ATMOSPHERIC CORROSION OF METALS

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Abstract-This work is dealing essentially with atmospheric corrosion to assess the degrading effects of air pollutions on various metals that are mostly used in the engineering systems. The exposure study was conducted in Oman. The common materials like aluminum, brass, copper, epoxy, galvanized, mild steel and stainless steel were used for investigation. The sites of exposure were chosen at five locations where the metals are likely to be used. Additive models using median polish were used to investigate the patterns of corrosion by metal type and location. Regression analysis was also used to develop a number of predictor models for corrosion, based on metal type, location, number of months of exposure, and number of degrading pollutants in the air. The results of the additive models showed that copper and mild steel were the most corrosive metals while stainless steel and epoxy were the least corrosive. Of the locations, Sohar came out as the site with the worst corrosion record. Carbonates were the main component of corrosion, followed by chlorides and sulphates. The site at Al-Rusail had the highest level of carbonates corrosion, while the Airport and Al-Fahl showed the highest level of chlorides and sulphates corrosion, respectively.

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1. INTRODUCTION

Atmospheric corrosion is probably the most common form of corrosion and is defined as the corrosion or degradation of material exposed to the air and its pollutants. Therefore, it is important to know the specific corrosion rate in a given application environment in order to affectively use metals in outdoor structures. A common method for estimating the life of metals has been the use of various types of metals and alloys for the different types of atmospheres. Recognition of marked differences in corrosivity has made it convenient to divide atmospheres into types. The major types are rural, urban, industrial, marine, or a combination of these.

Many investigators have examined the corrosion rates of various metals exposed to different atmospheres (Upham, 1967; Knotkova et al., 1995; Kucera and Fitz, 1995; Mikhailov et al., 1995). These exposure studies were conducted to evaluate the relative corrosion resistance of various metals to different atmospheric environmental conditions. A metal resisting one atmosphere may lack effective resistance elsewhere, and hence, relative performance of metals changes with location. For example, galvanized iron performs well in rural atmospheres but it is relatively less resistant to industrial atmospheres (Uhlig and Revie, 1985).

The term corrosion products refer to the substances produced during a corrosion reaction. These can be soluble or insoluble compounds. The presence of corrosion products is the way in which corrosion is detected (e.g. rust). In general, the properties of the corrosion product are often the determining factors in the atmospheric corrosion behaviour of metals.

Models for predicting the corrosion damage of metals in the atmosphere are useful for answering questions regarding the durability of metallic structures, determining the economic costs of damages associated with the degradation of materials, and acquiring knowledge about the effect of environmental variables on corrosion kinetics (Feliu and Morcillo, 1993; Feliu et al., 1993). These models have been shown to be effective in these areas:

- Determination of the influence of pollutants in corrosion or degradation rate by obtaining regression equations between the different variables.
- Predictions about corrosion aggressivity of the atmosphere can be made based on the characteristics of the environment and the materials.

Both deterministic and statistical models have been developed for better understanding the environment. Deterministic models are based on fundamental mathematical descriptions of atmospheric processes, in which effects (air pollution) are generated by causes (emissions). Examples of the deterministic types are Euler and Gaussian models (Zannetti, 1983, 1994). On the other hand, Statistical models are based on semi-emprical statistical relations among available data and measurements. They do not necessarily reveal any relation between cause and effect. They attempt to determine the underlying relationship between sets of input data (predictors) and targets (predictands). Examples of statistical models are regression analysis (Abdul-Wahab et al., 1996), time series analysis (Hsu, 1992) and artificial neural networks (Abdul-Wahab, 2001; Abdul-Wahab and Al-Alawi, 2001; Elkamel et al., 2001).

Most of the predictive models used are regression models that fit the data such that the root mean square error is minimized. They are used to express the relation between the quantity of corrosion and the reasons, and the predicting equation is obtained by multiple regression analysis. Generally, multiple regression analysis modeling is effective to identify areas of risk, i.e., correlating among the corrosive factors in an environment and the resultant corrosion and finally obtaining a regression equation for the prediction of corrosion risk (Mughabghab and Sullivan, 1989; Kajiyama and Koyama, 1997). It is most properly performed on an independent random sample of data. The effect of inputs on the output can be studied using regression coefficients, standard errors of regression coefficients, and the level of significance of the regression coefficients (Devore and Peck, 1996). It serves three major purposes: (1) description of the relation between variables; (2) control of predictor variables for a given value of a response variable; and (3) prediction of a response based on predictor variables (Sen and Srivastava, 1990; Neter et al., 1996). Atmospheric corrosion phenomena have been studied and statistical models based on regression analysis have been developed by many investigators (Sawant and Wagh, 1991; Spence and Haynie, 1992; Costa and Vilarrasa, 1993; Haagenrud et al., 1995; Knotkova et al., 1995).

The objective of this paper is to use regression analysis to predict corrosion rates of various metals at specific locations in Oman. The atmospheric corrosion of common metals was studied at five locations. The study was designed to be conduced for three years. However, the paper is presenting the preliminary results of the first 8 months exposure periods that extend from August 2000 through March 2001.

2. MATERIALS AND METHODS

Atmospheric exposure tests were conducted at 5 test stations in Oman. The locations of these sites along the Gulf of Oman coast are shown in Figure 1. The distances of each site from seacoast together with the heights above the sea level are also given in this Figure. All the sites are located within the city limits of Muscat except one, Sohar, which is located about 200 km northwest. These sites vary considerably with respect to moisture content, temperature and contaminants (e.g. dust content and gaseous impurities).

These sites, therefore, have been divided into types. Airport was classified as marine which is expected to be affected by particles of sea salt (e.g. chlorides) carried by wind and deposited on materials. Al-Khod was classified as urban site. It is subjected to normal precipitation patterns and typical urban contaminants emitted by traffic. Al-Rusail was classified as industrial area. It is identified with heavy industrial manufacturing facilities. The atmosphere of Al-Rusail can contain concentrations of SO2, chlorides, nitrates or other specific industrial emissions that are released from sources located nearby. Sohar is a heavily industrial area that is located close to the seacoast and hence it is both marine and industrial area.

Scope and methodology of conducting the corrosion studies were similar for all five locations. Aluminum, brass, copper, epoxy, galvanized, mild steel and stainless steel were selected for exposure at each test location. Epoxy is produced by paining mild steel surface with epoxy. It is one of the most effective methods for corrosion protection of mild steel. Like other metals, epoxy corrodes at certain rates depending on the environmental conditions.

For each metal type, flat specimens measuring 100 x 40 mm were sheared from 0.01 mm thick sheets, which were obtained from the same lot to insure uniform composition. Specimens exposed in Sohar, Airport, fahal and Russeel are orientated in such away that they face the most corrosive direction. This convection was used since all these four exposure sites are close to a source of pollutants such as seawater, refinery stacks or power stacks. However, specimens exposed in Khod are orientated in such away that they face south. This orientation was selected since Oman is located in the northern hemisphere. Moreover, the specimens were exposed at an angle equal to the latitude of the site. This convention was selected because maximum exposure to sunlight is desired.

Specimens were mounted on a test reclined rack as shown in Figure 2. The rack is made of wood and attached to a frame or stand. In order to identify the exposed specimens, stamped code numbers are used. The exposure racks are located in cleared areas such that the exposed specimens will be subjected to the full effects of the atmosphere. Shadows of trees, buildings, or structures should not fall on the specimens and local contamination of the atmosphere was avoided.

Seven specimens (Aluminum, brass, copper, epoxy, galvanized, mild steel and stainless steel) were removed from each site after exposure periods of 1,2,3,4,5,6,7 and 8 months. Guidelines from American Society for Testing and Materials (ASTM), the National Association of Corrosion Engineers (NACE) and the International Organization for Standardization (ISO) was used for the cleaning procedures required before exposure and for cleaning and evaluation after exposure.

The amount of metallic corrosion was determined by the weight-loss method. This involved cleaning and weighing each test specimen prior to exposure. Then after the exposure period, the product of corrosion from each specimen is carefully removed and the specimen is reweighed. The average weight loss per unit area provided a measure of the amount of metal lost by corrosion. The corrosion products of the exposed metals were then analyzed chemically to determine the concentration values of sulphates, nitrates, chlorides and carbonates. Each one of these variables exerts an influence on the corrosion rate of metals and so it is important in determining the test site corrosivity.

3. RESULTS AND DISCUSSION

3.1. Model fitting by median polish

An additive model, fitted to a two-way table, was used to investigate the patterns of corrosion, and the various chemical components of the corrosion, with the metals and the locations as the factors. The method applied here is known as median polish, and involves first subtracting the median of a row from all the numbers in the row, for each row, followed by a similar operation for each column, using these medians as partial descriptions for the corresponding rows and columns, respectively. The procedure is repeated until the medians of all the rows and columns are effectively zero. Finally, the process splits the data in the table into a common value, a set of row effects, a set of column effects and a matrix of residuals, all of which sum to the original data values. That is, a given data value for the cell in row i and column j is split as follows:

$Data_{ij}$ = common term + row_i effect + $column_j$ effect + $residual_{ij}$

The row effects account for differences in the data values between rows, relative to the common value. The column effects are similarly defined. Any extraordinary data value would leave a large residual. For more details of the methods see Velleman and Hoaglin (1981).

Table 1a shows the sum of the corrosion rates over the eight months of exposure, by metal type and location, and Table 1b is the final result of the median polish for the same data set. The row effects show that mild steel and copper (at 147 mg/cm^2 and 105 mg/cm^2 above the common level, 63 mg/cm^2, respectively) were clearly the most corroded of the seven metals, irrespective of the locations. The least corroded were stainless steel (-42 mg/cm^2), aluminum (-22 mg/cm^2) and epoxy (-20 mg/cm^2). In between are galvanized steel (at 79 mg/cm^2 above the common rate) and brass (0.0 mg/cm^2). The effects for locations were much smaller, with differences from the common value ranging from only –11 to 26 mg/cm^2. From these effects, it seems that, compared to the other locations, Sohar (at 26 above the common value) had the worst record of corrosion. The sites at the Airport and Al-fahl were the least affected.

There were substantial differences in the common values obtained from fitting additive models by median polish to the data on the amounts of the four major chemical components (sulphates, chlorides, carbonates and nitrates) causing the corrosion. Using the metal types and locations as the two factors, the highest common value was found to be that of carbonates (138 ppm), and the least was of nitrates (33 ppm). The common values for chlorides and sulphates were about equal (83 and 73 ppm, respectively). This indicates that a typical metallic corrosion consisted of about 42% carbonates, 25% chlorides, 22% sulphates and 10% nitrates. For carbonates, the effects for metal type were very small relative to the common value, and ranged from –8 to 11. Galvanized steel seemed to have the highest carbonates level, and the least were copper and stainless steel. There was equally not much difference with regard to the sites. The corrosion levels at the sites by the Al-Fahl and Al-Khod had the least levels of carbonates, while those from the industrial site of Al-Rusail had the highest. The effects by metal types of the amount of chlorides had very little variation, ranging between –5 and 8 about the common value. Corrosion from aluminum had a slightly high chlorides level, and the least from copper. The corrosion effects by sites were also very small, relative to the common value. Due to their locations close to the sea, Sohar and the Airport area showed slightly high chlorides level, with Al-Rusail, which is somewhat in the interior, having the least. The largest departures from the common value were found in sulphates level. The effects by metal types varied substantially from the common value (73) and ranged from -23 to 117. The mild steel was the worst affected, especially at the Al-Fahl site. The least affected metals were aluminum, Epoxy and galvanized steel. Copper and stainless steel were only moderately affected. Overall, the site at Al-fahl had the highest levels of sulphates corrosion. In the case of nitrates, substantial differences were found only in the effects of metal types. Mild steel had the highest difference (at 49 ppm above the common value of 33 ppm), especially at the site by the Airport, with copper (17) a distant second. The metals least corroded by nitrates substance were stainless steel, epoxy, aluminum, and galvanized steel.

Fitting regression models to the data

To further determine what relationships exist between the corrosion, the locations and the times of exposure of the metals, multiple linear regression models were fitted to the data. The corrosion rates and their chemical components were fitted separately, and for each metal type, using the locations as indicator variable, and the time in months as the independent variables. The months of exposure were split into two variable with the first four months as one variable and the last four as another. This is because initial examination of the plots of the data indicated a distinct difference in rates of change for the two periods of time.

3.2.1. *The corrosion rates*

The regression equations for predicting the corrosion rates (mg/cm^2) by the type of metal are shown in Table 6. The results for aluminum showed significantly high rate of corrosion in Sohar area compared to the other four locations. With respect to time, the rate of corrosion increased by 1.23 mg/cm^2 per month in the first four months, then dropped to 1.19 mg/cm^2 per month during the fifth to the eighth month. Sohar area also recorded very high corrosion for copper (8.95 mg/cm^2) and brass (8.10 mg/cm^2). During the first four months, the corrosion rates for the two metals increased at the rates of 5.62 mg/cm^2 and 1.18 mg/cm^2 per month, respectively, indicating the very fast build-up in corrosion rate in copper during these months, compared to the other metals. No further corrosion appeared to take place in either brass or copper after the fourth month of exposure, at all locations.

The epoxy specimens exposed in Al-Fahl and in Al Khod area showed the least degradation compared to either Al Rusail or Sohar. The later contributed about 3 mg/cm2 of the corrosion rate. The rate of degradation per month for the first four months was about the same as that of brass, with no further change with time thereafter.

There were marked variations in corrosion rates of galvanized steel by locations. The specimens of the metal in Sohar area accumulated a maximum corrosion rate of 13.31 mg/cm^2, compared to those either in Al Khod or Al-Rusail, which were 9.56 mg/cm^2 and 6.59 mg/cm^2, respectively. The overall corrosion rate grew by 1.817 mg/cm^2 per month, for the first four months, with no further increase in the months that followed.

Mild steel showed the highest rate of corrosion among the seven metals under investigation. With the exception of the specimens in the airport area that had relatively low rates, the average corrosion rate for mild steel appeared to have risen very quickly to about 26 mg/cm^2 from the start of the exposure, and then increased at the monthly rate of 2.9 mg/cm^2 during the fifth to the eighth month. Stainless steel showed the best corrosion resistance property among all the metals. Its corrosion rate averaged 2.23mg/cm^2 for all locations, except for Sohar for which the average rose to 5.9mg/cm^2. There was no discernable effect of time on the material.

Overall, except for mild steel, Sohar industrial area had the highest degradation impact on the metal specimens, contributing to corrosion rates ranging from 2.1 mg/cm^2 for aluminum to a high of 9.0 mg/cm^2 for copper. For most metals the rates increased monthly for the first four months and remained unchanged by time thereafter. This could be due to the fact that, after the first few months build-up, the crusts of the corrosion may coat the metal specimens in such a way as to reduce their chance of further degradation. The coefficients of determination "R^2" for the regression equations ranged from as low as 0.28 for mild and stainless steel to 0.61 for copper, indicating much of the variations in the data are due to some variables not included in the analysis.

3.2.2. The chemical components of the corrosion

Tables 7 to 10 present the linear regression equations of the amounts of sulphates (ppm), chloride (ppm), carbonates (ppm) and nitrates (ppm) found on the different metals, as functions of locations and times of degradation. The highest deposit of sulphates, when adjusted for locations and length of exposure, was that of mild steel (21.8 ppm). For the other metal specimens, the deposits ranged from 10.9 ppm for copper, to 6.4 ppm for galvanized steel. The deposits due to locations were entirely from Al-Fahl. Here again, the deposit of sulphates for mild steel was the highest, at 42.0 ppm. Copper and stainless were next, with 17.5 ppm and 15.5 ppm, above the other locations, respectively (table 7). There were drops of about 2.3 ppm per month for aluminum and epoxy, after the fourth month of exposure. However, in all cases, the coefficients of determination of the regression equations were generally low, especially for galvanized steel..

Except for epoxy, mild steel, and to a less extent, stainless steel, there appeared to be no linear relationship between deposits of chlorides and either the locations or the length of times of exposure on the other metals (Table 8). Sohar and airport areas gave above average deposits of chlorides (ppm) for epoxy and mild steel specimens, respectively, and only small increase in the quantities per month, beginning from the fifth month of exposure. The coefficients of determination were again low especially for stainless steel. The results for carbonates were similar, indicating no linear relationship between carbonates deposit and the other variables for all metals, except for galvanized and mild steel, for which the strengths of the relationship were negligible (Table 9). The result is indication that the carbonate deposits were essentially constant, and only slightly higher for galvanized and mild steel, and in conformation with that found by the median polish method

Strong to moderate relationships was found to exist between the amounts of nitrate deposits (ppm) and the locations and the length of time of exposure, for all the seven metals (Table 10). Once again, mild steel tended to have the highest deposits, especially in the airport and Al-Khod areas. The levels for Sohar industrial area were slightly elevated for the other metals. There were also discernable increases per month of nitrate deposits over the two parts of the eight months period of exposure. These ranged from about 0.4 ppm to 0.8 ppm. The coefficient of determination, "R^2", is highest for epoxy coated steel specimens (0.86) and lowest for mild steel (0.42).

SUMMARY AND CONCLUSIONS

The atmospheric corrosion of seven common metals was studied at five different sites in Oman. The work was undertaken to investigate the corrosive effects on various types of the metals, of the type of locations, the length of time of exposure, and the pollutants. The results of the study indicated a wide variability of corrosion rates among the different metals. Mild steel and copper were found to be the most corroded of the seven metals, irrespective of the locations. The most resistant metals to corrosion were stainless steel, aluminum and epoxy, whereas galvanized iron and brass were found to have moderate corrosion rates. The geographical locations of test sites had much smaller impact on the rates. However, Sohar industrial area was the most corrosive site, relative to the other locations.

The study also showed that the corrosion for galvanized steel had the highest carbonates level, and the least levels were found in copper and stainless steel. In general, corrosion in both Al-Fahl and Al-Khod had the least levels of carbonates, whereas the industrial area of Al-Rusail had the highest. Overall, carbonates contents of corrosion were the highest for all the metals compared to those of the other chemical components present.

Corrosion from aluminum had slightly high amounts of chlorides relative to other metals, and the least were from copper. The results also showed a clear relationship between the amounts of chlorides and proximity to the coast. Slightly higher concentrations of chlorides were observed in the Airport and Sohar area which are close to the sea shore.

The atmosphere at Al-fahl appeared to have been heavily polluted by sulphur compounds. Corrosion of all metals at Al-Fahl contained high amounts of sulphates, especially for mild steel. In the case of nitrates, substantial differences were found only in the effects of metal types. The metals least corroded by nitrates were stainless steel, epoxy, aluminium, and galvanized steel.

Further confirmation of these results were obtained by using the multiple linear regression techniques, this time by including the effect of lengths of period of exposure as independent variables in addition to location. For most metals, it was found that the rates of corrosion tended to increase monthly for the first four months and then remained unchanged thereafter. however, the coefficients of determination for the regression equations obtained were generally low. This may be attributed to other unknown variables that influence corrosion and were not considered in the statistical treatment. Regression equations, with locations and times of exposure as independent variables, were also obtained for the four chemical components, yielding results along the line summarized above.

Overall, the results of both analyses indicated that, stainless steel, aluminum and epoxy were the most suitable metals to use in the locations considered in the study, as they are the least corrosive under the atmospheric conditions prevailing in those sites. In the case of copper, it was found that the severity of corrosion in marine atmosphere is somewhat less than that in industrial atmosphere. The results for epoxy suggests that it can play an important role in lowering the corrosion level of mild steel.

The results of this study can prove useful in establishing the basis for future monitoring of locations following, for instance, a program of reduction in pollutant emissions. Furthermore, planners may use the results in carrying out major construction projects. Relevant authorities may also find the results of some use to determine the type of metals in constructing outdoor structures.

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Table 1a
The sum of corrosion rates (mg/cm^2) over the study period by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw effect**
Aluminum	37	41	36	42	56	41
Brass	63	79	62	42	126	63
Copper	146	147	168	174	230	168
Epoxy	43	24	12	45	67	43
Galvanized	90	88	165	142	195	142
Mild steel	144	225	207	210	210	210
Stainless steel	10	13	21	28	47	21

Table 1b
The final result of the median polish for the corrosion rates (mg/cm^2) over the study period by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw effect**
Aluminum	7	8	-4	0	-11	**-22**
Brass	11	24	0	-22	37	**0**
Copper	-11	-13	1	5	36	**105**
Epoxy	11	-11	-30	1	-2	**-20**
Galvanized	-41	-46	24	-1	27	**79**
Mild steel	-55	23	-2	-1	-26	**147**
Stainless steel	0	0	1	6	0.0	**-42**
Column effect	**-11**	**-8**	**1**	**1**	**26**	**63**

Table 2a
The sum of sulphates (ppm) over the study period by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw Effect**
Aluminum	39	101	56	60	49	56
Brass	73	160	49	77	71	73
Copper	105	227	74	82	88	88
Epoxy	33	109	47	51	55	51
Galvanized	38	95	43	50	72	50
Mild steel	238	511	98	171	190	190
Stainless steel	62	207	55	106	110	106

Table 2b
The final result of the median polish for the sulphates (ppm) over the study period by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw Effect**
Aluminum	-5	-42	14	4	-7	**-17**
Brass	12	0	-10	4	-2	**0**
Copper	29	52	0	-6	0	**15**
Epoxy	-6	-29	10	0	4	**-22**
Galvanized	0	-42	7	0	22	**-23**
Mild steel	60	234	-78	-19	0	**117**
Stainless steel	-32	14	-37	0	4	**33**
Column effect	**-12**	**87**	**-14**	**0**	**0**	**73**

Table 3a
The sum of chlorides (ppm) over the study period by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw effect**
Aluminum	97	88	91	87	105	91
Brass	80	83	81	88	90	83
Copper	80	77	78	80	90	80
Epoxy	93	87	79	84	101	87
Galvanized	91	77	82	78	88	82
Mild steel	99	87	81	81	87	87
Stainless steel	75	84	81	81	89	81

Table 3b
The final result of the median polish for the chlorides (ppm) over the study period by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw effect**
Aluminum	0	-3	0	-1	6	**8**
Brass	-9	0	2	8	-1	**0**
Copper	-4	-1	0	5	4	**-5**
Epoxy	0	0	-8	0	6	**4**
Galvanized	4	-4	1	0	-1	**-2**
Mild steel	9	3	-3	0	-5	**1**
Stainless steel	-12	3	0	3	0	**-1**
Column effect	**6**	**0**	**0**	**-3**	**8**	**83**

Table 4a
The sum of carbonates (ppm) over the study period by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw effect**
Aluminum	136	126	138	141	145	138
Brass	134	106	126	145	143	134
Copper	129	105	122	138	142	129
Epoxy	147	140	136	162	134	140
Galvanized	155	139	100	158	142	142
Mild steel	135	141	130	138	139	138
Stainless steel	130	119	119	139	131	130

Table 4b
The final result of the median polish for the carbonates (ppm) over the study period by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw effect**
Aluminum	-1	0	9	-5	7	**-1**
Brass	0	-17	0	2	8	**-4**
Copper	0	-13	1	0	12	**-9**
Epoxy	0	4	-3	6	-14	**9**
Galvanized	6	1	-41	0	-8	**11**
Mild steel	-3	14	0	-9	0	**0**
Stainless steel	0	0	-3	0	0	**-8**
Column effect	**0**	**-11**	**-8**	**9**	**1**	**138**

Table 5a
The sum of nitrates (ppm) over the period of study by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw Effect**
Aluminum	32	30	31	32	44	32
Brass	36	36	36	41	47	36
Copper	49	50	61	45	55	50
Epoxy	30	35	31	33	37	33
Galvanized	28	28	30	30	35	30
Mild steel	117	61	93	82	72	82
Stainless steel	29	31	36	28	37	31

Table 5b
The final result of the median polish for the nitrates (ppm) over the study period by metal type and location

	Airport	Al-Fahl	Al-Khod	Al-Rusail	Sohar	**Raw Effect**
Aluminum	1	-2	0	0	7	**-1**
Brass	1	0	1	5	6	**3**
Copper	0	0	12	-5	0	**17**
Epoxy	-2	2	-1	0	-1	**0**
Galvanized	-1	-2	1	0	0	**-3**
Mild steel	36	-21	12	0	-15	**49**
Stainless steel	1	0	6	-3	1	**-2**
Column effect	**-1**	**0**	**-1**	**0**	**5**	**33**

Table 6

The multiple linear regression equations for the corrosion rate (mg/cm^2) by type of metal

No.	Metal type	Model	R^2
1	Aluminum	-0.62 + 2.09 (Sohar) + 1.23 (month14) + 1.19 (month58)	0.572
2	Brass	0.92 + 8.10 (Sohar) + 1.81 (month14)	0.443
3	Copper	-1.22 + 8.95 (Sohar) + 5.62 (month14)	0.611
4	Epoxy	1.18 – 2.52 (Al-Fahl) – 4.032 (Al-Khod) + 2.93 (Sohar) + 1.15 (momth14)	0.535
5	Galvanized	4.29 + 9.56 (Al-Khod) + 6.59 (Al-Rusail) + 13.31 (Sohar) + 1.817 (month14)	0.427
6	Mild steel	26.59 – 8.58 (Airport) + 2.87 (month58)	0.277
7	Stainless steel	2.23 + 3.70 (Sohar)	0.283

Table 7
The multiple linear regression equations for the sulphates (ppm) by type of metal

No.	Metal type	Model	R^2
1	Aluminum	8.06 + 6.25 (Al-Fahl) – 2.25 (month58)	0.207
2	Brass	8.46 + 11.49 (Al-Fahl)	0.343
3	Copper	10.89 + 17.53 (Al-Fahl)	0.403
4	Epoxy	7.51 + 7.86 (Al-Fahl) – 2.32 (month58)	0.254
5	Galvanized	6.35 + 5.49 (Al-Fahl)	0.095
6	Mild steel	21.79 + 42.02 (Al-Fahl)	0.510
7	Stainless steel	10.41 + 15.51 (Al-Fahl)	0.452

Table 8
The multiple linear regression equations for chlorides (ppm) by type of metal
(Only metals that have an equation appear in the table)

No.	Metal type	Model	R^2
1	Epoxy	10.19 + 1.88 (Sohar) + 0.70 (month58)	0.273
2	Mild steel	9.88 + 1.83 (Airport) + 0.82 (month58)	0.418
3	Stainless steel	9.78 + 0.67 (Al-Fahl)	0.159

Table 9
The multiple linear regression equations for carbonates (ppm) by type of metal
(Only metals that have an equation appear in the table)

No.	Metal type	Model	R^2
1	Galvanized	18.58 – 6.04 (Al-Khodl)	0.162
2	Mild steel	22.24 – 1.38 (month14)	0.125

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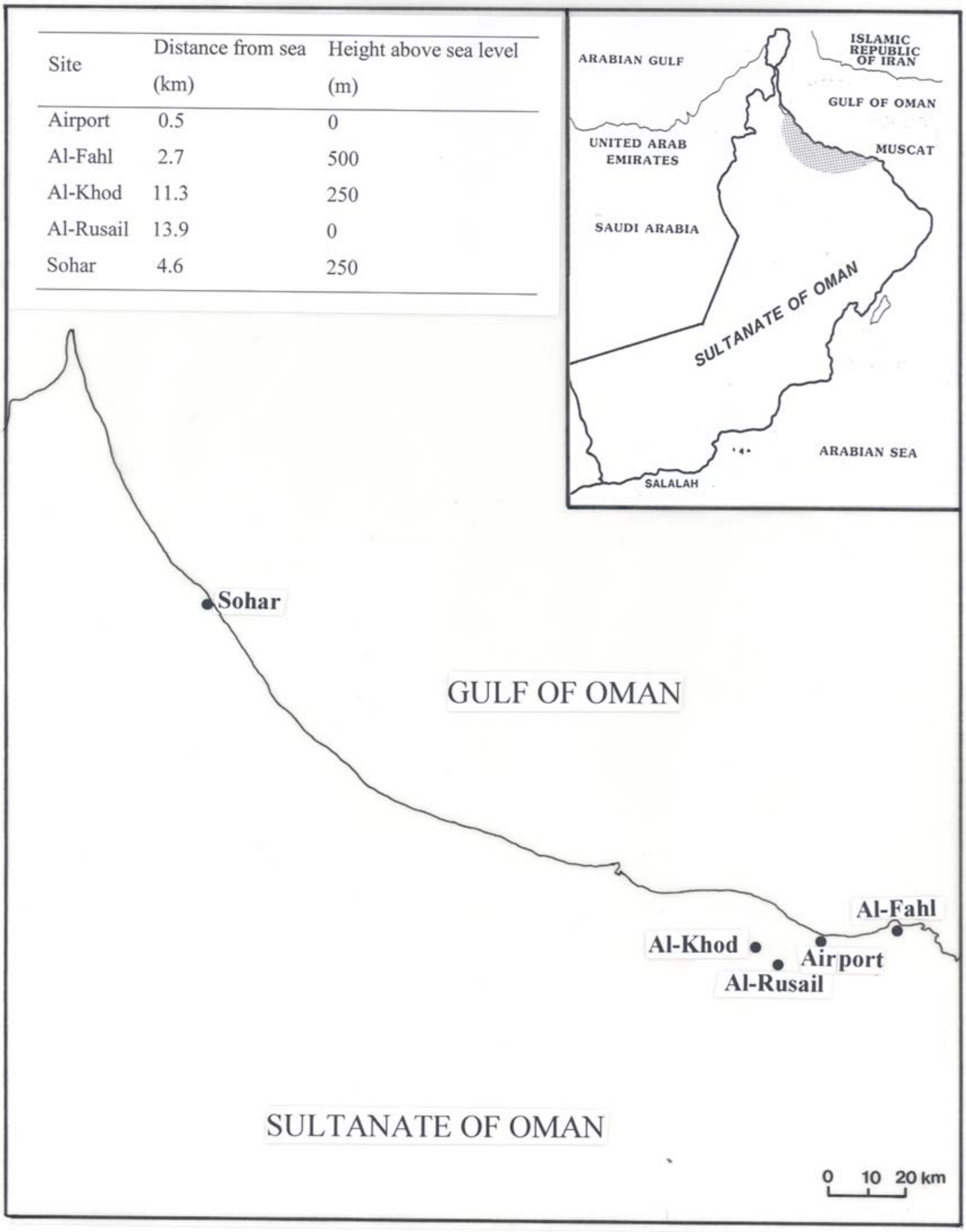
Table 10
The multiple linear regression equations for nitrates (ppm) by type of metal

No.	Metal type	Model	R^2
1	Aluminum	2.33 + 1.61 (Sohar) + 0.31 (month14) + 0.51 (month58)	0.639
2	Brass	2.92 + 0.60 (Al-Rusail) + 1.36 (Sohar) + 0.31 (month14) + 0.56 (month58)	0.710
3	Copper	5.4 + 1.68 (Al-Khod) + 0.87 (Sohar) + 0.81 (month58)	0.518
4	Epoxy	3.76 + 0.52 (Sohar) + 0.39 (month58)	0.862
5	Galvanized	2.76 + 0.77 (Sohar) + 0.38 (month58)	0.678
6	Mild steel	12.87 + 5.68 (Airport) + 2.69 (Al-Khod) – 1.05 (month14)	0.419
7	Stainless steel	3.34 + 0.81 (Al-Khod) + 0.97 (Sohar) + 0.48 (month58)	0.517



Site	Distance from sea (km)	Height above sea level (m)
Airport	0.5	0
Al-Fahl	2.7	500
Al-Khod	11.3	250
Al-Rusail	13.9	0
Sohar	4.6	250

Fig. 1. Location of the exposure sites in relation to Muscat city and other areas of Oman.

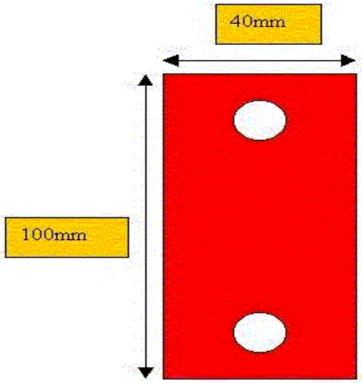


Fig. 2. Atmospheric-corrosion test rack.