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GENERAL PROBLEMS OF CORROSION

Corrosiveness of the Atmosphere in Various Climatic Regions of the Russian Federation

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Abstract—The results of three 1-year field expositions of standard metals at seven climatic stations in the territory of the Russian Federation are presented. On the basis of the average annual meteorological and aerological parameters, an informative assessment of the aggressiveness of the atmosphere is given. According to the metal corrosion data for the first year, the categories of atmospheric corrosiveness were determined in accordance with the ISO 9223 standard. Using the dose—response functions (DRFs) presented in the ISO 9223 standard and developed for the continental territory of the Russian Federation, a forecast of metal corrosion losses for the first year (K_1^{pr}) is given. Based on the predicted values of K_1^{pr}, an assessment of the corrosiveness category of the atmosphere is given. A comparison of the defined and evaluated categories of atmospheric corrosiveness is presented. It is shown that for the territory of the Russian Federation, the new DRFs developed directly for the territory of the Russian Federation are to be prioritized.

Keywords: corrosion, atmosphere corrosiveness, full-scale tests, dose, response function, structural metals

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1. INTRODUCTION

Most metal structures that are exposed to external atmospheric factors during their operation are subject to atmospheric corrosion, which is the main reason for the decrease in their durability, accidents, and failures of constructions and facilities, which later necessitate expensive repairs, downtime, and so on. The main reasons for such situations are: untimely detection of corrosion damage of parts most often located in hidden cavities that are inaccessible for inspection; the use of insufficient means of protection, as well as the use of materials not intended for use in aggressive conditions [1–4].

The possibility of using metallic materials and their protection for operation in certain climatic conditions is preliminarily assessed by the corrosiveness of the atmosphere of a given area. The aggressiveness of the atmosphere of the regions intended for the operation of metal structures is taken into account from the point of view of the aggressive impact of climatic and aerochemical factors and is expressed in points. The corrosiveness of the atmosphere is determined by the weight loss of standard materials samples after the first year of full-scale exposure (K_1^{ex}). In global practice, the standards ISO 9223, ISO 9225, and ISO 9226 are used for this [5–7]. If it is impossible to carry out annual full-scale tests, an assessment of corrosiveness is carried out according to the predicted values of corrosion losses for the first year (K_1^{pr}). To calculate the values of K_1^{pr}, the dose-response functions (DRFs) are used. In addition, for test sites, an informative assessment of the corrosiveness of the atmosphere is given by atmospheric pollution and the time of wetness (TOW) [5]. In general, corrosive aggressiveness, determined or estimated by the value of K_1^{ex}/K_1^{pr}, and an informative assessment constitute a complex characteristic of test sites.

There have been no previous studies in which a comprehensive characteristic of the corrosive aggressiveness of the atmosphere of any regions of the Russian Federation is given.

The purposes of this work are:

- a comprehensive characteristics of the corrosive aggressiveness of the atmosphere of five climatic regions on the territory of the Russian Federation;
- comparison of atmospheric corrosiveness categories, determined by K_1^{ex} values and estimated by K_1^{pr}, calculated using different DRFs;
- a comparative assessment of the reliability of the K_1^{pr} values and the choice of reliable DRFs for their

application in any places on the territory of Russian Federation.

2. METHODOLOGY OF WORK

To study the complex corrosive aggressiveness of the atmosphere, the following regions were selected: the coasts of the Black, Japanese, and Barents Seas, the Moscow Region, and Yakutia. The tests were carried out in seven representative points of these districts: Gelendzhik city, Sochi city, Vladivostok city, the village of Dalniye Zelentsy, Moscow city, the city of Zvenigorod, and Yakutsk city—in the Gelendzhik and Moscow climatic test centers of VIAM, at the North, Zvenigorod and Far Eastern corrosion stations of the IPCE RAS, on the territory of the Caucasian State Natural Biosphere Reserve and at the Yakutsk station of the V. P. Larionov Institute of the Physical-Technical Problems of the North of the Siberian Branch of the Russian Academy of Sciences (IPTPN SB RAS). These are hereby designated as follows, respectively: GCTC, MCTC, NCS, ZCS, FECS, CSNBR and IPTPN.

Standard metals (sheets 2 mm thick) were used as samples for testing: carbon steel (steel St3), zinc (Ts0), copper (M1), and aluminum (A5m).

The tests were carried out over three 1-year periods. The samples were installed in accordance with the standard [8] with the upper side to the south, at an angle of 45°. The corrosive aggressiveness of the atmosphere was determined from the obtained K_1^{ex} values.

At the same time, meteorological parameters were recorded at the stations, the deposition rates of sulfur dioxide [SO_2] (deposition method on an alkaline plate) and chlorides [Cl^-] (wet candle method) were determined according to the methods presented in GOST 9.039 [9] and ISO 9225 [6] standards (a comparative assessment of methods for determining the corrosiveness of the atmosphere is given in [10]). Average annual deposition rates of [SO_2] and [Cl^-] were expressed in mg/(m^2 day). For each test site, the average annual or total annual parameters of atmospheric aggressiveness were determined.

For an informative assessment of the aggressiveness of the atmosphere, the TOW value (h) was calculated as the total time per year during which air humidity RH ≥ 80% at a temperature $T \geq 0$°C.

The assessment of corrosiveness was carried out according to the values of K_1^{pr} (K_1). To calculate them, we used the DRFs presented in the ISO 9223 standard for any atmospheres of the world [5], and new DRFs developed for the continental territory of the world [11–13], which take into account the long-term average annual meteorological and aerochemical parameters of the atmosphere.

DRF, data in the standard [5], (hereinafter DRF^S) are presented for two temperature intervals $T \leq 10$°C and $T > 10$°C (equations (1)–(4) (in the original K_1^{pr} is denoted as r_{corr}, expressed μm/year)):

for carbon steel:

$$\begin{gathered} K_1 = 1.77P_d^{0.52}\exp(0.020\mathrm{RH} + f_{St}) \\ + 0.102S_d^{0.62}\exp(0.033\mathrm{RH} + 0.040T), \\ f_{St} = 0.150(T-10), \text{ when } T \leq 10°\mathrm{C}; \\ \text{for } T > 10°\mathrm{C}\ f_{St} = -0.054(T-10); \end{gathered} \quad (1)$$

for zinc:

$$\begin{gathered} K_1 = 0.0129P_d^{0.44}\exp(0.046\mathrm{RH} + f_{Zn}) \\ + 0.0175S_d^{0.57}\exp(0.008\mathrm{RH} + 0.085T), \\ f_{Zn} = 0.038(T-10), \text{ when } T \leq 10°\mathrm{C}; \\ \text{for } T > 10°\mathrm{C}\ f_{St} = -0.071(T-10); \end{gathered} \quad (2)$$

for copper:

$$\begin{gathered} K_1 = 0.0053P_d^{0.26}\exp(0.059\mathrm{RH} + f_{Cu}) \\ + 0.01025S_d^{0.27}\exp(0.0.36\mathrm{RH} + 0.049T), \\ f_{Cu} = 0.126(T-10), \text{ when } T \leq 10°\mathrm{C}; \\ \text{for } T > 10°\mathrm{C}\ f_{St} = -0.080(T-10); \end{gathered} \quad (3)$$

for aluminum:

$$\begin{gathered} K_1 = 0.042P_d^{0.73}\exp(0.025\mathrm{RH} + f_{Al}) \\ + 0.0018S_d^{0.60}\exp(0.020\mathrm{RH} + 0.094T), \\ f_{St} = 0.009(T-10), \text{ when } T \leq 10°\mathrm{C}; \\ \text{for } T > 10°\mathrm{C}\ f_{St} = -0.043(T-10). \end{gathered} \quad (4)$$

where T is the average annual air temperature, °C; RH is the average annual relative air humidity, %; P_d is the average annual deposition of SO_2, mg/(m^2 day); S_d is the average annual deposition of Cl^-, mg/(m^2 day).

For an exposure of 1 year, the value of r_{corr}, μm/year, is numerically equal to K_1 (K_1^{pr}), μm. To convert K_1 [μm] to K_1 [g/m^2], the following ratio was used:

K_1, g/m^2 = K_1 (μm) × d (g/cm^3).

where d is the density of the material.

New DRFs [11–13] (hereinafter DRF^N), also developed for two temperature intervals $T \leq 10$°C and $T > 10$°C, are presented in equations (5)–(8)

- for carbon steel:

$$\begin{gathered} K_1 = 7.7[SO_2]^{0.47}\exp\{0.024RH + 0.095(T-10) \\ + 0.00056P_{rec}\}\ T \leq 10°\mathrm{C}; \\ K_1 = 7.7[SO_2]^{0.47}\exp\{0.024RH + 0.095(T-10) \\ + 0.00056P_{rec}\}\ T > 10°\mathrm{C}; \end{gathered} \quad (5)$$

- for zinc:

Table 1. Districts, points, climate type, designation and type of corrosion test stations

District	Representative point	Test station	Climate type	Station type
Black Sea	City of Gelendzhik	GCTC	Moderately warm with a mild winter	Seaside
	City of Sochi	CSNBR	Moderately warm humid	Continental
Barents Sea	Village of Dalniye Zelentsy	NCS	Moderately cold	Seaside
Sea of Japan	City of Vladivostok	FECS	Moderately moist	Seaside
Moscow region	City of Moscow	MCTC	Moderate	Continental
	City of Zvenigorod	ZCS	Moderate	Continental
Yakutia	City of Yakutsk	IPTPN	Very cold	Continental

$$K_1 = 0.45[SO_2]^{0.36}\exp\{0.023RH + 0.025(T-10) + 0.00035P_{rec}\}\ T \le 10°C;$$
$$K_1 = 0.45[SO_2]^{0.36}\exp\{0.023RH - 0.055(T-10) + 0.00035P_{rec}\}\ T > 10°C; \quad (6)$$

• for copper:

$$K_1 = 0.50[SO_2]^{0.38}\exp\{0.025RH + 0.085(T-10) + 0.0003P_{rec}\}\ T \le 10°C;$$
$$K_1 = 0.50[SO_2]^{0.38}\exp\{0.025RH - 0.040(T-10) + 0.0003P_{rec}\}\ T > 10°C; \quad (7)$$

• for aluminum:

$$K_1 = 0.010[SO_2]^{0.67}\exp\{0.039RH + 0.032(T-10) + 0.0001P_{rec}\}\ T \le 10°C;$$
$$K_1 = 0.010[SO_2]^{0.67}\exp\{0.039RH - 0.065(T-10) + 0.0001P_{rec}\}\ T > 10°C, \quad (8)$$

where K_1 is the corrosion losses of metals for the first year, g/m^2; T is the average annual air temperature, °C; RH is the average annual relative air humidity, %; P_{rec} is the total amount of precipitation for the year, including wet (rain), wet-solid, and solid (snow) precipitation, mm; $[SO_2]$ is the average annual concentration of SO_2, μg/m^3.

To convert the SO_2 concentration into the deposition rate, the ratio was used according to the standard [5]:

1 μg/m^3 = 1.25 mg/(m^2 day);

1 mg/(m^2 day) = 0.8 μg/m^3.

2. TEST RESULTS AND DISCUSSIONS

2.1. Characteristics of Test Sites

Table 1 describes the type of climate of the test sites and the type of corrosion stations (CS) according to their location relative to the sea shore (the stations are divided into seaside and continental). According to GOST 9.906 [8], stations are divided into land-based and coastal ones, where the latter include stations located at the water's edge of oceans, seas and reservoirs; nevertheless, to describe the corrosive aggressiveness of the atmosphere, it is impossible to combine stations located in seaside regions with stations located near fresh water bodies, due to the significant difference in the deposition rate of chloride ions.

The stations GCTC, NCS, and FECS are located within 100–200 m of the sea coastline. The CSNBR corrosion station is a high-altitude continental station in Sochi, and it is located at an altitude of 570 m above sea level, approximately 30 km away from the sea coast, which relates it to stations of the continental type.

The test sites cover a wide range of climatic parameters (Table 2). Thus, the intervals of average annual parameters are 8.1 ... +16.2°C in temperature, 65–80% in relative humidity, and 224–2014 mm in precipitation. The air temperature depends on the geographic location. The least amount of precipitation falls in the cold region of Yakutsk (IPTPN) and in Dalniye Zelentsy (NCS). The high P_{rec} values at the CSNBR station are due to the heavy snowfalls characteristic of the high-altitude location of this station. Despite the amount of precipitation falling in each region, the relative humidity is highest in the NCS, at 79–80%, the and it is the lowest in the IPTPN (66%) and FECS (65%), and in the CSNBR, it is only 71%.

The difference in T, RH, and P_{rec} at the test sites is significant, however, the duration of total wetting at all sites differ by only 1.5 times, while not all sites show a correspondence between TOW and RH. The smallest TOW value in the MCTC is 2081 h/year, and the largest in the ZCS, at 3138 h/year. The duration of wetting depends to a large extent on factors that are not recorded and therefore are not presented in Table 2. For example, the ZCS is located among large trees that create shade for long periods during the day, so the precipitation and abundant dew evaporate over a long period, which leads to increased humidity in the warm period and, accordingly, to high TOW values. On the NCS, despite the high humidity, TOW is lower than on the ZCS at RH = 79–80%, which is associated with negative temperatures for long periods of the year.

The range of pollution of the atmosphere with sulfur dioxide in all places is 1.0–7.0 mg/(m^2 day).

Table 2. Average annual meteorological parameters of climatic station sites for the periods of exposure of material samples

Symbol	One-year test number	T, °C	RH, %	P_{rec}, mm/year	SO_2, mg/(m day)	Cl^-, mg/(m day)	TOW, h/year [5]
Gelendzhik GCTC	1	15.9	71	576	3.3	43.1	2953
	2	16.2	71	617	3.3	51.1	2861
	3	16.1	71	760	3.2	51.7	2929
Moscow MCTC	1	6.6	71	583	1.8	2.4	2081
Zvenigorod ZCS	1	5.8	78	815	1.0	1.87	2974
	2	5.7	76	810	1.0	2.00	3055
	3	6.1	77	772	1.0	1.73	3138
village of Dalniye Zelentsy NCS	1	1.7	80	395	6.3	49.4	2522
	2	2.0	79	428	5.9	52.3	2350
	3	2.2	79	393	7.0	55.5	2280
Vladivostok FECS	1	5.5	65	748	4.6	27.1	2730
	2	5.4	65	632	4.5	33.5	2739
	3	5.5	65	715	4.9	44.3	2592
Sochi CSNBR	1	9.8	71	2014	1.0	1.1	–
Yakutsk IPTPN	1	–8.1	66	224	1.0	2.2	–

According to the standard [5], the background concentration of $[SO_2] \le 5$ mg/(m^2 day), therefore, only on the NCS the SO_2 concentration exceeds the background concentration. In continental CSs, the salinity of the atmosphere is within the background, $[Cl] \le 3$ mg/(m^2 day). At the seaside CSs, the high rate of chloride ion deposition, on the NCS, 49.4–55.5 mg/(m^2 day), and the lowest on the FECS, 27.1–44.3 mg/(m^2 day).

2.2. Informative Assessment of Atmospheric Corrosiveness

An informative assessment of the corrosiveness of the atmosphere according to ISO 9223 is given by the TOW value (5-point gradation) and the deposition rate of the chloride ions and sulfur dioxide (4-point gradation). In accordance with the obtained aerochemical data, the CSs have gradations according to $[SO_2]$ P_0 and P_1, and according to [Cl] $-S_0$ and S_1 (Table 3). Higher indicators in TOW, constituting τ_4, are seen only at NCS and MCTC: τ_3. In general, the informative corrosiveness of the atmosphere of CS C_2 and C_3, which is due to high gradations in TOW, is only seen in city of Sochi, and in the city of Yakutsk, the corrosive aggressiveness has low ratings, C_1–C_2 and C_1, respectively.

2.3. Determination of the Corrosiveness of the Atmosphere Based on the Results of the First Year Corrosion Losses of Samples of Standard Materials

Corrosive aggressiveness of the atmosphere according to the standard [5] has gradations C1–C5, as well as CX for extremely aggressive atmospheres. For standard metals, corrosiveness is determined by their corrosive losses during the first year of exposure (K_1^{ex}), the ranges of which suggest the corresponding gradation of corrosiveness [5]. On the continental territory of Russian Federation, which constitutes a large part of the total area, corrosive aggressiveness generally corresponds to the C2 category [14, 15], which includes a fairly large range of K_1^{ex} values. In view of this, in order to increase the information content of the characterization of the degree of aggressiveness, three additional gradations have been introduced for the territory of Russian Federation in the C2 category: C2-1, C2-2, and C2-3 [14, 15] (Table 4).

Experimental corrosion losses of metals (K_1^{ex}) obtained after one to three annual exposure periods are presented in Table 5. The differences in the obtained K_1^{ex} values for 3-year exposures at each CS are insignificant, which can be explained by the absence of significant differences in the average annual parameters of atmospheric aggressiveness for 3 years at these stations. However, there are exceptions: for example, in GCTC the K_1^{ex} ranges are: for St3 steel, 267.2–441.6 g/m^2; for Ts0, 10.88–20.93 g/m^2; and for A5m 0.87–1.96, g/m^2. In addition, in FECS for Ts0 7.5–16.2 g/m^2 and in ZCS for A5m 0.14–0.32 g/m^2. All the highest values for K_1^{ex} were observed at exposure 2 at the GCTC and at exposure 1 at the FECS and ZCS, although the aggressiveness of the atmosphere of these annual exposures did not differ from other annual exposures. This difference in K_1^{ex} at each of the CSs is quite possible, since when determining the corrosiveness only the main influenc-

Table 3. Informative assessment of the aggressiveness of the atmosphere of corrosion stations in accordance with the standard [5]

Test site	One-year test number	Atmosphere gradation by			Corrosive aggressiveness
		$[SO_2]$, mg/(m^{2}day)	[Cl], mg/(m^2 day)	TOW, h/year	
Gelendzhik GCTC	1	P_0	S_1	τ_4	C_2–C_3
	2	P_0	S_1	τ_4	C_2–C_3
	3	P_0	S_1	τ_4	C_2–C_3
Moscow MCTC	1	P_0	S_0	τ_3	C_2
Zvenigorod ZCS	1	P_0	S_0	τ_4	C_2
	2	P_0	S_0	τ_4	C_2
	3	P_0	S_0	τ_4	C_2
Village of Dalniye Zelentsy NCS	1	P_1	S_1	τ_4	C_3
	2	P_1	S_1	τ_3	C_3
	3	P_1	S_1	τ_3	C_3
Vladivostok FECS	1	P_1	S_1	τ_4	C_3
	2	P_1	S_1	τ_4	C_3
	3	P_1	S_1	τ_4	C_3
Sochi CSNBR	1	P_0	S_0	–	C_1–C_2
Yakutsk IPTPN	1	P_0	S_0	–	C_1

Table 4. Categories of corrosiveness according to ISO 9223 with additional gradations of category C2

Corrosivity category		Corrosion losses of metals for the first year, K_1				
		Unit	Carbon steel	Zinc	Copper	Aluminum
C1		g/m^2	$K_1 \le 10$	$K_1 \le 0.7$	$K_1 \le 0.9$	Insignificant
		micron	$K_1 \le 1.3$	$K_1 \le 0.1$	$K_1 \le 0.1$	–
C2	C2-1	g/m^2	$10 < K_1 \le 50$	$0.7 < K_1 \le 1.5$	$0.9 < K_1 \le 1.5$	$K_1 \le 0.2$
		micron	$1.3 < K_1 \le 6.4$	$0.1 < K_1 \le 0.21$	$0.1 < K_1 \le 0.17$	–
	C2-2	g/m^2	$50 < K_1 \le 100$	$1.5 < K_1 \le 3.0$	$1.5 < K_1 \le 3.0$	$0.2 < K_1 \le 0.35$
		micron	$6.4 < K_1 \le 12.8$	$0.24 < K_1 \le 0.42$	$0.17 < K_1 \le 0.34$	–
	C2-3	g/m^2	$100 < K_1 \le 200$	$3.0 < K_1 \le 5$	$3.0 < K_1 \le 5$	$0.35 < K_1 \le 0.6$
		micron	$12.8 < K_1 \le 25$	$0.42 < K_1 \le 0.7$	$0.34 < K_1 \le 0.6$	–
C3		g/m^2	$200 < K_1 \le 400$	$5 < K_1 \le 15$	$5 < K_1 \le 12$	$0.6 < K_1 \le 2$
		micron	$25 < K_1 \le 50$	$0.7 < K_1 \le 2.1$	$0.6 < K_1 \le 1.3$	–
C4		g/m^2	$400 < K_1 \le 650$	$15 < K_1 \le 30$	$12 < K_1 \le 25$	$2 < K_1 \le 5$
		micron	$50 < K_1 \le 80$	$2.1 < K_1 \le 4.2$	$1.3 < K_1 \le 2.8$	–
C5		g/m^2	$650 < r_{corr} \le 1500$	$30 < r_{corr} \le 60$	$25 < r_{corr} \le 50$	$5 < r_{corr} \le 10$
		micron	$80 < r_{corr} \le 200$	$4.2 < r_{corr} \le 8.4$	$2.8 < r_{corr} \le 5.6$	–
C*X*		g/m^2	$1500 < r_{corr} \le 5500$	$60 < r_{corr} \le 180$	$50 < r_{corr} \le 90$	$r_{corr} > 10$
		micron	$200 < r_{corr} \le 700$	$8.4 < r_{corr} \le 2$	$5.6 < r_{corr} \le 10$	–

ing factors are taken into account, but there are no other parameters that also contribute to the processes of corrosion destruction. These include, for example, solar radiation, as well as, for seaside CSs, the orientation of the samples relative to the sea coast.

The results obtained indicate a wide range of the obtained K_1^{ex} values at all CSs, which are representative places of large regions of Russian Federation. Thus, the intervals of K_1^{ex} values are 13.7–441.6; 3.4–20.93; 1.0–33.2 and 0.14–2.62 for St3, Ts-0, M1, and A5m, respectively. For all CSs, the difference between K_1^{ex} is 32.2 times for St3 and M1, 18.7 times for A5m, and 6.2 times for Ts-0. At the same time, for continental CSs, the differences is 4.3, 2.3, 6.8, and 8.0 times, and for seaside CSs they are 2.3, 2.8, 4.1, and 3.0 times for St3, Ts-0, M1, and A5m, respectively, caused by the difference in meteorological and aerochemical parameters of the atmosphere.

In accordance with the standard [5], for all CCs, according to experimental data for all metals, the categories of atmospheric corrosiveness are determined (see Table 5). For continental sites, the categories were: C2-1 to C2-2, C2-3 to C3, C2-1 to C3, and C2-1 to C3 for St3, Ts-0, M1, and A5m, respectively. For seaside atmospheres, the higher categories were: C2-3 to C4, C3 to C4, C3 to C5, and C3 to C4 for St3, Ts-0, M1, and A5m, respectively. The seaside CSs of the category of atmospheric aggressiveness determined by K_1^{ex} (see Table 5) were higher than the categories estimated by $[SO_2]$, [Cl] and TOW (see Table 2).

Parameters $[SO_2]$ and [Cl], characterizing the aggressiveness of the atmosphere, are actual data, and the value of TOW is calculated. Therefore, the discrepancy for all CSs between TOW and RH (see paragraph 2.2), as well as the discrepancy between the categories of corrosiveness determined by K_1^{ex} and by the informative assessment, taking into account TOW, indicates the need to revise the method for determining TOW. In particular, the freezing point of the salt electrolyte is –4°C, while sea salts on the surface of metals adsorb water at RH ≥ 70%. Accordingly, for seaside areas, the TOW value should be considered as the total time per year during which RH ≥ 70% at $T \geq -4$°C.

2.4. Selection of Priority DRFs for the K_1 Forecast in Places with any Type of Atmosphere on the Territory of Russian Federation

The use of DRF for calculating corrosion losses of metals for the first year the K_1^{pr} is justified and necessary. The calculation of the K_1^{pr} values according to the DRF eliminates the need for annual or repeated annual full-scale tests of samples in specific places. The K_1^{pr} values are calculated according to the DRF, taking into account the average annual (or total for the year) atmospheric parameters, which are recorded by a large number of meteorological stations in Russian Federation. To determine the K_1^{pr} values, it is more expedient to use the average annual long-term parameters, taking into account the possible significant difference between the annual climatic and aerochemical parameters of the atmosphere from the average long-term ones in a given location.

For the application of DRF, it is necessary, first of all, to select functions that provide the values of K_1^{pr} corresponding to the values of K_1^{ex}. DRF^S [5] (equations (1)–(4)) were proposed for all kinds of atmospheres of the world, but DRF^N [11–13] (equations (5)–(8)) was developed only for the continental territories of the world. This led to the need to supplement equations (5)–(8) with the [Cl] parameter for the possibility of using DRF^N in places with a marine atmosphere, at least on the territory of the Russian Federation. It was proposed to consider the effect of chlorides as corrosion acceleration by introducing the factor $[Cl]^\beta$ into equations (5)–(8), where [Cl] is the average annual deposition of Cl^-, mg/(m^2 day), and β is the exponent. The β values were determined from the few data from these tests. The most suitable β values were 0.28, 0.26, 0.32, and 0.37 for St3, Zn, Cu, and Al, respectively. Thus, DRF^N with the factor $[Cl]^\beta$ (hereinafter DRF^{N*}) was used to calculate K_1 (g/m^2) in continental and seaside CSs.

The choice of priority DRFs to obtain reliable values of K_1^{pr} requires verification. The use of the averaged of K_1^{pr} values and parameters of the aggressiveness of the atmosphere of the test sites for three 1-year exposures would lead to incorrect results, which is associated with the nonlinear dependence of K_1^{pr} on the parameters. Therefore, the calculation of the K_1^{pr} values is given for each year of exposure on the CS (see Table 5).

The K_1^{pr} values obtained by DRF^S and DRF^{N*} have different discrepancies with K_1^{ex}. This can be explained by various reasons: first, the imperfection of each DRFs, and inaccurate data of the parameters of atmospheric aggressiveness, as well as errors in determining the weight loss of the samples during their etching in solutions. In addition, in marine atmospheres, the orientation of the samples relative to the coast affects the corrosion of metals. Therefore, for the seaside CSs, the discrepancies between K_1^{pr} and K_1^{ex} can be significant.

Comparison of K_1^{pr} calculated by different DRFs with K_1^{ex} for each metal is shown in Figs. 1–4. These figures show the lines of relative errors K_1^{pr} (δ, %),

Table 5. Corrosion losses of metals for the first year of K_1^{ex} exposure and the categories of atmospheric corrosiveness, determined by K_1^{ex} and estimated by K_1^{pr}

Metal	Test site	Exposition No.	K_1^{ex} g/m^2	K_1^{pr}, g/m^2		Aggressiveness categories according to ISO 9223		
				DRF^S	DRF^N	K_1^{ex}	K_1^{pr} according to DRF^S	K_1^{pr} according to DRF^N
St3	Yakutsk, IPTPN	1	13.7	11.7	9.5	C2-1	C2-1	C1
	Sochi, CSNBR	1	56.9	68.4	131.7	C2-2	C2-2	C2-3
	Moscow, MCTC	1	58.3	64.8	79.0	C2-2	C2-2	C2-2
	Zvenigorod, ZCS	1	64.2	83.5	95.53	C2-2	C2-2	C2-2
		2	61.1	80.7	92.0	C2-2	C2-2	C2-2
		3	59.3	81.9	92.3	C2-2	C2-2	C2-2
	Vladivostok, FECS	1	195.9	122.6	208.9	C2-3	C2-3	C3
		2	211.5	129.9	203.0	C3	C2-3	C3
		3	193.2	146.0	239.1	C2-3	C2-3	C3
	Village of Dalniye Zelentsy	1	239.3	185.0	233.5	C3	C2-3	C3
		2	225.8	186.6	236.0	C3	C2-3	C3
		3	198.1	196.3	256.2	C2-3	C2-3	C3
	Gelendzhik GCTC	1	267.2	238.1	185.1	C3	C3	C2-3
		2	441.6	257.6	194.5	C4	C3	C2-3
		3	298.5	256.0	207.0	C3	C3	C3
Ts-0	Yakutsk, IPTPN	1	3.4	1.1	1.8	C2-3	C2-1	C2-2
	Sochi, CSNBR		7.9	3.0	6.4	C3	C2-2	C3
	Moscow, MCTC	1	6.0	3.4	4.7	C3	C2-3	C2-3
	Zvenigorod, ZCS	1	–	4.1	6.3	C3	C2-3	C3
		2	–	3.9	6.1	C3	C2-3	C3
		3	5.7	4.0	6.0	C3	C2-3	C3
	Vladivostok, FECS	1	16.2	5.3	1.6	C4	C3	C3
		2	7.5	5.5	11.4	C3	C3	C3
		3	8.1	6.0	13.2	C3	C3	C3
	Village of Dalniye Zelentsy	1	10.3	8.6	16.2	C3	C3	C4
		2	9.0	8.3	16.1	C3	C3	C4
		3	10.2	8.8	17.0	C3	C3	C4
	Gelendzhik GCTC	1	10.88	10.03	9.8	C3	C3	C3
		2	20.93	10.94	10.34	C4	C3	C3
		3	14.7	0.9	10.9	C3	C3	C3
M1	Yakutsk, IPTPN	1	1.0	1.1	0.8	C2-1	C2-1	C1
	Sochi, CSNBR	1	3.6	5.0	5.5	C2-3	C2-3	C3
	Moscow, MCTC	1	3.8	4.4	4.7	C2-3	C2-3	C2-3
	Zvenigorod, ZCS	1	5.9	6.3	6.2	C3	C3	C3
		2	5.0	5.8	6.0	C3	C3	C3
		3	6.8	6.1	6.0	C3	C3	C3

Table 5. (Contd.)

Metal	Test site	Exposition No.	K_1^{ex} g/m^2	K_1^{pr}, g/m^2		Aggressiveness categories according to ISO 9223		
				DRF^S	DRF^N	K_1^{ex}	K_1^{pr} according to DRF^S	K_1^{pr} according to DRF^N
	Vladivostok, FECS	1	8.9	4.9	12.1	C3	C2-3	C4
		2	8.1	5.0	12.3	C3	C2-3	C4
		3	10.1	5.2	14.2	C3	C3	C4
	Village of Dalniye Zelentsy	1	15.2	8.1	15.6	C4	C3	C4
		2	12.4	8.0	15.7	C4	C3	C4
		3	15.2	8.1	17.0	C4	C3	C4
	Gelendzhik GCTC	1	29.3	9.8	15.8	C5	C3	C4
		2	33.2	10.1	16.7	C5	C3	C4
		3	28.9	10.1	17.2	C5	C3	C4
A5m	Yakutsk, IPTPN	1	0.29	0.06	0.10	C2-2	C2-1	C2-1
	Sochi, CSNBR	1	0.25	0.12	0.13	C2-2	C2-1	C2-1
	Moscow, MCTC	1	0.48	0.16	0.32	C2-3	C2-1	C2-2
	Zvenigorod, ZCS	1	0.32	0.22	0.21	C2-2	C2-2	C2-2
		2	0.14	0.21	0.20	C2-1	C2-2	C2-1
	Vladivostok, FECS	1	0.95	0.39	1.11	C3	C2-3	C3
		2	1.09	0.41	1.19	C3	C2-3	C3
		3	2.03	0.46	1.37	C4	C2-3	C3
	Village of Dalniye Zelentsy	1	2.00	0.59	2.81	C3	C2-3	C4
		2	1.99	0.58	3.44	C3	C2-3	C4
		3	2.62	0.63	2.65	C4	C3	C4
	Gelendzhik GCTC	1	0.87	0.98	1.06	C3	C3	C3
		2	1.96	1.10	0.81	C3	C3	C3
		3	1.13	1.09	0.77	C3	C3	C3

which make up the intervals for St3, Zn and Cu −33% ...+50% and for Al −50%...+100% in accordance with the uncertainty intervals according to [5].

Carbon steel (see Fig. 1). According to DRF^N*, the K_1^{pr} values are comparable to K_1^{ex} except for the CSNBR and three exposures in the GCTC, especially for exposure 2. The overestimation of the K_1^{pr} values for the mountain city of Sochi is apparently associated with a large amount of precipitation (P_{rec} = 2014 mm/year, see Table 2), taking into account the high value of the coefficient at P_{rec} (equation (9)). The calculated K_1^{pr} according to DRF^S are comparable to K_1^{ex} or have underestimated values, especially for the FECS and the second annual period of the GCTC. In general, almost all K_1^{pr} according to DRF and DRF^N* are included in the presented interval of the relative calculation error −δ% ... +δ%. It should be noted that on practically the same parameters of the aggressiveness of the atmosphere of the three exposures in the GCTC, no model can give K_1^{pr}, which differs by a factor of 1.6.

Zinc (see Fig. 2). The values of K_1^{pr} calculated for both DRFs are in most cases not comparable with K_1^{ex}, while K_1^{pr} according to DRF^S have underestimated values, some of which go beyond the interval −δ%. For DRF^N*, some K_1^{pr} exceed +δ%. In the GCTC for both models, the K_1^{pr} is significantly less than K_1^{ex}, at one half of it.

Copper (see Fig. 3). The K_1^{pr} values according to DRF^N* are comparable to K_1^{ex} or have overestimated

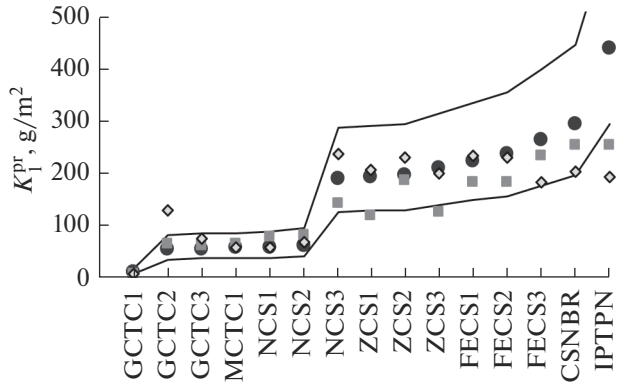

Fig. 1. Carbon steel. Comparison of K_1^{pr} values calculated by DRF^S (■) and by DRF^{N*} (◆) with K_1^{ex} (●). Thin lines designate the lines of relative errors K_1^{pr} + 50 and −33%.

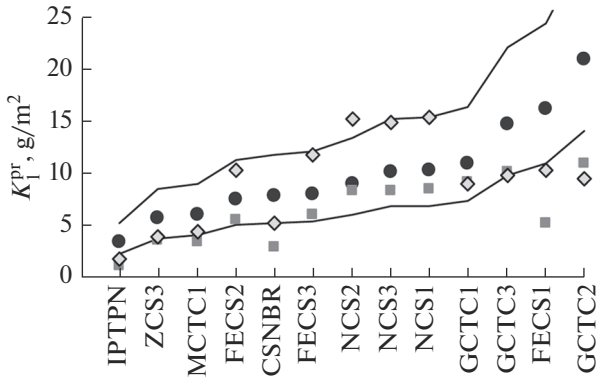

Fig. 2. Zinc. Comparison of K_1^{pr} values calculated by DRF^S (■) and by DRF^{N*} (◆) with K_1^{ex} (●). Thin lines designate lines of relative errors K_1^{pr} + 50 and −33%.

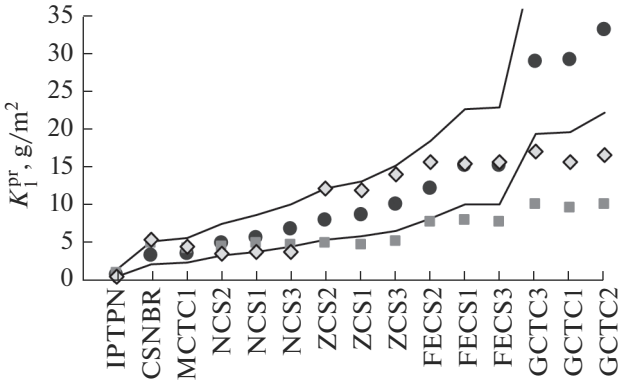

Fig. 3. Copper. Comparison of K_1^{pr} values calculated by DRF^S (■) and by DRF^{N*} (◆) with K_1^{ex} (●). Thin lines designate lines of relative errors K_1^{pr} + 50 and −33%.

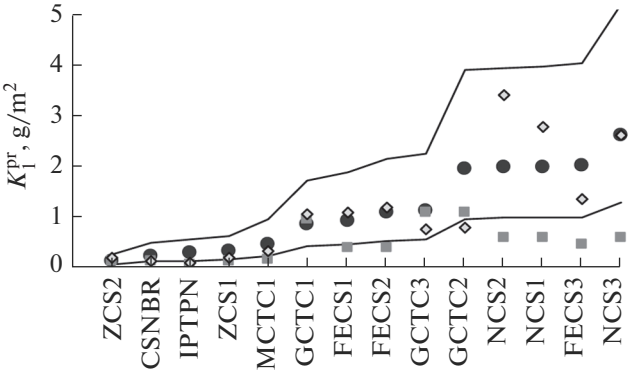

Fig. 4. Aluminum. Comparison of K_1^{pr} values calculated by DRF^S (■) and by DRF^{N*} (◆) with K_1^{ex} (●). Thin lines designate lines of relative errors K_1^{pr} + 100 and −50%.

values that do not go beyond +δ%, with the exception of GCTC, for which K_1^{pr} is significantly less. The calculated K_1^{pr} according to DRF^S, with the exception of continental CSs, have underestimated values, going beyond −δ%.

Aluminum (see Fig. 4). All K_1^{pr} obtained by DRF^{N*}, having comparable, underestimated or overestimated values in comparison with K_1^{ex}, practically do not go beyond the intervals of the relative error of −50% ... +100%. According to DRF^S, the K_1^{pr} values are generally underestimated in comparison with K_1^{ex}, while the majority of K_1^{pr} have values below −50%.

Thus, it has been shown that the obtained K_1^{pr} according to DRF^S and DRF^{N*} for all metals in GCTC are underestimated or significantly underestimated in comparison with K_1^{ex}, except for Al at exposure 1. For the rest of the CSs for St3, it is preferable to use DRF^{N*}. For Zn, both models give unreliable K_1^{pr} values, while for DRF^{N*} they are mostly overestimated, and for DRF^S, they are underestimated in comparison with K_1^{ex}. Considering that for design work it is preferable to appeal with well-estimated K_1^{pr} values, it is recommended to use DRF^{N*}. For Cu and Al, reliable K_1^{pr}, with a relative calculation error in the intervals of ±δ, can be obtained using only DRF^{N*}.

2.5. Evaluation of Atmospheric Corrosiveness by K_1^{pr} Values

Note that the orientation of the samples to the seashore was not taken into account when carrying out

full-scale international (for the development of DRF^S) and real tests. For example, in GCTC for metal samples with the upper side oriented to the south in accordance with GOST 9.906 [8], the reverse side of the sample turned out to be facing the sea. With significant salinity in the atmosphere, marine aerosols falling in large quantities on the lower side and not being washed away by precipitation could lead to significant corrosion of metals [16]. Such conditions correspond to the test conditions in a louvered room, where over time, taking into account the accumulation of salts on the surface, the corrosion losses of metals are greater than in an open atmosphere [17, 18]. In the FECS, the orientation of the upper side facing south practically coincides with the orientation to the seashore, i.e., to the predominant directions of the sea wind. In the NCS, the sea coast is on three sides; however, the orientation of the samples to the prevailing offshore winds, which creates a significant outflow of sea salts, is unclear. The results of K_1^{ex} obtained with different orientation of samples to the offshore winds do not allow the development of a DRF to obtain reliable K_1^{pr} for coastal CSs.

In spite of the methodological errors of tests at the seaside CSs, Table 5 gives an assessment of the corrosiveness of the atmosphere according to K_1^{pr} not only for continental but also for coastal CSs. Note that the categories of corrosiveness have clear boundaries for the values of K_1 and the difference between K_1^{pr} from the boundary value by only 0.1 g/m^2 will give another category or an additional gradation of the C2 category.

Continental CSs. For St3, the evaluation categories on K_1^{pr} for DRF^S and DRF^N* correspond to the categories on K_1^{ex}, with the exception of the city of Sochi (CSNBR) for DRF^N*. For Zn according to DRF^N* there is a mismatch of categories only in the IPTPN, category C2-2 instead of C2-3 and in the MCTC C 2-3 instead of C3. According to DRF^S, there are understated categories for all expositions. For Cu, the estimated categories on K_1^{pr} for DRF^S correspond to the categories on K_1^{ex}, and for DRF^N* do not correspond only for IPTPN and CSNBR, with the difference between K_1^{pr} and the boundary K_1 by only 0.8 and 0.5 g/m^2, respectively. For Al, the estimated categories according to DRF^S for all exposures, except for ZCS1, are underestimated, while in the MCTC, instead of category C2-3 is the category C2-1. According to DRF^N* the coincidence of categories for ZCS1 and ZCS2, underestimated for IPTPN, CSNBR, and in MCTC instead of category C2-3, is the category C2-2.

Seaside CSs. For St3, the estimated categories for DRF^N* and DRF^S coincide with those determined on K_1^{ex} for four exposures. If there is a discrepancy for the rest of the exposures, according to DRF^N*, the categories are overestimated, with the exception of GCTC1 and GCTC2, and according to DRF^S, all categories are underestimated. For Zn, with a mismatch between the categories according to DRF^S, the estimated categories are underestimated (FECS1 and GCTC2), and on DRF^N*, they are underestimated (FECS1 and GCTC2) and overestimated (NCS1-3). For Cu according to DRF^S, the estimated categories are underestimated, while for all exposures on the NCS and GCTC it is significant. According to DRF^N*, the estimated categories coincide (NCS1-3), overestimated (FECS1-3) and underestimated (GCTC1-3). For Al, the estimated categories according to DRF^S coincide only for GCTC1-3, for the rest of the CSs, the categories are underestimated. According to DRF^N*, the categories are the same for FECS1-2, NCS3, and GCTC1-3, underestimated for FECS3 and overestimated for NCS1,2.

The presented results indicate that the coincidences of the estimated categories of atmospheric corrosiveness by K_1^{pr}, calculated by DRF^N* and DRF^S, with the categories determined by K_1^{ex}, are not observed for all exposures. Nevertheless, for continental CSs, K_1^{pr} according to DRF^N* and DRF^S can be used to assess categories, and for coastal CSs there are more coincidences and increased categories according to DRF^N*.

Despite the fact that for all metals the values of K_1^{pr} according to DRF^N* are more reliable for most exposures in comparison with K_1^{pr} according to DRF^S, the DRF^N* cannot be recommended as a DRF for all types of atmospheres. This is only the first step towards the creation of DRFs for coastal atmospheres based on DRF^Ns developed for the continental territories of the world. However, the presented K_1^{pr} results according to DRF^N*, obtained for a small number of exposures, indicate the possibility of creating more advanced DRFs. However, their creation requires new tests in seaside areas with appropriate conditions for the exposure of metal samples.

CONCLUSIONS

1. For continental and coastal CSs, according to the average annual values of atmospheric pollution SO_2, mg/(m^2 year) and Cl^-, mg/(m^2 year), as well as to the total time of wetness TOW per year, hour/year, an informative assessment is given for the corrosive aggressiveness of the atmosphere.

2. According to the experimental data on corrosion losses for the first year , g/m^2, the categories of corro-

siveness of the atmosphere of continental and coastal CSs with respect to each metal were determined.

3. It is shown that the discrepancy between the informative assessment of the corrosiveness of the atmosphere and that determined from the values of K1ex for the coastal CSs is due to an inaccurate assessment of the time of wetness TOW. It is recommended to consider the TOW value as the total time per year, during which RH ≥ 70% at $T \geq -4$°C.

4. To calculate the first-year corrosion losses without testing, the DRFs presented in the international standard (DRF^S) and the new DRFs developed for the continental territories of the world (DRF^N) were used. For the application of DRF^N in coastal CSs, it was proposed to introduce the factor $[Cl]^\beta$ into the equations, which corresponds to the acceleration of metal corrosion due to chlorides (DRF^{N*}). The β values are given for each metal.

5. Comparison of the K_1^{pr} values calculated by DRF^S and DRF^{N*} with for all metals showed that DRF^{N*} are priority for their use in continental and coastal CSs.

6. It is shown that the discrepancy between the categories of corrosiveness, determined by the values of K_1^{ex} and estimated by K_1^{pr}, is not only due to the imperfection of the DRF, but also, for the coastal CSs, to the unequal exposure of the samples relative to the prevailing sea winds directions, causing the removal of sea salts.

7. It is shown that at present DRF^{N*}s cannot be recommended for use in coastal atmospheres. DRF^{N*}s should be tested or improved based on the results of new tests carried out in seaside areas with the same orientation of the samples relative to the sea coastline.

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