

Effect of Environmental Parameters on Atmospheric Corrosion of Carbon Steel Infrastructures in Montreal, Qc, Canada: Past, Current and Future Scenarios

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ABSTRACT

Atmospheric corrosion plays a critical role in structural metal loss and thus infrastructure service life. Since the 1920's, many studies have focused on the effect of environmental parameters on the corrosion of major construction metals and it has been shown that chlorides, pollutants in the air such as sulfur dioxide, temperature, and relative humidity are the main environmental factors affecting the corrosion rate. Several studies have come up with a dose response function to predict the corrosion rate of a specific metal based on the environmental factors it is exposed to. The predicted corrosion rate is a critical design factor to secure safe and reliable infrastructure performance during its design service life. Therefore, future climatic changes in the environment may need to be considered when selecting a proper material and its required thickness as changes in environmental factors due to climate change in certain regions may affect the corrosion rates. Currently, historical data is used for designing infrastructures without considering the future climatic changes. This study summarizes the effort on atmospheric corrosion programs involving Canada's climate and illustrates the changes in corrosion rate of carbon steel in the City of Montreal over the past 70 years and up to 80 years in the future using the projections of climatic models. The goal is to demonstrate the effect of climate change and the variation in atmospheric exposure conditions for future durability designs of infrastructures such as bridges against atmospheric corrosion.

Keywords: Atmospheric corrosion, environment, relative humidity, temperature, air pollutant, climate change

INTRODUCTION

Structural steel, which is a critical component of many infrastructures, can suffer from deterioration of steel by reaction with air and its pollutants known as atmospheric corrosion when exposed to the environment. The risks associated with corrosion of newly-built and ageing infrastructure are high and their consequences costly. The recent International Measures of Prevention, Application, and Economics of Corrosion Technologies (IMPACT) study led by NACE International (now renamed as AMPP) [1] has shown for Canada the estimated annual corrosion cost to be \$51.9 billion, which is 2.9 % of Canada's GDP. Engineers need to know the magnitude of atmospheric corrosion over time to

design exposed structures safely and sustainably by adopting proper anti-corrosive protection measures or considering a more cautious material selection.

The atmospheric corrosion damage mainly depends on exposure time (t) and some climatic factors such as relative humidity (RH), temperature (T), sulfur content, salinity (chloride), time of wetness (TOW) and the presence of some other pollutants such as airborne particles, nitrogen dioxide, etc. [2]. Corrosion of steel requires oxygen and electrolyte, and in a natural environment, the water from rain, splashing, or condensation can form a thin layer of electrolyte over the surface of steel. The thickness of the electrolyte layer is a function of its formation mechanism; for example, if due to rain, it can be 50-2000 μm , while the thickness decreases to 50-200 μm if the electrolyte formation is due to condensation, and to less than 5 μm if due to relative humidity. Oxygen alongside pollutants in the atmosphere can be dissolved in this layer of electrolyte and be readily transported to the metal surface, which will instigate and accelerate the corrosion process. The relative humidity is another environmental parameter that plays a significant role in atmospheric corrosion. There is a critical relative humidity in each environment under which the corrosion rate is negligible, and this critical relative humidity is 60-80 % in rural and urban atmospheres but can be as low as 20-30 % in the presence of air pollutants. The period of time when this critical humidity is exceeded is called the time-of-wetness (TOW) and it is the most important factor promoting atmospheric corrosion of metals [3].

The effect of temperature on atmospheric corrosion is complex. Like any other electrochemical reaction, the corrosion rate is following the Arrhenius law and is dependent on the ambient temperature. As a rule of thumb, increasing the temperature by 10°C, doubles the rate of corrosion within a range of ambient temperature of 20-30°C [4]. However, this extent of temperature dependence is only present at a very high humidity level and the corrosion reaction can only occur if a layer of electrolyte is present on the metal surface. In reality, a metal surface goes through various wetting and drying cycles where at nights the temperature decreases, RH increases and a moisture layer forms on the surface and when the temperature rises in the daytime, RH decreases and the moisture layer evaporates [5].

The main air pollutant that affects the corrosion rate is sulfur dioxide (SO_2). When SO_2 dissolves in water, it forms sulfuric acid, and this acidic solution prevents passivation of steels and also introduces a new cathodic reaction for the corrosion reaction. In the absence of sulfuric acid, the only cathodic reaction supporting corrosion is oxygen reduction and the reaction is in control of oxygen concentration in the electrolyte. Airborne salinity is another aggressive species causing the breakdown of the passive oxide film and corrosion initiation. Although this is more of a concern in marine environments close to the shore, the use of de-icing salt on Canadian roads in winter can also be a contributing factor to the salinity of the environment, especially in sections of infrastructure exposed to splash zones.

The primary step in service life estimation of steel structures is the prediction of thickness loss of metal due to atmospheric corrosion. Various studies [6–8] have shown, in general, that the long-term atmospheric corrosion of a metal is described by the following equation:

$$C_{\text{atm}} = C_0 t^n \quad (1)$$

Where C_{atm} is the atmospheric corrosion depth (in mm), after t years in service, C_0 (mm) is the corrosion depth at the end of the first year, and n is a power factor < 1 .

The estimation of the first year corrosion depth and the prediction of the overall thickness loss of a specific metal exposed to a certain environment is thus essential in service life design. Many efforts in long-term corrosion testing have been made to develop and prove the mathematical model of corrosion kinetics in various types of atmosphere, which will be reviewed in this paper.

The goal of this study is also to provide engineers with an insight on the impact of atmospheric corrosion on steel structures to consider using predicted future climatic data when designing new infrastructures. This paper summarizes the main atmospheric corrosion programs that have investigated the effect of atmospheric parameters on the corrosion of carbon steel in Canada and came

up with dose response functions. The validated ISO 9223 model was then used to demonstrate the changes in corrosion rate of carbon steel in Montreal, Canada over the past 70 years (i.e., 1950) and up to 80 years in the future (i.e., 2100) using the atmospheric information predicted by using climatic models.

INTERNATIONAL ATMOSPHERIC CORROSION PROGRAMS INVOLVING CANADA

American Society for Testing and Materials (ASTM)

ASTM has been investigating atmospheric corrosion since 1937 [9]. During the period of 1948 to 1955, ASTM Committee B3 on corrosion of non-ferrous metals initiated a 10-year study to calibrate the atmospheric corrosiveness of 19 sites in the United States and Canada using carbon steel and zinc specimens. Figure 1 indicates the location of such exposure sites in Canada [10], where ground sites are shown in green and roof sites are red.



Figure 1: Map of Canada showing the locations of exposure sites. [10]

The National Research Council of Canada participated in this study and a metal exposure program begun in Canada through the Associate Committee on Corrosion Research and Prevention (ACCRP) to obtain information on corrosion behavior of different architectural metals at 8 locations in Canada [3,10,11]. Several environmental factors were monitored in this program such as pollutants (SO_2), time of wetness, temperature, and atmospheric chloride.

At the time, the lead peroxide method was used for measuring the activity of sulfur dioxide in the atmosphere [11], this technique is obsolete now and it does not measure the volumetric concentration of SO_2 in the atmosphere directly, but presents an integrated measure of the SO_2 "activity" during the period of exposure. The salinity of the atmosphere was measured using either the wet candle method or the rainfall method. Details of these methods are still in use and explained in the literature [11]. The period when moisture is present on the steel surface was defined as the time of wetness and was obtained from the record of the moisture sensing element which was exposed in the same manner and

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location as the test sample [3]. The sites were provided with tubular racks and stainless steel frames for mounting the samples to the ASTM zinc and carbon steel specimens. The selected sites in Canada provide different exposure types, such as: east and west coast marine atmosphere, marine industrial, industrial, high humidity, low humidity, and far northern atmosphere are described below [12]:

1. Ottawa (On), semi-rural site.
2. Saskatoon (Sk), rural site.
3. Montreal (Qc), industrial site located on the roof of a building in Pointe St-Charles district.
4. Halifax (NS), marine-industrial site located on the roof of a federal public building in the downtown area near the harbor.
5. York Redoubt (NS), rural-marine site at elevation of 30 m and 90 m from the ocean.
6. Norman Wells (NWT), rural site located 150 km south of the Arctic Circle.
7. Esquimalt (BC), rural-marine site located at the southeast extremity of Vancouver Island, with elevation of 15 m and 450 m from the ocean.
8. Trail (BC), semi-rural site [13].

The ASTM corrosiveness index was derived by exposing ASTM standard mild steel samples at sites across Canada and United States. After a given length of time at each site the weight loss of samples due to corrosion was measured. In this study, the results at State College, Pa, were considered as the reference baseline (unity), and the corrosiveness of the other locations were ranked with respect to that of the State College. For example, an index of 2 for a location represents twice the corrosion rate at State College. The ASTM indices for corrosiveness and first year corrosion penetration of carbon steel (CS) samples of sites in Canada are given in Table 1 [14,15].

Table 1: ASTM indices of various locations in Canada

Location	Climate	ASTM indices	First year corrosion penetration CS (μm)
1- Ottawa	Semi-Rural	1.0	28.43
2- Saskatoon	Rural	0.6	18.96
3- Montreal	Industrial	1.5	46.54
4- Halifax	Marine-industrial	3.8	97.37
5- York Redoubt (Halifax)	Rural-Marine	1.5	38.58
6- Norman Wells	Rural	0.03	1.68
7- Esquimalt	Rural-Marine	0.5	11.46
8- Trail	Semi-Rural	1.4	39.8

Halifax shows the highest corrosion rate in the first year, as expected for a marine-industrial location, followed by Montreal that was classified as an industrial location at the time. Although both Esquimalt and York Redoubt were classified as rural-marine, the corrosion rate was significantly lower in Esquimalt (11.46 μm) than in York Redoubt (35.58 μm). The Trail site with semi-rural climate also showed similar but slightly higher corrosion rate (39.8 μm) than that of York Redoubt (38.58 μm), while Ottawa with the similar type of climate had a lower corrosion rate (28.43 μm). The two rural locations, Saskatoon (18.96 μm) and Norman wells (1.6 μm), were amongst the sites with the lowest corrosiveness, as expected.

Figure 2 shows the cumulated metal loss of ASTM carbon steel in Canadian corrosion sites after 10 years of exposure. The results demonstrate that highest corrosion rates are expected in Atlantic Canada. Corrosion levels in subarctic Canada (Norman Wells) may be considered negligible. It is noted that de-icing salts started to be used on roads and highways mostly after the start of this program, and are believed to have not accumulated significantly enough to play a major role in the environmental corrosion of the test samples.

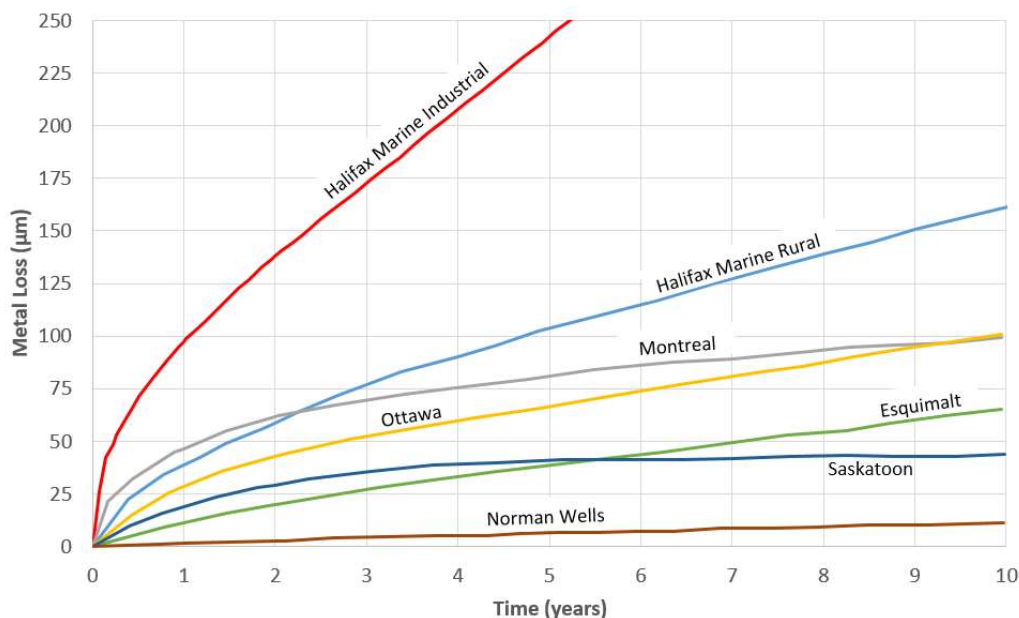


Figure 2: Corrosion metal loss vs. time of ASTM low carbon steel specimens in Canadian corrosion sites. [16]

The other regions had intermediate levels of corrosion rates. While the slope of curves for the marine sites is steeper than the other sites, very little corrosion had taken place in samples of Norman Wells. The corrosion rate versus time curves show that the rate of metal loss decreased rapidly over the first two years, and then approached a more constant rate with increasing time. This is mainly because of the corrosion product development on the steel surface protected the steel and slowed down the initial corrosion rate. However, in the three marine locations, the highest rates of corrosion were observed between 5 and 10 years, indicating the protection by the corrosion products forming in the presence of chlorides to be lower than the protection of those in other environments.

Many attempts were made to find a correlation between the corrosion response and the environmental factors in each location [17,18]. In the ASTM program, statistical analysis showed that the measured atmospheric factors namely TOW, temperature, atmospheric SO₂ and chloride completely control the rate of corrosion at all sites for at least the initial month [19]. For longer periods of time, the control of corrosion remained either with atmospheric factors, corrosion products formed on the surface, or foreign factors.

The atmospheric factors and corrosion data were analyzed by the following techniques:

1. Regression analysis using a quadratic equation with time of wetness, temperature, and sulfur dioxide concentration as the variables for inland locations and with time of wetness, temperature, sulfur dioxide concentration, and atmospheric chloride count as the variables for marine sites [19].

2. Curve-fitting where

for inland sites,

- time of wetness and sulfur dioxide data and time of wetness and temperature data

For marine sites

- time of wetness and atmospheric chloride data

and for Kure Beach Site,

- time of wetness and temperature data