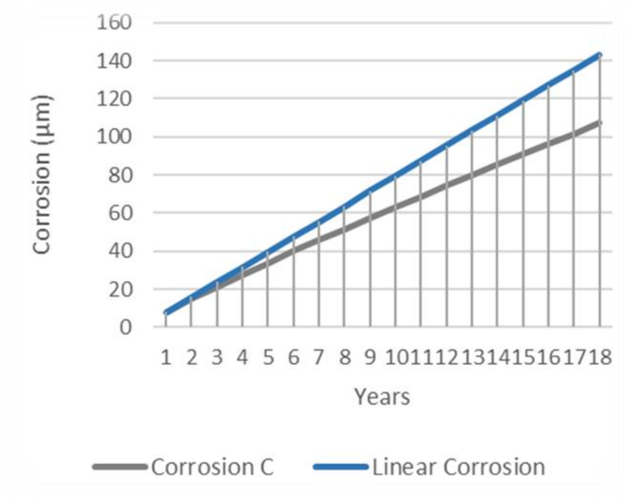


Table 11 as well as figure 2 can be very useful, since they allow engineers and designers, to see the evolution of the corrosion and consequently, to optimize the type of coating and its cost.

For the case study, since the requirement was a 15-years guarantee against corrosion, from Table 11, it can be seen that such requirement could only be met by a cable tray with a minimum coating of 90,96 µm which, going to standard thicknesses values (table 10), corresponded to a 100 µm tray, i.e. a tray made of wires, whose calculated corrosion resistance time was t_{max} = 16,665 years. Moreover, the nominal thickness of the same tray, could be reduced to 90,96 µm, or in other words, a reduction in costs of approximately 10%.

4.2 ZM / ZA coatings

The corrosion function that followed the present case study was: $C(t) = 0{,}68 \cdot t^{0{,}866}$

All results calculated for each case are presented in table 12. The graphic representation of long-term corrosion expression is shown in figure 3 for all ZM alloys cases and in figure 4 for the ZA alloy.

Table 12: Long-term corrosion equations for corrosivity categories in ZM and ZA alloys

Alloy	Corrosivity category	First year corrosion (*A*)	Cumulated corrosion Y2	*n*	Long-term corrosion function
ZM	C2	0,2	0,43	1,104	$C_2(t) = 0{,}2 \cdot t^{1{,}104}$
ZM	C3	0,68	1,24	0,866	$C_3(t) = 0{,}68 \cdot t^{0{,}866}$
ZM	C4	2,33	3,92	0,75	$C_4(t) = 2{,}33 \cdot t^{0{,}75}$
ZM	C5	4,8	9	0,906	$C_5(t) = 4{,}8 \cdot t^{0{,}906}$
ZM	CX	6,23	12,08	0,955	$C_x(t) = 6{,}23 \cdot t^{0{,}955}$
ZA	C3	0,6	1,1	0,87	$C_{3ZA}(t) = 0{,}6 \cdot t^{0{,}87}$

Figure 3: Corrosion evolution in ZM alloys for C2-CX corrosivity class (µm vs years)

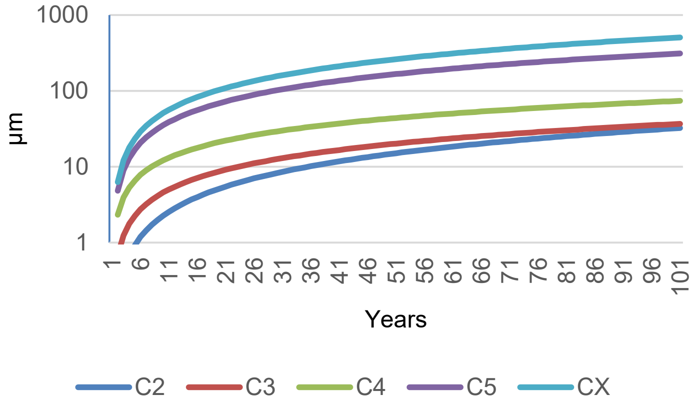
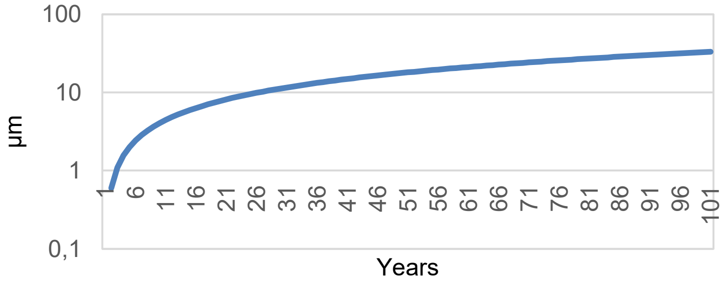


Figure 4: Corrosion evolution in ZA alloys for C3 corrosivity class (µm vs years)



In this way, it is possible to estimate the corrosion resistance of a given ZM or ZA alloy, just by knowing its thickness. For instance, for a ZM thickness of 20 µm in a C3 environment, the approximated corrosion resistance in years is calculated, either using the graphs or applying equation (14):

$$20 = 0{,}68 \cdot t^{0{,}866}$$

And once resolved, t = 49,6 years.

5. Conclusions

The calculation for medium and long-term corrosion accepted by most researchers today, followed the model established in the equation (1).

Selection of parameter *n* was key in the calculations and it was highly dependent on the environmental conditions of the location.

In the case of *zinc-based coatings*, for the calculation of the annual corrosion, *A*, the methods analysed that best fitted the actual corrosion values were Method 1 for rural atmospheres and Method 4 for contaminated atmospheres.

In the case of *ZM-based coatings*, many types of field tests were found, but with a high dispersion. All these tests have been consolidated and it has shown the way to calculate long-term corrosion resistance for different corrosivity categories. Included also, is the logarithmic behaviour of the corrosion function for corrosion products.

The corrosion function, especially in the first 10 years of exposure, showed a logarithmic and non-linear behaviour. This means that, with small increments in thickness of the coating, it is possible to exponentially increase the duration of the coating. Consequently, the duration is much greater in proportion than the extra cost to which this increase of thickness leads to. With this in mind, it can be assumed that using conventional techniques in many cases, installations with unnecessary costs could be prescribed. This aspect is especially relevant in cases where the parameter *n* moves away from the unit (rural areas or pollution-free), because the behaviour of the corrosion rate is less linear in the first years of exposure. Likewise, the reduction of the thickness required for the same duration is guaranteed.

All in all, the decision about what type of coating should be chosen, will depend on several aspects, but mostly on the conditions of the environment, and not always is obvious that ZM / ZA alloys can directly substitute zinc-based coatings. A previous analysis has to be done based in the given guidelines. Finally, the thickness of the ZM / ZA products offered in the market today are limited, so, even the behaviour these alloys can be better (slow corrosion speed), sometimes it can be compensated by the high thickness that can be reached in traditional zinc-based coatings.

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