ATMOSPHERIC CORROSION OF CARBON STEEL IN THE PRAIRIE REGIONS

William J.D. Shaw, P.Eng.
Department of Mechanical Engineering
University of Calgary
Calgary, AB

Jan I. Andersson, P.Eng.
Husky Oil Operations Limited
Calgary, AB

Atmospheric Corrosion of Carbon Steel in the Prairie Regions

William J.D. Shaw, P.Eng.
Department of Mechanical Engineering
University of Calgary
Calgary, AB

Jan I. Andersson, P.Eng.
Husky Oil Operations Limited
Calgary, AB

ABSTRACT

An extensive study and analysis of atmospheric corrosion has been conducted which covers the theory, understanding and behavior of carbon steel located in the prairie regions of Canada. The paper covers both general behavior and various standards for establishing and predicting corrosion in atmospheric conditions. Expected atmospheric corrosion of steel tanks at the Hardisty terminal as well as comparison to monitoring information at this site is also presented and compared.

Keywords: Atmospheric Corrosion, Time of wetness, Mechanisms, mild steel, protective films, prairie regions, corrosion prediction.

INTRODUCTION

The background for the information in this paper is taken from three reports generated by one of the Authors [1-3]. The reports focused upon answering the question as whether the ERCB Directive G-55, which requires tanks to be either painted or made from weather resistant material, has a sound corrosion engineering basis. Husky's experience and that of other operators, is that carbon steel that experiences natural exposure is a weather resistant material in the prairie region of Alberta.

It is generally recognized that on the prairies the atmosphere contains a mild degree of pollutants and a relatively dry climate with cold temperatures throughout substantial portions of the year occur. This mild corrosive condition suggests that the oxide film of magnetite that normally forms adjacent to steel, once matured, is very stable, tenacious and adheres well to the steel, giving a protective coating. It will not wash off nor is it easily removed. The question then arises as to whether this oxide coating give sufficient protection that mild steel itself can be deemed to be corrosion resistant.

Long term atmospheric corrosion monitoring has been performed at a number of locations throughout Canada and more notably for a prairie condition at Saskatoon [4]. This information gives direct verification to the analysis contained in this paper.

Atmospheric corrosion, the mechanism and parameters that control this form of metal degradation need to be clearly understood prior to undertaking any analysis and subsequent prediction of corrosion occurring on carbon or mild steel in the prairie regions.

ATMOSPHERIC CORROSION THEORY AND MECHANISMS

Theory

There is a major difference between gaseous corrosion and atmospheric corrosion, these two corrosion conditions are both singly unique. Gaseous corrosion occurs at considerably elevated or high temperatures and takes place in dry gaseous environments. As opposed to this atmospheric corrosion requires an aqueous film to be present on the metal surface, and as such it is a special form of general aqueous corrosion.

The principles and parameters involved in the mechanisms and control of aqueous corrosion apply equally to atmospheric corrosion. Atmospheric corrosion is a special case of aqueous corrosion, where regular electrochemical reactions and mechanisms actively control the corrosion. For atmospheric corrosion to occur sufficient moisture must be present in the atmosphere. Atmospheric corrosion requires that a moisture film must form and be present within the rust layer right down to the metal surface. This moisture film can be extremely thin or it can be reasonably thick even to the level that it can be seen by eye as water residing on the metal and corrosion film surface. The amount of moisture required for atmospheric corrosion to begin is known as the critical level of relative humidity. Once this level is achieved an active aqueous electrolyte has formed on the steel surface.

For atmospheric corrosion to occur, four key factors are necessary, the same as for regular aqueous corrosion to occur. These four factors are; there must be an anode, a cathode, an ionic conducting electrolyte and an electrical conducting path between the anode and the cathode. If any one of these four factors is missing corrosion does not occur. When the electrolyte is missing corrosion does not occur. This is the case that occurs for atmospheric corrosion at specific times. When the metal surface is dry or does not have a sufficient layer of moisture, the electrolyte is absent. At these specific times atmospheric corrosion does not occur.

The differences between regular aqueous corrosion and atmospheric corrosion are with respect to the electrolyte. Aqueous corrosion is for immersed components, where they are continually exposed to either large amounts of electrolyte or in the very least relatively thick layers of ionic salt mixtures and where the presence of the electrolyte is continuous. In atmospheric corrosion the metal surface is at times dry and at other times exposed to a film of aqueous electrolyte. The film of an aqueous electrolyte in atmospheric corrosion varies from a very thin surface film to a very thick film depending on the atmospheric conditions. This difference means that atmospheric corrosion is periodic, it is occurring at some specific times and not at others. The magnitude of the atmospheric corrosion varies with film conditions. Since these surface aqueous film conditions are constantly changing, it becomes more challenging to accurately predict the amount of corrosion. The electrolyte for atmospheric corrosion contains pollutants as found in the air, and these are very site specific. Oxygen from the air is absorbed into the thin film and diffuses to the metal surface. Atmospheric corrosion is indeed aqueous corrosion, where the electrolyte is complex in chemical species, resulting from the pollutants present. Initially with the easy presence of oxygen, the corrosion is the same as aerated aqueous corrosion. Later as the oxide film grows, it becomes more difficult for oxygen to diffuse through the corrosion layer and make its way to the metal interface. The corrosion condition then changes and moves towards the deaerated condition.

For steels, atmospheric corrosion normally results in uniform attack, thus the life of a steel component can be established based upon the rate of oxide film growth over time. This life varies considerably, according to the pollutants and specific atmospheric conditions present at the site specific location. The variability and complexity of the atmospheric pollutants are what drives most of today’s refinement and research taking place in this specific area of corrosion.

Corrosion mechanism

Aqueous corrosion in a near neutral pH condition results in the formation of protective oxide films on the surface of mild steel. If the pH becomes fairly acidic, less than 4, the iron oxide film will dissolve and fresh metal will become exposed to the aqueous solution and very aggressive corrosion will then occur. Alkaline pH above 10 significantly reduces the corrosion rate. The desirable range of pH for aqueous water solutions is from 4.5 to 14, in terms of having protective film formation take place on mild steel. The pH of rain water in the prairies [5] is between 5.5 and 6.5, providing a desirable pH environment for protective film formation.

The corrosion of iron in an aqueous solution as occurs from prairie rain water, starts with the formation of ferro hydroxide or goethite, FeOOH. As this oxide grows or matures, it continually moves upward maintaining contact with the aqueous solution. Adjacent to the metal interface the oxide changes over time to that of a thin layer of maghemite, Fe_2O_3. As the film grows further the layer of Fe_2O_3 moves upward and the interface oxide layer transforms into magnetite, Fe_3O_4 . This film is the most protective and tenacious, giving excellent protection to the iron substrate. This mature film comprised of the three oxides, takes time to form, but once formed the diffusion of oxygen and water down to the metal interface becomes more restricted and more difficult. This restriction in the oxygen diffusion is the critical step in reducing the corrosion rate of the steel and is known as the rate determining step in the corrosion reaction. A schematic of the established film formation for atmospheric corrosion of steel is shown in Figure 1.

Controlling parameters for atmospheric corrosion

The conditions comprising the make up of the atmosphere are very complex and continually changing. The atmosphere can contain acid rain, chloride salts, nitrogen compounds, ammonia, sulfur dioxide, hydrogen sulfide, carbon dioxide and other industrial contaminants. Climatic factors affecting atmospheric corrosion are items such as;

solar radiation
relative humidity
air chemistry
particles carried by the atmosphere (sand, soil, dust)
air temperature
rain
winds

As can be appreciated these factors are numerous, complex and interactive. It is extremely difficult to account for all of the above factors. Fortunately it is know that a few specific factors dominate the atmospheric corrosion condition. This allows some simplification and in fact becomes very site specific. This is the major reason why atmospheric corrosion sites are grouped according to the type of exposure or specific atmospheric conditions. The site of interest in Alberta is normally taken to be the “rural prairie” environment, which is reasonably dry and has minimal chloride and sulfur dioxide.

A major factor in atmospheric corrosion is rain water and its associated pH or acidity. In industrial settings highly acidic rain can occur. Sulfur dioxide in the presence of oxygen in rain water or in an aqueous film is easily converted to sulfuric acid, which is a major source of acidity and or acid rain. However the atmospheric condition on the prairies is only very mildly acidic.

Now days it can generally be expected that the acidity in rainfall has decreased especially over the more recent years. This is a result of the current more stringent environmental regulations. This means that an even a more favorable pH is occurring in rainfall at this time period, most likely being from 6 to 7. Currently the pH value is far removed from the passive oxide film breakdown, which occurs at a pH equal to 4.

Temperature has a major effect on corrosion and interacts synergistically with relative humidity. It is generally known as a *temperature-humidity complex*. A general rule is that corrosion can increase by an order of magnitude for every 10 ^oC increase in temperature. At freezing, corrosion effectively stops and just above freezing, atmospheric corrosion is insignificant. Atmospheric corrosion generally peaks at an ambient temperature around 38 ^oC as shown in Figure 2. Therefore it can be appreciated that significant corrosion occurs at 30 ^oC [6], while a considerably reduced amount of corrosion takes place at 20 ^oC and a further major reduction occurs at 10 ^oC. Corrosion ceases altogether when the temperature drops to 0 ^oC. This temperature relationship is why atmospheric corrosion at the Norman Wells station is the lowest of all the Canadian stations, as shown in Figure 3. The combination of cold temperatures combined with below freezing conditions for most of the year at this station results in very minimal atmospheric corrosion. Thus the total amount of corrosion is always an integration of both temperature and relative humidity acting together. If a structure such as a tank is operating at a high temperature, above the ambient, there will be a reduction in the normal amount of atmospheric corrosion. The high temperature of the structure in this condition will act to drive off moisture and hence lower the relative humidity on its surface and within its oxide. This action will work to reduce the amount of moisture that can be absorbed onto its surface and into the corrosion oxide film layer. It will keep the surface dry for longer periods of time as compared to a regular ambient temperature surface, hence the reduction in normal or expected corrosion amounts.

A beneficial action of rain that is not normally identified is that it will wash pollutant ions off the steel surface. This washing action will reduce the level of corrosion. In addition a thick aqueous layer above the oxide barrier is not as corrosive as a thin aqueous layer primarily due to the dilution of ions. This means there is a complexity to the amount of wetness occurring on the structures surface. This is shown in Table 1, in a very relative manner, where is can be seen that at lower humidity, more aggressive corrosion occurs as compared to a liberally wet surface [7]

The magnetite oxide film that forms adjacent to the steel, once matured is very stable, it is tenacious and adheres well to the steel, it will not wash off nor is it easily removed. Once formed and matured, it provides a long term solution to corrosion control.

It should be noted from Figure 3 that coastal regions do not reach a limiting film thickness, but rather continue to grow. This is a result of the high chloride ion concentration in these locations which prevents magnetite oxide film formation and keeps the corrosion film growing at a nearly constant and continuous growth rate. In these locations Weathering Steels must be used or protective coatings must be applied to carbon steels.

Time of Wetness

For any specific location the main or dominate factor affecting the level of atmospheric corrosion is the time of wetness, TOW. This is the time duration at which an aqueous film has formed and continually wets the steel structures surface. When the surface is covered by a thin layer of aqueous electrolyte, the corrosion cell becomes active. Therefore the corrosion is active and occurring throughout the duration of the time the surface interface is wet, hence the parameter TOW. The TOW is caused by rain, fog, snow, dew condensation and by capillary action as occurring in sufficiently elevated levels of relative humidity.

Surface oxide products have a major effect on aqueous film formation. Metal oxide itself is hydroscopic and for steel a moist film is found to occur at a relative humidity level of 80%. This is known as the critical relative humidity level. Correspondingly the temperature must be above 0 ^{o}C. When chloride salts are present in the atmosphere and are deposited on the steel structures surface, they act to lower the critical relative humidity level. The chlorides are more hydroscopic than the iron oxide layer and can reduce the critical RH to a level as low as 40%. The presence of other salts such as ammonium sulfate, cause other alterations in the hydroscopic effects, either increasing or decreasing the critical relative humidity condition. The initial critical relative humidity curve was established by Vernon in the early 1930's [8]. The most popular approach is to use annual information for values of humidity from 80% and higher, integrating the time for these occurrences, being taken as the TOW. This approach is simple, fast and reasonably accurate.

Major contaminates

The two most common pollutants normally considered are chlorides and sulfur dioxide. Other pollutants affecting atmospheric corrosion are gaseous constituents of ammonia, hydrogen sulfide, nitrous oxides and carbon dioxide. Normally in rural locations one would expect the gaseous constituents to be absent or if present to be extremely low having minimal effect. In the prairie regions both the chlorides and sulfides would also normally be expected to be absent or present in trace amounts.

Pollutants of chlorides and sulphur dioxide along with TOW are measured at atmospheric corrosion stations and corrosion monitoring sites according to either ASTM or ISO standards. These two pollutants are the ones most dominant in their effect on the corrosion of steel. The average overall pollutant of sulfur dioxide in the prairie regions is generally being approximately 0.001 ppm [9], while that of chlorides is also low being approximately 0.15 ppm [10].

STANDARDS & PREDICTIONS

Standards

There are two standards organizations that specify the methods and techniques required for measurement of pollutants. These are ASTM and ISO organizations and their respective standards. In addition the standards cover the setting up and operation of site specific coupon stations. The critical level of relative humidity was established as a value of 80% RH in ISO 9223 [11]

In the prediction area, there are three main data bases used throughout the world. The first and main one is ISOCORRAG [12,13] which is mainly combined North American and European, the methodology is based in ISO 9223 [11]. The second is MICAT [14], which is mainly Latin American, Spanish and Portuguese information, and is for mild steel resulting in an Iberoamerican corrosion map. The third is ICP/UNECE [15], the United Nations Economic Commission for Europe and the International Co-operative Program on Effects on Materials. The most popular data base is the ISOCORRAG, which is the main one used throughout North America as well as throughout most of the world.

Predictions

There are many algorithms that have been developed, and continue to be developed, that describe the corrosion according to TOW, Cl^-, and SO_2 [16-20]. These will undoubtedly continue to become better and more accurate over time.

Commercial computer programs can also be obtained to predict atmospheric corrosion, these have built in algorithms and are based on the use of data bases for validation. A major program of this type is that of KORRFIELD [21], and can be obtained from the Swedish Corrosion Institute.

The ISO 9223 uses classification conditions for TOW - (τ - rating), SO_2 - (P - rating) , and Cl – (S - rating). The combinations of these classifications result in a category - (C). The groupings use rough numerical limits, and the categories range from mild, C_1, to severe, C_5. The short term or first year corrosion amounts for steel according to these categories are shown in Table 2.

A popular long term algorithm based upon ISO 9223 and the ISOCORRAG approach was developed by Knotkova et al [12]. It is a general description of the interactive parameters and does not limit itself to specific categories. The equation was established by statistically fitting to many data bases, it is given for steel in equation (R1) below;

$$r = 1.3269 + 0.4313 \{SO_2\} + 0.0057 \{TOW\} + 0.1384\{Cl^-\} \quad \text{- - - - (R1)}$$

where r is corrosion rate in *μm/yr*, SO_2 is in $\mu g/m^3$, TOW is in *hrs/year,* and Cl^- is in mg/m^2-*day.*

The relationship can be put in more convenient corrosion units, being mils for a one year period, and then becomes the relationship given in equation (R2),

$$r = 0.0522 + 0.0170 \{SO_2\} + 2.244\times10^{-4} \{TOW\} + 0.0054 \{Cl^-\} \quad \text{- - - - (R2)}$$

This relationship does not give the full picture as the rate is calculated as a yearly rate and is only reasonably accurate for the first year when a protective corrosion film is initiating and forming. The rates for subsequent years will be progressively less since the corrosion film will continually slow down the reaction as it thickens and establishes itself into a more stable form. For the prairies, within a period of approximately 10 years, the film will have become very stable and will essentially stop any further atmospheric corrosion from occurring. If a protective film does not form and the corrosion rate continues, year after year, the relationship will predict an accurate corrosion condition.

A further predictive approach is required for long term corrosion as established from the stable film formation. In the prairies information collected from atmospheric corrosion coupons, over a 10 year period, from the Saskatoon station is the most representative for this region. The corrosion rate follows a slowing and limiting exponential function as shown in Figure 4.

The graph in Figure 4 can be normalized and then used for establishing film thickness over time for the prairie regions. The normalized relationship gives the relative or fractional amount of atmospheric corrosion as a function of time. The relationship is given in equation (R3).

$$f = 1 - e^{-0.486\,x} \quad \text{- - - - (R3)}$$

where f is the fractional amount of film formed and x is the number of years of exposure.

The film is essentially fully established after 10 years of exposure and does not change from that time forward into the future. This means that the progressive but diminishing film growth each year is the key parameter identifying the final corrosion outcome. The growth per year, in mpy, is not as meaningful, since it continues to diminish each year until practically, from an engineering perspective, it becomes zero at the ten year interval.

The two relationships can be used together, establishing the amount of corrosion in the first year using equation (R2) and then extrapolating using equation (R3) for the amount of mature film at 10 years. However when combined the relationship under predicts the amount of corrosion by about 30 % when tested against the information obtained from the Saskatoon station. For the prairies, the amount of corrosion contribution from sulphur dioxide is 9.5% and the amount of contribution from the chloride ion is ½%. The amount of contribution to the corrosion from the TOW is 80% and the base constant gives 10%. This shows that TOW controls and dominates the corrosion. An adjustment in tuning equation (R2) such that when equalling the growth of the Saskatoon station for the 10 year period, results in an adjusted and combined equation (R4) is given by,

$$r = 0.1956 + 0.0637 \{SO_2\} + 8.4128\times10^{-4} \{TOW\} + 0.0203 \{Cl^-\} \quad \text{- - - - (R4)}$$

The relationship, equation (R4), accurately predicts the stable film thickness or corrosion amount on flat mild steel surfaces after a 10 year exposure for any region throughout the prairies.

This equation can be further simplified by using the average values for sulfur dioxide and chloride ion as occurring on the prairies, since these values are fairly constant and do not vary significantly from location to location. The relationship then becomes one of using only the TOW, which is location specific. The equation (R5) then predicts the corrosion amount in mils for the stable film condition achieved after a period of 10 years of exposure.

$$r = [\ 0.3863 + 8.4128\text{x}10^{-4}\ \{\text{TOW}\}\ ] \quad \text{- - - - (R5)}$$

where r is in mils after a period of 10 years and TOW is in hrs/yr

The relationship of stable film formation or corrosion amount in mils after a 10 year period as dependent upon TOW is shown in Figure 5. For a few select locations the 10 year corrosion amount and the corresponding TOW is shown in Table 2.

These prairie locations all predict low amounts of corrosion due to the mild and relatively dry prairie conditions as well as the long periods of time where the ambient temperature is below freezing.

HARDISTY CORROSION RESULTS

Hardisty location

Weather information for the Hardisty location is not available, therefore other surrounding major cities for which good historical weather information exists need to be used for approximating the TOW for the Hardisty location. The town of Hardisty lies approximately 38 km southwest of Wainwright, which places it in a regular rural setting. It is approximately 330 km west of Saskatoon, approximately 110 km southwest of Lloydminster, approximately 180 km southeast of Edmonton and approximately 260 km northeast of Calgary. Historic temperature and combined moisture information from the surrounding sites of Saskatoon, Lloydminster, Edmonton and Calgary are used to approximate the specific TOW value for the Hardisty site shown in Table 5. An averaging of these sites gives a TOW for Hardisty of 1522 hrs/yr. The TOW values from the surrounding sites are 10 year average values.

Just outside of Hardisty is a tank farm and Husky initially had two unpainted storage tanks. The work in this paper was undertaken in order to establish the expected corrosion amounts that these tanks would experience and to determine whether it would be in good practice to leave the tanks unpainted.

Expected corrosion amounts

The expected amount of corrosion can be established using equation (R5), since the location is in a typical rural prairie region. Using the estimated TOW and the predictive relationship established previously, the stable and maximum corrosion thickness is expected to grow to a value of 1.67 mils. Once established after 10 years this corrosion amount is expected to remain constant for 20 to 40 years or longer. The growth prediction over the years up to and including 10 years is given in Table 4.

The corrosion value established after 10 years is extremely small, and should be compared with the corrosion allowance normally designed into the thickness of such tanks. The corrosion allowance would normally be 100 mils, and even if applying a safety factor of 2, this would still give an allowance of 50 mils which is many times greater that what the tank is expected to lose from corrosion over its entire lifetime.

Measured corrosion amounts

A program was carried out at the Hardisty tank site using both coupons and direct measurements taken on the tank walls. Using a total of 12 coupon specimens located in different locations on the tank, top, NW side, East side an average value of 0.57 mpy and a standard deviation of 0.22 mpy. These values were obtained using a 14 month exposure time. This average value can be compared to that of one year in Table 4 and also Figure 6, where it can be seen to be relatively equal to that predicted or occurring for Saskatoon. If anything the predictive relationship is giving a slightly more aggressive corrosion condition than that measured from the site coupons.

Ultrasonic thickness readings were taken in a few specific locations on the tank and followed over a five year time period. Evaluation of the oxide film on the tanks indicates the film is very thin and tenacious and no measurable thickness loss has been found to occur according to the ultrasonic measurements.

ATMOSPHERIC CORROSION IN ALBERTA

Expected atmospheric corrosion rates at various locations in Alberta

Long term TOW data is available for a number of locations in Alberta indicted in Table 5. The locations are a good representation of industrial and rural locations as well as prairie and mountain locations. In all locations the TOW is lower than in Saskatoon, which was taken as the reference location. Long term sulphur dioxide data occurring in the atmosphere is available in a number of Alberta locations, the values are extremely low and can be taken as the average value indicated previously.

Chloride levels are low in all locations, and have negligible impact on atmospheric corrosion of carbon steel.

Since only small variations occur in all parameters, TOW, chloride and sulfur dioxide, as affecting atmospheric corrosion growth and final film thickness, it is reasonable to expect that the corrosion rate estimated for Hardisty is representative for all locations throughout Alberta.

Comparison of carbon steel with weather resistant steels.

Copper-Nickel/Chrome bearing steels, with improved atmospheric corrosion resistance, such as USS Cor-Ten and Bethlehem Steel Corporation Mayari R have been on the market since the mid 1930's. In the mid 1960's Bethlehem Steel began referring to its Mayari R steel as weathering steel, a term now commonly used for these types of steels.

P. Albrecht et.al.[22] established a Medium Corrosivity band for Weathering Steels, based on a Modified ISO 9224 Method, that takes into account that the corrosion rate for weathering steels (and carbon steels) which is not constant during the first 10 years. See Figure 7. The Medium Corrosivity Band defines the degree of thickness loss expected from well-performing weathering steel. When NRCC Saskatoon carbon steel data and Husky Hardisty one year corrosion coupon data are plotted, they fit very well into the Weathering Steel "Medium" range.

Comparing the NRCC Saskatoon Carbon Steel corrosion test data with the NRCC Copper-Nickel (Weathering Steel) corrosion data from all Canadian test locations, shows that carbon steel in Saskatoon in the long term, in general outperforms Weathering Steel. The exceptions are weathering steel in Saskatoon and in Norman Wells, NWT, known internationally for negligible atmospheric corrosion. This means that normal carbon steel, in the prairie regions, could be considered as equivalent to that of using weathering steels for these regions.

DISCUSSION

Atmospheric corrosion of steel is controlled by the time of wetness of the metal surface. Two other parameters affect the corrosion, these being sulphur dioxide and chloride ion. The sulphur dioxide has a reasonably strong effect; however the chloride ion does not, at least in the prairie regions. The prairies have a unique environment, being generally fairly dry with a low relative humidity over much of the summer time. A good portion of the year sees temperatures below freezing and these two conditions act to limit the amount of time for which active atmospheric corrosion occurs. In addition the prairies experience low levels of both sulphur dioxide and chlorides. This makes the TOW as the most important and all dominate parameter causing the corrosion of mild steel. The pH of the rainfall in the prairies is favourable in not attacking any corrosion films formed on steel surfaces.

Without a high sulphur or chloride environment, the corrosion film that forms on steel transforms into a very tenacious and protective layer over time. In the prairie regions it establishes itself within a few years and becomes stable and fully established after 10 years. This means that the corrosion effectively ceases to occur after 10 years and the steel component will have a long life from 20 to 40 years or more. This is a very unique environment in Canada and because of this; steel components will survive an extremely long life when directly exposed to the atmospheric conditions.

Predictive methods have previously been developed, primarily based upon large data bases. These methods are reasonably good for predicting the first year amount of corrosion, but do not account for any film protection that forms and comes into play in subsequent years. This aspect of film growth and protection has been incorporated in this paper and the best previous prediction technique has been tuned to actual atmospheric corrosion coupon information obtained at a prairie station, Saskatoon, over a 10 year period. The new predictive relationship is simple and can be applied through the prairie regions. It will give accurate results provided the sulphur dioxide level does not become elevated in any location where it is being used. The predictive relationship requires the time of wetness for that location. These values can be obtained from government weather data bases.

The prediction of the atmospheric corrosion of mild steel at the Hardisty location is quite accurate as verified by on site coupons at this location. Another parameter also comes into play that being the elevated temperature of the tank surfaces. This will act in a manner that reduces the TOW, by driving moisture off and reducing the relative humidity.

Correlation of atmospheric data shows that carbon steel will perform as good or better in the prairie region of Alberta as well as Alberta in general as compared with Saskatoon. It has also been shown that carbon steel is a better choice in Alberta than weathering steels.

CONCLUSIONS

An accurate predictive method of establishing corrosion amounts over elapsed yearly times has been developed in this paper. This prediction technique is established for the prairie regions, as in these regions a protective film of magnetite iron oxide grows and establishes itself over time. The film becomes fully mature within 10 years and no further measurable corrosion occurs after this period. This means that in Alberta carbon steel is a corrosion resistant material when it comes to atmospheric corrosion and as such does not require a further protective coating such as painting.

In Alberta carbon steel can be expected to have equal or better atmospheric corrosion behaviour than that of well-performing weathering steel.

The predictive method presented here is tuned to the 10 year information from the Saskatoon station and further verified against coupon tests at the Hardisty tank farm. The method incorporates the time of wetness which can be readily acquired or reasonably accurately estimated for any location in or throughout Alberta.

TABLE 1.

RELATIVE EFFECT OF DEGREE OF WETNESS ON CORROSION RATE [7]

Environmental condition	Amount of water, g/m^2	Supply of corrosion products, mole/L-day
Critical Relative Humidity	0.01	30
100% RH	1	0.3
Covered by Dew	10	0.03
Wet from Rain	100	0.003

TABLE 2.

SUMMARY OF ATMOSPHERIC CORROSION OF STEEL ACCORDING TO CATEGORY [11].

Category	Relative Corrosivity	Short Term Corrosion Rate, mils-yr
C_1	very low	< 0.05
C_2	Low	0.05 - 1.0
C_3	medium	1.0 - 2.0
C_4	High	2.0 - 3.25
C_5	very high	> 3.25

TABLE 3:

SELECT 10 YEAR PREDICTED CORROSION AMOUNTS OF MILD STEEL AND CORRESPONDING TOW

Location	r, mils	TOW, hrs/yr
Calgary	1.32	1108
Edmonton	1.74	1613
Lloydminster	1.68	1541
Saskatoon	1.92	1826

TABLE 4.

PREDICTED ATMOSPHERIC CORROSION GROWTH RELATIONSHIP TOWARDS A FULLY ESTABLISHED CORROSION FILM THICKNESS AT 10 YEARS

Year	Corrosion amount, mils
1	0.64
2	1.04
5	1.52
10	1.67

TABLE 5

TOW ENVIRONMENT CANADA WEATHER STATIONS IN SASKATOON SK, VARIOUS ALBERTA LOCATIONS AND KAMLOOPS B.C.

	Edmonton		Lloydminster		Saskatoon		Calgary	
Year	**Hours T>0 and RH>80%**	**Percent**	**Hours T>0 and RH>80%**	**Percent**	**Hours T>0 and RH>80%**	**Percent**	**Hours T>0 and RH>80%**	**Percent**
1997	1848	21.1	1836	21.0	1873	21.4	1111	12.7
1998	1756	20.0	1347	15.4	1861	21.2	1563	17.8
1999	1322	15.1	1715	19.6	2128	24.3	1189	13.6
2000	1607	18.3	1826	20.8	1873	21.3	964	11.0
2001	1523	17.4	1177	13.4	1667	19.0	609	7.0
2002	1040	11.9	761	8.7	1597	18.2	619	7.1
2003	1310	15.0	1530	17.5	1410	16.1	808	9.2
2004	1906	21.7	1873	21.3	1908	21.7	1337	15.2
2005	1984	22.6	1904	21.7	2059	23.5	1462	16.7
2006	1831	20.9	1445	16.5	1887	21.5	1418	16.2
Average	**1613**	**18.4**	**1541**	**17.6**	**1826**	**20.8**	**1108**	**12.7**

	Ft Mc. Murray		Peace River		High Level		Red Deer	
Year	**Hours T> 0 and RH>80%**	**Percent**	**Hours T> 0 and RH>80%**	**Percent**	**Hours T> 0 and RH>80%**	**Percent**	**Hours T> 0 and RH>80%**	**Percent**
1997			1220	13.9	1715	19.6	1513	17.3
1998			23	0.3	1498	17.1	1754	20.0
1999			225	2.6	1097	12.5	285	3.3
2000			1058	12.0	1157	13.2	1645	18.7
2001			1039	11.9	945	10.8	742	8.5
2002			816	9.3	246	2.8	920	10.5
2003			925	10.6	1070	12.2	698	8.0
2004			855	9.7	897	10.2	1092	12.4
2005			664	7.6	1364	15.6	1681	19.2
2006			1051	12.0	1578	18.0	1788	20.4
2007								
2008	1237	14.1						
2009	1608	18.4						
Average	**1423**	**16.2**	**765**	**9.0**	**1157**	**13.2**	**1212**	**13.8**

	Banff		Jasper		Grand Prairie		Pincher Creek	
Year	**Hours T> 0 and RH>80%**	**Percent**	**Hours T> 0 and RH>80%**	**Percent**	**Hours T> 0 and RH>80%**	**Percent**	**Hours T> 0 and RH>80%**	**Percent**
1997			1755	20.0	1262	14.4	957	10.9
1998	1657	18.9	1407	16.1	1087	12.4	1127	12.9
1999	1509	17.2	1360	15.5	879	10.0	826	9.4
2000	1049	11.9	1440	16.4	1143	13.0	537	6.1
2001	959	10.9	1481	16.9	962	11.0	626	7.1
2002	476	5.4	1063	12.1	783	8.9	1096	12.5
2003	895	10.2	77	0.9	705	8.0	577	6.6
2004	1349	15.4	1472	16.8	1407	16.0	1281	14.6
2005	1647	18.8	1906	21.8	1018	11.6	1182	13.5
2006	1350	15.4	1294	14.8	1057	12.1	1170	13.4
Average	**1210**	**13.8**	**1326**	**15.1**	**1030**	**11.8**	**938**	**10.7**

Table 5 continued

	KamloopS, BC	
Year	Hours T> 0 and RH>80%	Percent
1997	1669	0.19
1998	1723	0.20
1999	1529	0.17
2000	1189	0.14
2001	946	0.11
2002	1303	0.15
2003	1070	0.12
2004	1673	0.19
2005	1140	0.13
2006	1039	0.12
Average	**1328**	**0.15**

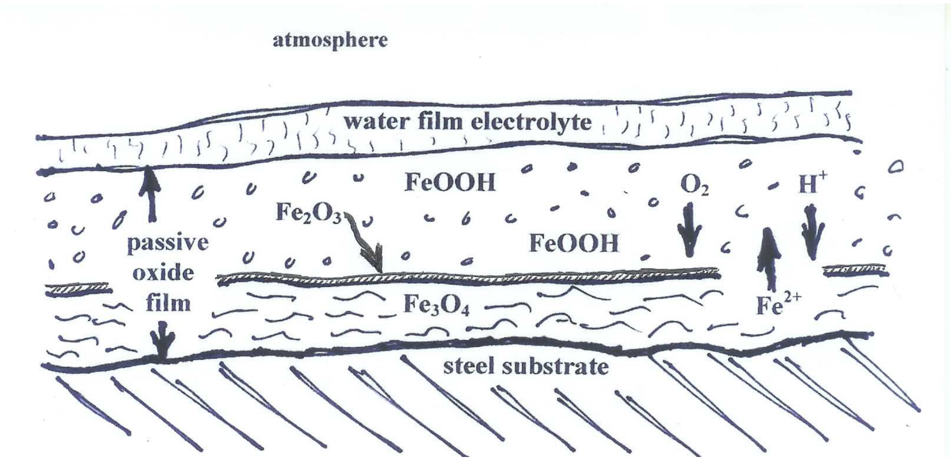

Figure 1. Schematic representation of formation of a protective atmospheric corrosion film

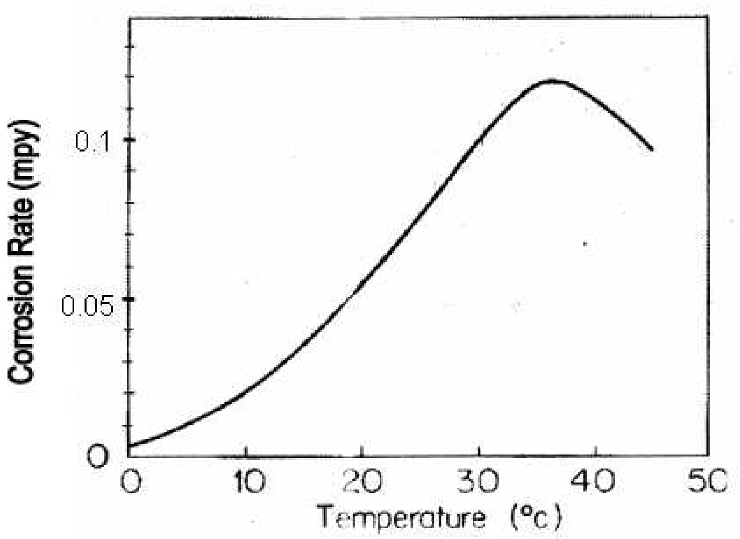

FIGURE 2. Atmospheric corrosion effect of temperature on iron [6]

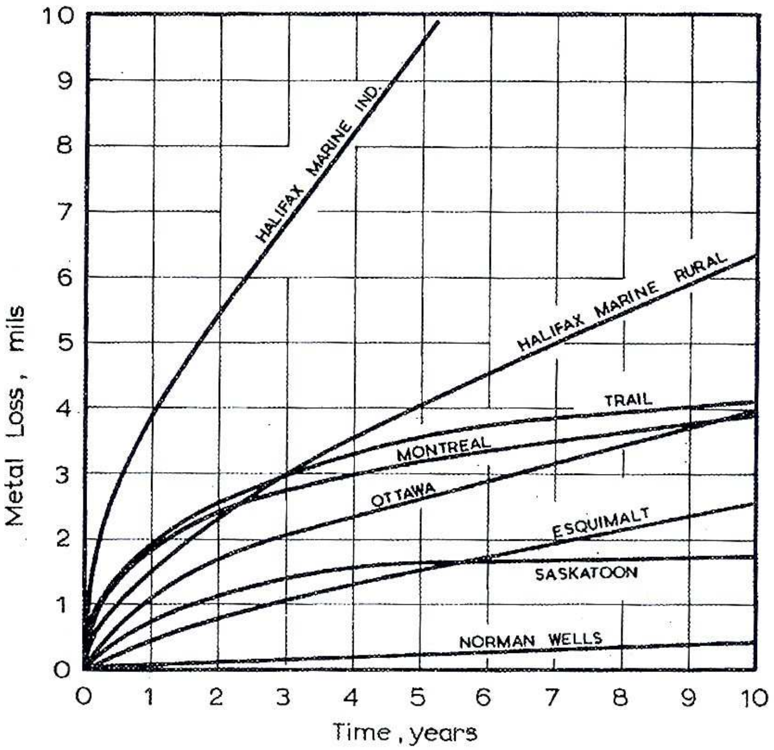

FIGURE 3. Corrosion verses time curves for low carbon steel at various Canadian corrosion sites [4]

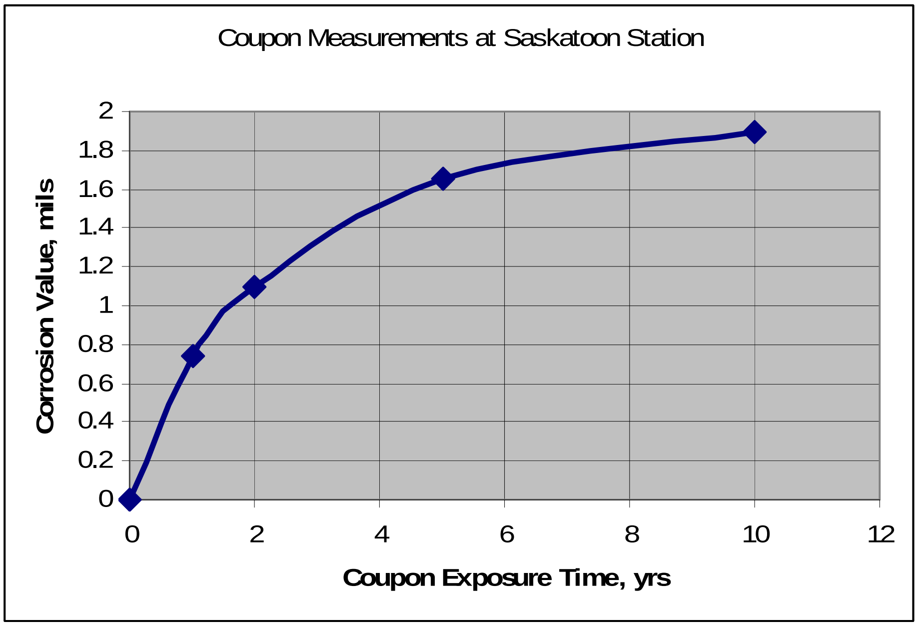

FIGURE 4. Atmospheric corrosion coupon measurements at Saskatoon station

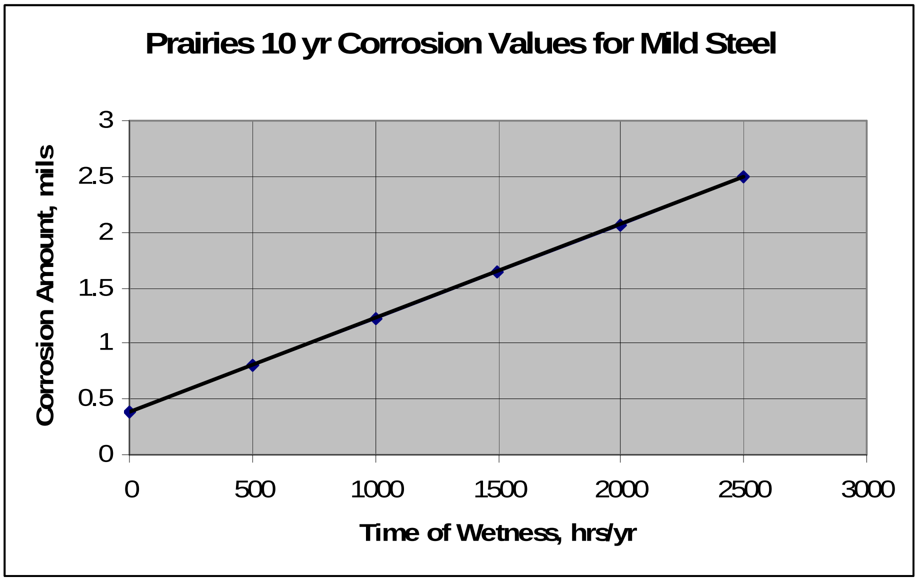

FIGURE 5. Corrosion of mild steel after 10 years exposure in the prairie regions as controlled by TOW

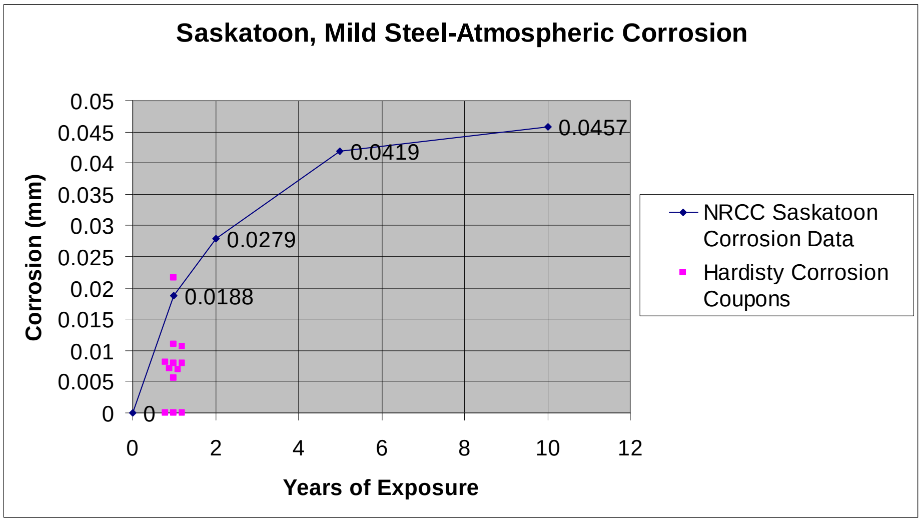

FIGURE 6. Hardisty atmospheric corrosion coupons compared with atmospheric corrosion coupon measurements at Saskatoon station

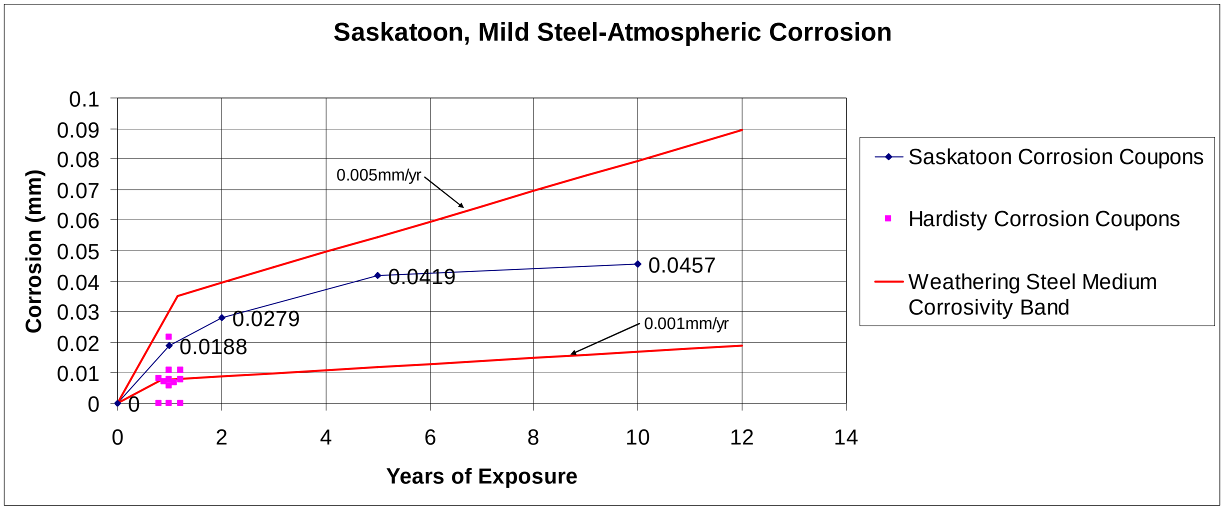

FIGURE 7. Medium corrosivity band for weathering steels with Hardisty atmospheric corrosion coupons compared with atmospheric corrosion coupon measurements at Saskatoon station.

REFERENCES

1. Dr. W.J.D. Shaw, P.Eng.,*"Hardisty Atmospheric Corrosion Monitoring Program"*, Husky in-house report., 2007

2. Dr. W.J.D. Shaw, P.Eng., *"Atmospheric Corrosion Theory and Understanding"*, Husky in-house report., 2007

3. Dr. W.J.D. Shaw, P.Eng., *"Expected Atmospheric Corrosion of Steel Tanks at Hardisty Terminal"*, Husky in-house report., 2007

4. Gibbons, E.V. , *"The Corrosion Behavior of the major Architectural and Structural Metals in Canadian Atmospheres: Summary of Ten-Year Results of Group 1"* , NRCC_0011630, 1970 Figure25.

5. CSA-370, 2004, Connectors for Masonry, Missisauga, Ontario, Figure 2.8

6. Barton, K, Protection Against Atmospheric Corrosion, John Wiley & Sons, 1976, pg. 55.

7. Mattsson, E., *„The atmospheric Corrosion Properties of Some Common Structural Materials – A Comparative Study"* , Material Performance, July 1982, pgs. 9-19

8. Vernon, W.H.J., "*British Non-Ferrous Metals Research Association (Second experimental report to the atmospheric corrosion research committee)*", Transactions Faraday Society, 1927, V23, N74, pgs.113-185

9. CSA – A370, 2004, Connectors for Masonry, Mississauga, Ontario, Figure 2.9

10. Corrosion of Materials, ASM Handbook, V13C, 2001, pg.44.

11. ISO 9223, Corrosion of Metals and alloys – corrosivity of atmospheres – Classification, 1992.

12 Knotkova, d., Boschek, P. and Kreislova, K., *"Results of IOSCORRAG Program: Processing of One-Year Data in Respect to Corrosivity Classification"*, ASTM STP 1239, 1995, pgs. 38-55..

13. Dean,S.W., "*Analysis of Eight Years of Exposure Data from the USA Contribution to the ISOCORRAG Program*", 13th International Corrosion Congress, NACE, 1998, paper 011, pgs. 1-8.

14. Morcillo, M., "*Atmospheric Corrosion in Ibero-America: The MICAT project*", ASTM STP 1239, 1995, pgs. 257-275.

15. Tidblad, J., Mikhailov, A.A. and Kucera, V., Statistical Analysis of 8 Years Material Exposure and Acceptable Deterioration and Pollution Levels, Swedish Corrosion Institute, Stockholm, Sweden, 1998, UNECE ICP Report No. 30.

16. Klinesmith, D.E., McCuen, R.H. and Albrecht, P., "*Effect of environmental Conditions on Corrosion rates*", J. of Materials in Civil Engineering, 2007, V19, N2, pgs. 121-129

17. Kihira, H., Senuma, T., Tanaka, M., Nishioka, K., Fujii, Y. and Sakata, Y., "*A Corrosion Prediction Method for Weathering Steels*", Corrosion Science, 2005, V47, pgs. 2377-2390.

18. Roberge, P.R., Klassen, R.D. and Haberecht, P.W., "*Atmospheric Corrosivity Modeling -a Review*", Materials & Design, 2002, V23, pgs. 321-330.

19. Tidblad, J., Mikhailov, A.A. and Kucera, V., "*Model for the Prediction of the Time of Wetness from Average, Annual Data on Relative Air Humidity and Air Temperature*", Protection of Metals, 2000, V36, N6, pgs. 533-540.

20. ASTM G 101, Standard Guide for Estimating the Atmospheric Corrosion Resistance of Low-alloy Steels, 2004.

21. KORRFIELD Data Base and Prediction Program, Swedish Corrosion Institute , Stockholm, Sweden, 2005. www.claes.taxen@corr-institute.se

22. Albrecht, P. and Hall Jr. T., *"Atmospheric Corrosion Resistance of Structural Steel"* . Journals of Materials in Civil Engineering, January/February. 2003, 150th Anniversary Paper, pgs. 2-24.