Chapter 26 – ENVIRONMENTAL SEVERITY ASSESSMENT AND AIRCRAFT WASH OPTIMIZATION

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26.1 INTRODUCTION

Removing salt deposits on aircraft is an important component of a successful corrosion maintenance program and this is particularly true for equipment operated in marine environments. Both rinsing and washing aim at preventing corrosion damage by reducing the surface concentration of corrosive agents on aircraft exterior surfaces. While rinsing is a relatively simple operation typically carried out by taxiing through a "bird bath" upon returning from a mission, as illustrated in Figure 26-1, the washing process is much more complex and often carried out in special hangars.

Figure 26-1: A C-130J Hercules is Cleaned Up in the New "Bird-Bath" System at Keesler Air Force Base, Biloxi, Mississippi. Aircraft from the Air Force Reserve fly many hours over the Gulf of Mexico. Salt and moisture could lead to corrosion if aircraft are not kept clean. (U.S. Air Force photo / Tech Sgt. Jame Pritchett).

The question of how frequently to wash aircraft is one of the many management decisions on minimizing the total cost of asset maintenance. Washing an aircraft directly incurs costs while not washing an aircraft indirectly incurs costs from future corrosion damage. Reducing the period between washes may reduce the cost of corrosion damage but increases the cost of washing.

26.2 ENVIRONMENTAL SEVERITY ASSESSMENT

26.2.1 USAF Environmental Severity Index (ESI)

An environmental assessment scheme based on atmospheric parameters has been developed for the United States Air Force (USAF) by Summitt and Fink as early as 1980 [1]. The scheme, code named PACER LIME, was constructed on the parametrically fitted corrosion behaviour of aircraft materials such as uncoated aluminum, steel, titanium and magnesium alloys. The ESI rankings were based on four parameters: proximity to the sea, total particulate level, sulphur dioxide concentration and amount of rainfall. An important advantage of this approach was that required data were typically available at most weather stations. The section of the Corrosion Damage Algorithm (CDA) presented in Figure 26-2, for example, considers distance to salt water, leading either to the very severe AA rating or lesser ratings based on a consideration of moisture factors. An algorithm for aircraft washing based on similar corrosivity considerations is presented in Figure 26-3.

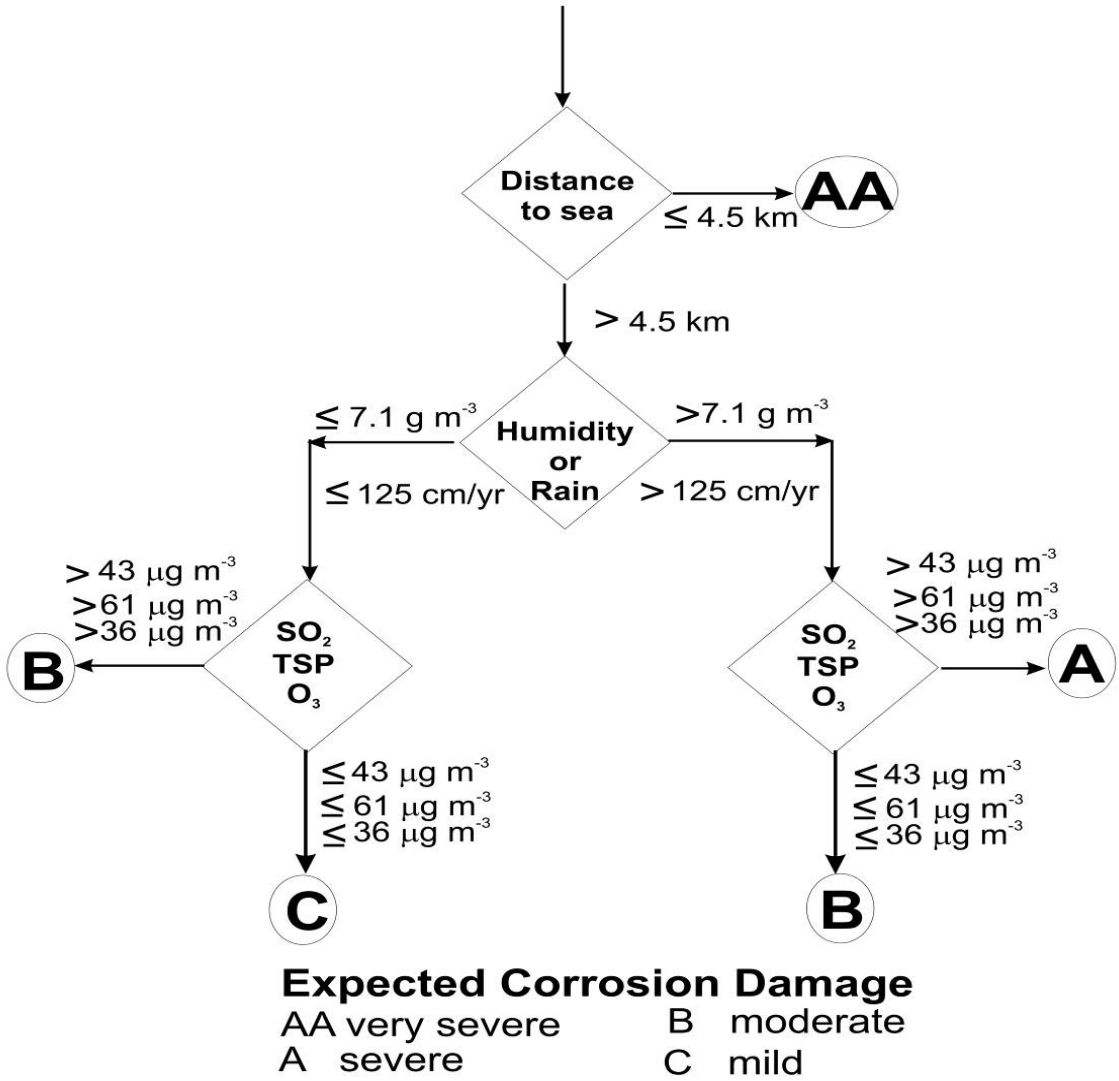


Figure 26-2: Section of the Corrosion Damage Algorithm that Considers Distance to Salt Water, Leading Either to the Very Severe AA Rating or a Consideration of Moisture.

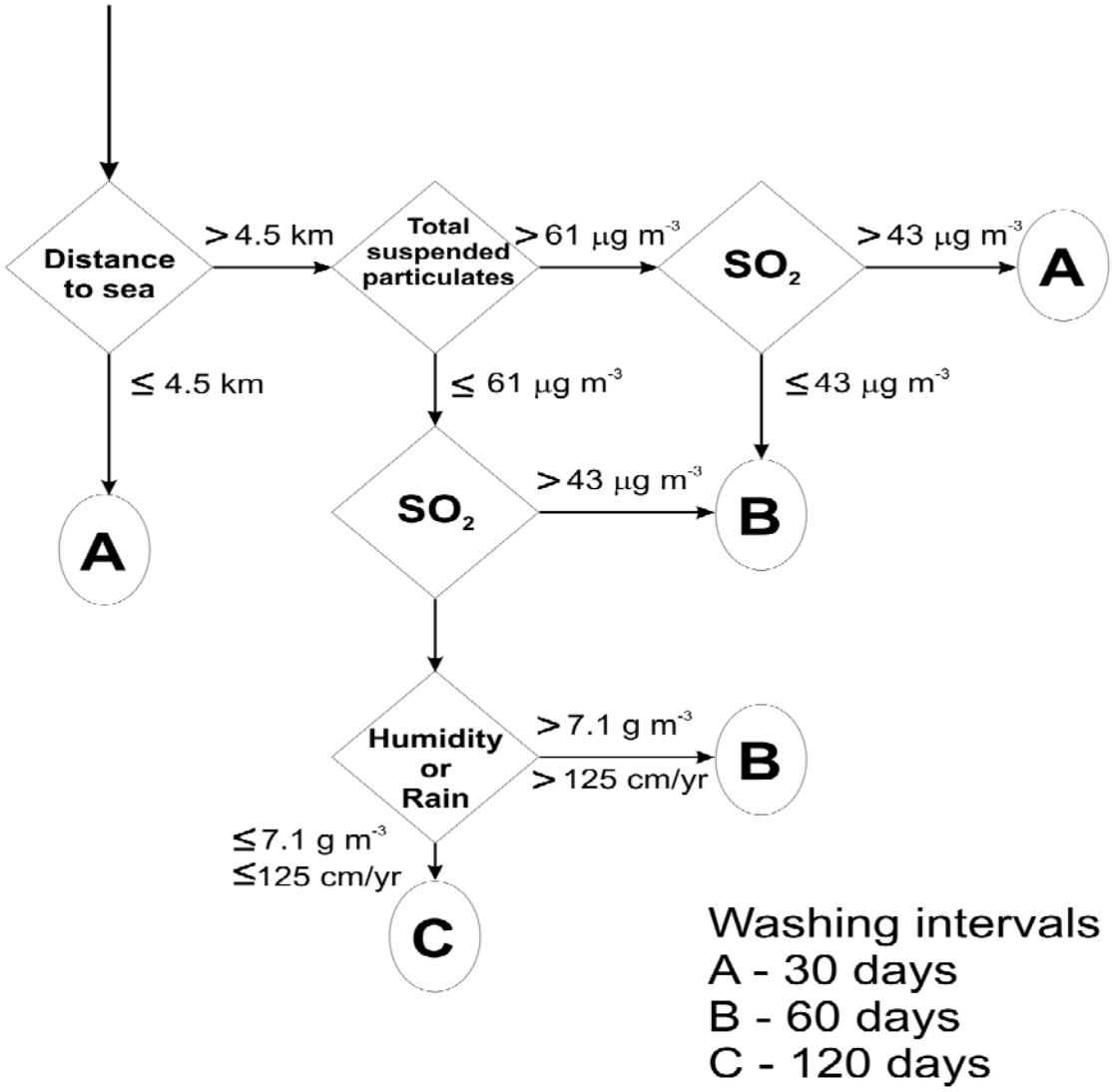


Figure 26-3: Section of the Corrosion Damage Algorithm for Planning a Washing Schedule.

The environmental corrosivity, predicted from the CDA algorithm, of six marine air bases has been compared to the actual corrosion maintenance effort expended at each base. Considering the simplicity of the algorithms and simplifying assumptions in obtaining relevant environmental and maintenance data the correlation obtained was considered to be reasonable. However, subsequent attempts to enhance the PACER LIME algorithm by using the results obtained from broad based corrosion testing programs failed to provide enough differentiation between moderately corrosive environments [2].

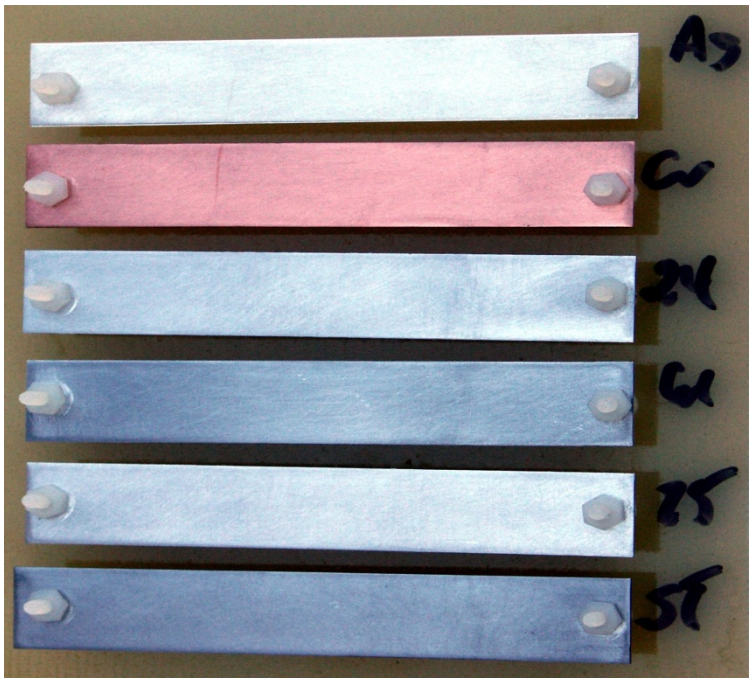
In order to remedy the deficiencies in the CDA scheme, Battelle was tasked to monitor the atmospheric corrosivity of Air Force and other sites worldwide [3]. The database describing the relative corrosive severity levels of different locations and actual corrosion rates of a variety of metals has now grown to more than 100 sites worldwide. The following metals were included in that study: three aluminum alloys (A92024, A96061, and A97075), copper, silver and steel.

Data have been collected for metals directly exposed to the outdoor environment in a standard sample mounting configuration and test package. A typical plastic test rack with its metallic coupons is shown in

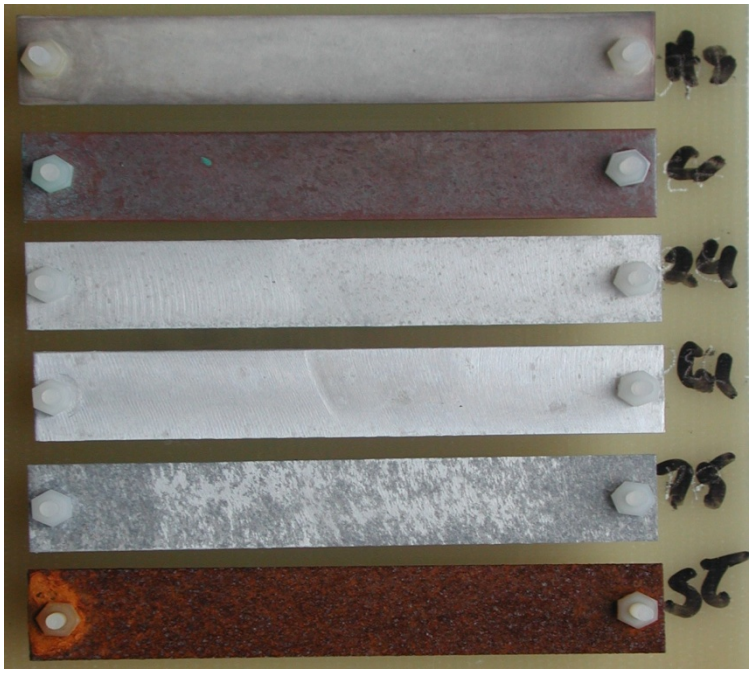
Figure 26-4 besides a CLIMAT coupon[1] exposed at the Kennedy Space Center (KSC) beach corrosion test site, a test site renowned for having the highest corrosivity in the continental United States [6]. Figure 26-5(a) shows a close-up view of the coupons before exposure. Once exposed to the environment for a given period of time the corroded metal strips (Figure 26-5(b)) are sent back to the laboratory for mass loss measurements following standard methods [7] and further analysis.

Figure 26-4: Metal Coupons in a Plastic Test Rack Exposed at the Kennedy Space Center Beach Corrosion Test Site Besides a CLIMAT Coupon (Courtesy of Battelle).

[1] The use of bimetallic specimens in which a helical A91100 aluminum wire is wrapped around a coarsely threaded bolt is described as the Classify Industrial and Marine Atmospheres (CLIMAT) coupon [4],[5].



(a)



(b)

Figure 26-5: Metal Coupons Before Exposure to the Environment (a) and After a Three Month Exposure in a Rural Environment (b) (Courtesy of Battelle).

These efforts established a correlation between the corrosivity of various Air Force Base environments and the costs associated with the maintenance of various aircraft. Figure 26-6 summarizes three years of corrosion data compared to maintenance records taken directly from the Air Force database (REMIS). It has now been shown that there is a relatively good correlation between base level ESI values and base

level corrosion related maintenance [3]. Not only is the correlation surprisingly good, but it also appears to be intuitively correct to show a definite effect of size of the aircraft and surface area.

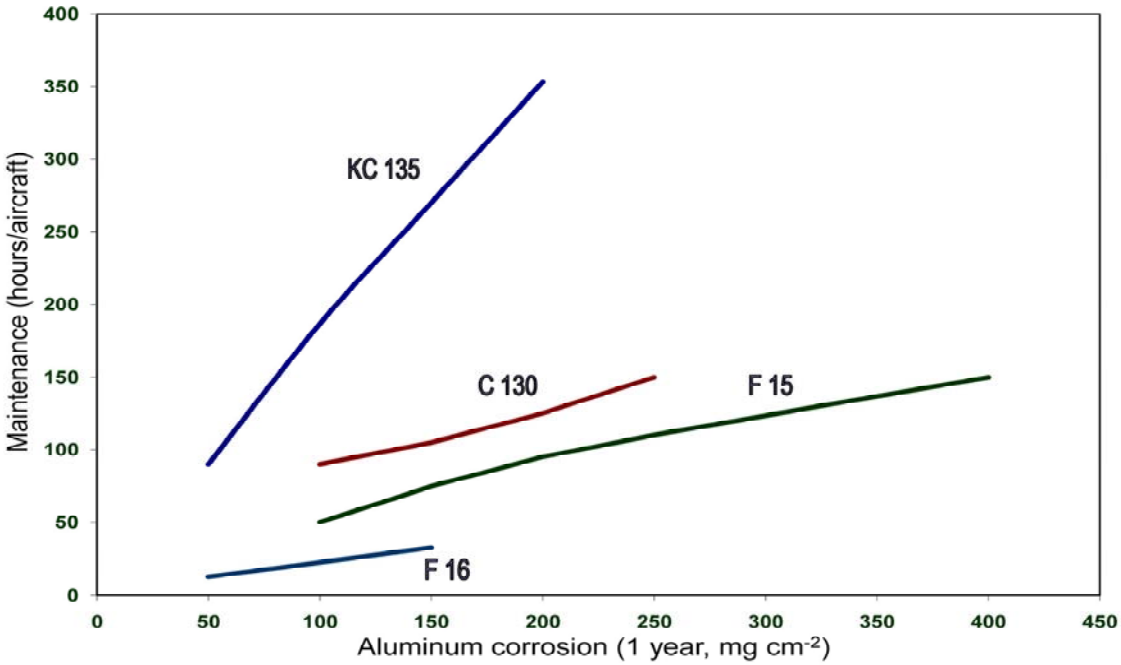


Figure 26-6: Maintenance Costs for Various Aircraft as a Function of the Corrosivity of Air Force Base Environments Towards the Corrosion of Aluminum (KC 135 is the re-fueling support aircraft; CC130 is the Hercules airlift mission aircraft; F15 and F16 are fighter aircraft).

26.2.2 International Organization for Standardization (ISO) Classification Scheme

A scheme widely accepted by architects and designers for the classification of outdoor environments has been developed by a Working Group (WG 4) of the International Organization for Standardization (ISO) corrosion Technical Committee (TC 156) [8].

In the program nicknamed ISO CORRAG, specially prepared coupons of steel, copper, zinc, and aluminum were exposed for 1, 2, 4, and 8 years at 51 sites located in 14 nations in order to generate the necessary data for predicting atmospheric corrosivity from commonly available weather data [9]. Triplicate specimens were used for each exposure. The program was initiated in 1986 and terminated in 1998. After a planned exposure, each specimen was sent to the laboratory that had done the initial weighing for cleaning and evaluation. Based on these data, a simple classification scheme of five corrosivity classes was established for each metal (Table 26-1). The environmental and weather data gathered in this program were based on SO_2, and Cl^- deposition rates combined with Time Of Wetness (TOW)[2] measurements at each site. These five corrosivity categories can be roughly translated into five outdoor situations in the following decreasing order of corrosivity, i.e., industrial, tropical marine, temperate marine, urban, and rural.

[2] Time spent above 80% relative humidity (RH). TOW is typically expressed in number of hours above 80% RH in one month or in one year.

Table 26-1: ISO 9223 Corrosion Rates After One Year of Exposure Predicted for Different Corrosivity Classes.

Corrosion Category	Steel (g/m^2 year)	Copper (g/m^2 year)	Aluminum (g/m^2 year)	Zinc (g/m^2 year)
C1	= 10	= 0.9	Negligible	= 0.7
C2	11 – 200	0.9 – 5	= 0.6	0.7 – 5
C3	201 – 400	5 – 12	0.6 – 2	5 – 15
C4	401 – 650	12 – 25	2 – 5	15 – 30
C5	651 – 1500	25 – 50	5 – 10	30 – 60

26.2.3 Seasonal and Local Variations

While the data gathered for the development of these two classification schemes are from relatively well characterized locations, the actual information on topographical or other local variables is not considered in the general assessment. Similarly no effort is spent in these general schemes to include seasonal variations that may also vary greatly at each location.

In a study focused on the shielding effects due to buildings in a marine environment, the directional impact of marine aerosols was revealed by comparing the level of patina on copper rods of CLIMAT coupons exposed for three winter months at a facility on the Pacific coast [10],[11]. What became evident in that study was that the pattern of the bluish-green patina attributed to the corrosion product $CuCl_2.2H_2O$ was not uniformly distributed around the circumference of each copper rod.

A template with the sixteen points of the compass was placed on the outside of each boldly exposed coupon in order to visually quantify the intensity of the bluish-green color. The relative degree of corrosion for each compass point was assessed by assigning a number between zero and ten with zero corresponding to zero bluish-green patina and ten corresponding to 100% coverage of the coloured corrosion product. The average corrosion index for each of the sixteen points of the compass for the copper rods is shown in Figure 26-7. One attempt to correlate the directional corrosivity observed on the copper rods with weather data was to plot the fraction of time that winds came from the sixteen points of the compass during the three-month exposure period. The dominant direction was the north to north-east. However, the pattern of corrosion product did not correspond to the most frequent wind direction but did correspond to the direction with the highest wind speeds, which were in the west to south quadrant at this particular site (Figure 26-7).

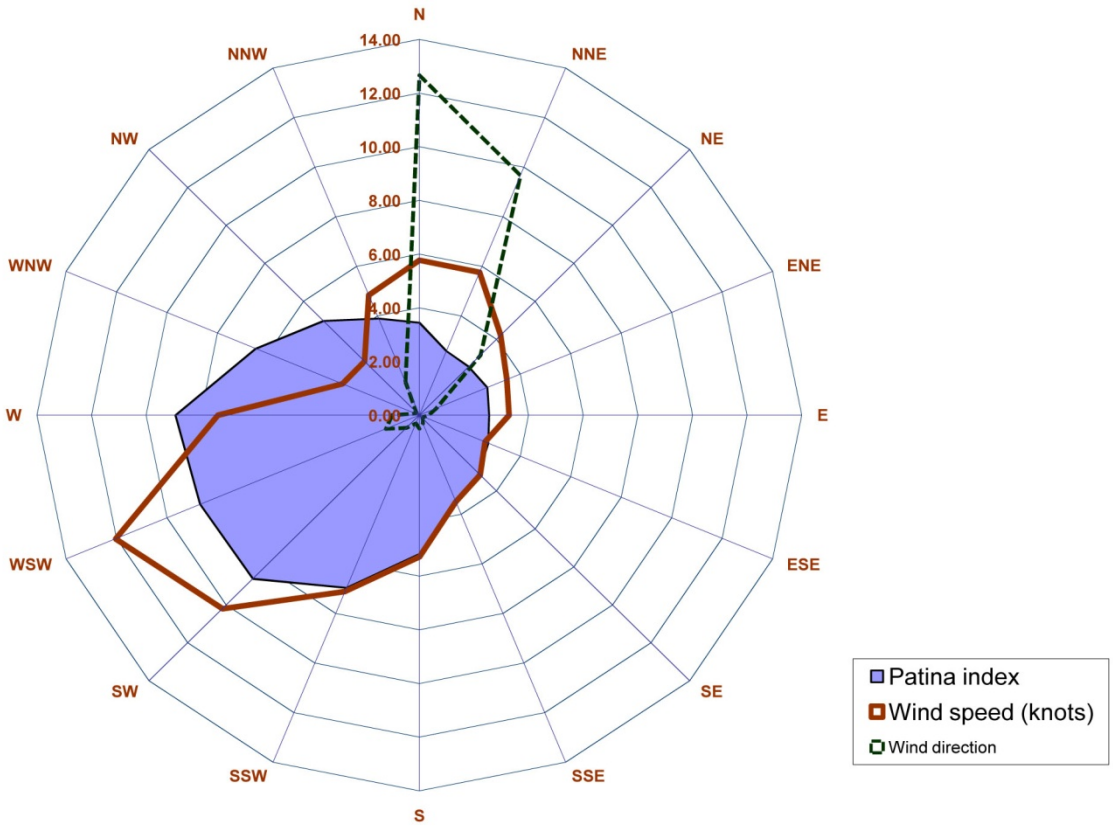


Figure 26-7: Average Corrosion Index for the Copper Rods Exposed on the Rooftop and the Average Wind Speed Recorded at the Local Weather Station as a Function of the Sixteen Points of the Compass.

This is consistent with observations made by others that a minimum wind speed or threshold of approximately 11 km h^{-1} is required for the entrainment of marine aerosols over a salt-water body [12].

26.3 WASH COSTS OPTIMIZATION

The conclusions of an experimental study on the effects of wash intervals on corrosion indicate that the relative benefit of washing increases with increasing severity of the environment [13]. One recommendation of the study was also that while wash intervals in severe environments should not be relaxed and maintained at a minimum of 30 days, wash cycles in mild environments on the other hand could be relaxed beyond 120 days. Following this study, each air base was assigned an Environmental Severity Index (ESI), i.e., either mild, moderate or severe. The wash period and certain maintenance work was then scheduled according to the ESI. Some wash periods currently assigned to a sample of air bases by the USAF are shown in Table 26-2 [14].

Table 26-2: Wash Periods Assigned to Sample of Bases According to Environmental Severity.

Air Base Name and Location	Wash Period by Severity		
	Severe (One Month)	Moderate (Three Months)	Mild (Four Months)
Aj Taif, SA			X
Allen C. Thompson Fld., Jackson, MS			X
Altus AFB, OK			X
As Sulayyil, SA			X
Anderson AFB, GU	X		
Anchorage IAP, AK			X
Bagram AB, Afghanistan		X	
Bahrain	X		
Bangor IAP, ME			X
Barksdale AFB, Shreveport, LA			X

Determining an optimal aircraft wash interval requires combining a model for damage due to atmospheric corrosion and economic factors. Cumulative metal loss under atmospheric conditions is generally found to follow a power law or bi-logarithmic relationship with exposure time [15],[17]:

$$C = Kt^n \tag{1}$$

where C is the cumulative metal loss, t is the exposure time, K is a constant specific to a location and n is an exponent. The fitted value of the exponent is a rough indicator of the corrosion mechanism. An exponent of 0.5 is consistent with the corrosion rate being dependent on diffusion through a protective film that grows as corrosion proceeds. An exponent of unity is consistent with a corrosion rate that is independent of corrosion products accumulated on a surface. Typically, the exponent is between 0.5 and unity [15]. The rate constant, K, depends on the atmospheric corrosivity [16],[17]. If one assumes that corrosion-related maintenance required on aircraft follows the law of equation (1), a cumulative metal loss may now be expressed as equation (2):

$$M = kt^n \tag{2}$$

where M is the corrosion-related maintenance required and k is a constant, analogous to K in equation (1). M is expected to increase with time until periodic maintenance brings accumulated damage down to a lower level. As washing was shown to decrease the cumulative corrosion damage of coupons [13], aircraft washing is expected to decrease required maintenance. Figure 26-8 illustrates these concepts qualitatively.

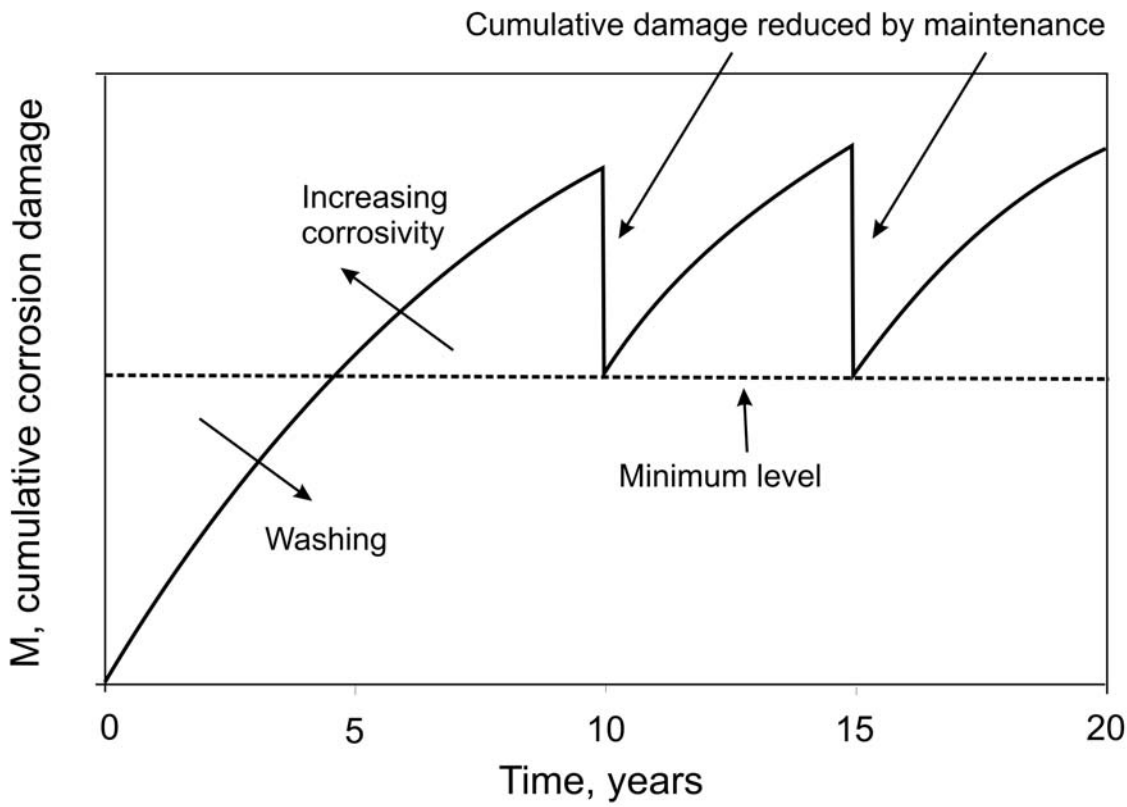


Figure 26-8: Schematic of Cumulative Corrosion Damage on Aircraft as a Function of Time.

The data available for M, and thus for estimating k and n, is limited to periodic maintenance records. The maintenance records of three phases for a fleet of marine patrol aircraft are listed in Table 26-3. Each phase corresponds to a Depot Level Inspection and Repair (DLIR). There was no corrosion-related maintenance at phase 1 DLIR for any aircraft. The number of flight hours, months since the last DLIR, number of non-corrosion related man-hours required and the number of corrosion-related man-hours are listed for each of eighteen aircraft. The parameters for modeling the level of required maintenance may be extracted from such data with the following assumptions:

1) Each periodic maintenance effort brings the overall level of required maintenance down to a lower level as shown in Figure 26-8.
2) The exponent, n, is assumed to be between 0.5 and unity.
3) The rate constant is assumed to increase with atmospheric corrosivity and wash interval as expressed in equation (3):

$$k = k_M c T_{wash} \tag{3}$$

where c is a measure of atmospheric corrosivity, T_{wash} is the wash interval and k_M is a characteristic maintenance rate constant.

Table 26-3: Periodic Inspection and Repair Records for Marine Air Patrol Fleet.

No.	Flt Hrs	Months Since Last Phase	Non-Corrosion Hrs	Corrosion Hrs
Phase 2				
1	4918	50	6239	656
2	5311	55	4706	729
3	5779	61	8249	3550
4	5531	56	5864	847
5	4665	52	5165	684
6	5374	57	7044	977
7	3339	35	6737	546
8	4487	43	6272	1010
9	4652	53	6576	585
10	5111	54	6154	651
11	5041	50	6736	737
12	5591	59	6888	723
13	4771	54	7210	1218
14	5194	59	12277	1856
15	5043	54	8145	1481
16	5432	57	6300	1145
17	5129	52	5182	341
18	5648	60	5984	824
Phase 3				
1	4674	52	7824	1455
2	4449	50	7681	1681
3	3269	37	5308	1107
4	4324	48	5379	1704
5	4266	49	6818	1425
6	3812	48	5653	1010
7	4766	51	5948	1326
8	4680	54	10171	3479
9	5001	50	6274	1472
10	3093	41	5493	689
11	4321	50	5175	1189
12	3055	39	8160	1155
13	5021	54	6763	1690
14	3343	41	6444	1647
15	2995	42	7622	1429
16	3704	51	7956	1609
17	4384	52	6156	1297
18	2954	41	6980	1022

No.	Flt Hrs	Months Since Last Phase	Non-Corrosion Hrs	Corrosion Hrs
Phase 4				
1	3479	53	7682	1109
2	3119	59	12949	2129
3	3732	57	9940	1746
4	3652	58	11452	1377
5	3723	54	6838	951
6	–	–	–	–
7	4124	60	8931	1231
8	3849	55	7316	1204
9	3445	55	7314	1046
10	–	–	–	–
11	3688	58	9091	1841
12	–	–	–	–
13	3428	58	11760	1961
14	3083	61	12558	2955
15	–	–	–	–
16	–	–	–	–
17	3712	57	6525	987
18	–	–	–	–

With these assumptions, k_M can be extracted by combining equations (2) and (3) for each phase and each aircraft according to equation (4):

$$k_M = \frac{M - M_{acceptable}}{cT_{wash}T_{DLIR}^{0.75}} \tag{4}$$

where T_{DLIR} is the number of months in each phase between DLIR and $M\text{-}M_{acceptable}$ is the amount of maintenance applied at a DLIR phase as measured in man-hours. This method requires a measure of atmospheric corrosivity, c, that the planes are exposed to. Any method will do as long as the same method is used for calculating the wash interval as described below.

In the present study, the ground-level corrosivity has been measured for several years using CLIMAT coupons at the home base for this fleet. Figure 26-9 shows the monthly corrosivity at CFB Greenwood, Nova Scotia averaged over three years. As indicated in Figure 26-10, the airfield at CFB Greenwood is only eight km from the Bay of Fundy and downwind from the highest speed winds of winter.

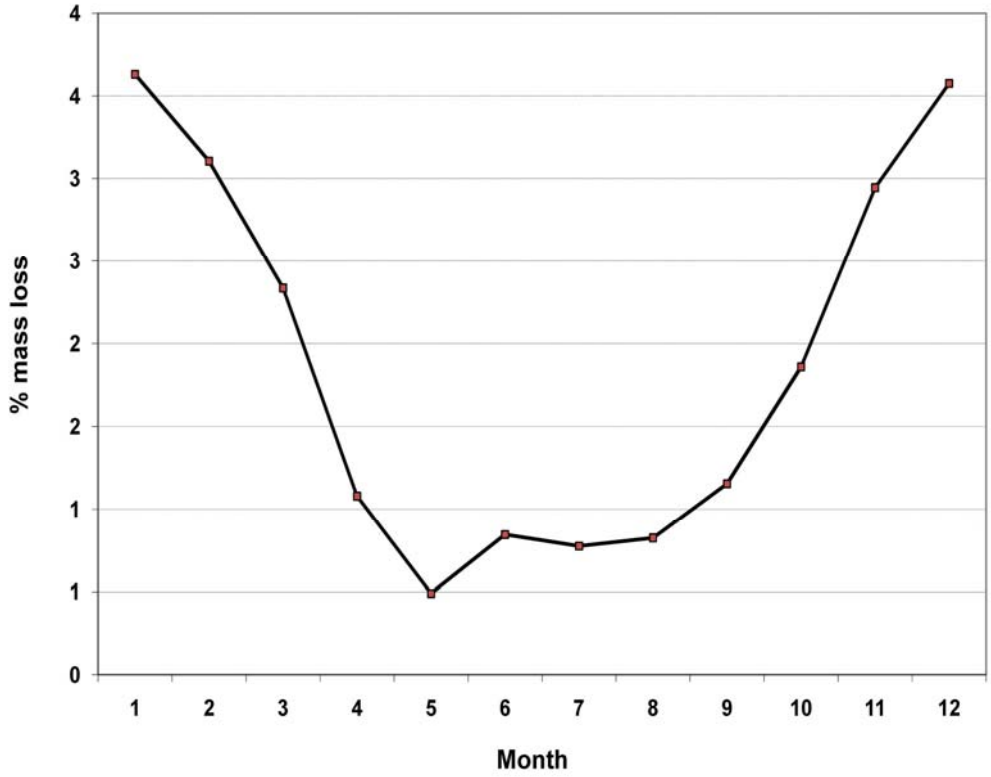


Figure 26-9: Monthly Corrosivity at Canadian Forces Base (CFB) Greenwood, Nova Scotia, as Mass Loss of CLIMAT Coupons Between 2002 and 2006.

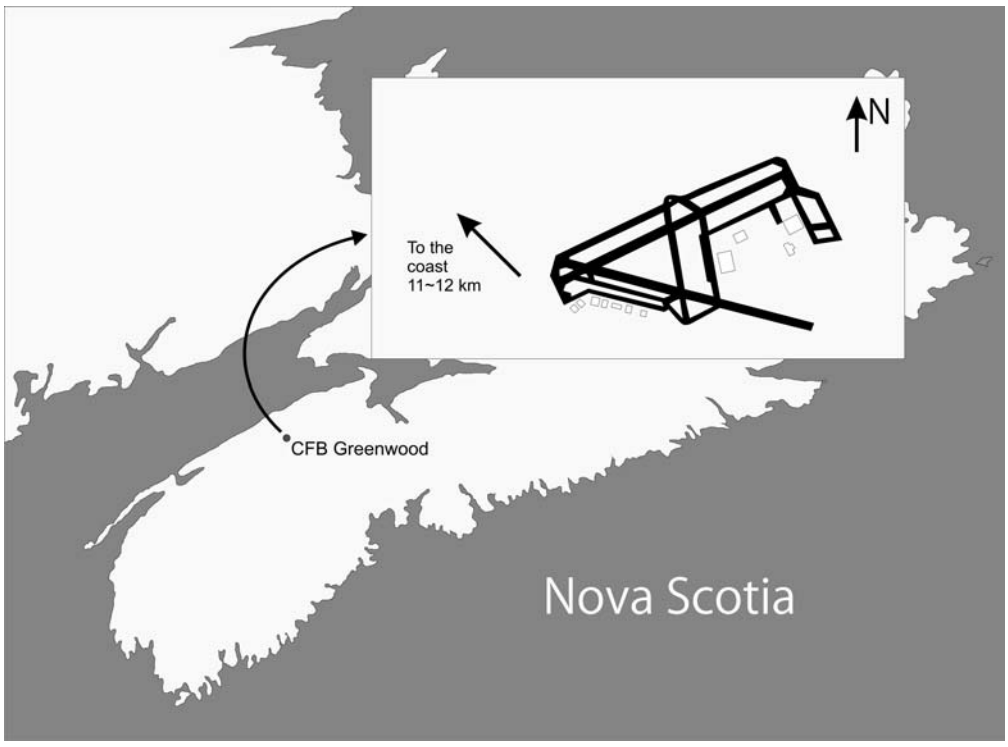


Figure 26-10: Geographical Position of CFB Greenwood in Nova Scotia and in Relation to the Sea.

Month 1 and month 12 in Figure 26-9 correspond respectively to January and December. The corrosivity is highest in the winter and lowest in the summer. The units of k_M with CLIMAT coupons as the measure of corrosivity are man-hours/(CLIMAT mass loss x month$^{1.75}$) or man-hours'.

The maintenance factor, k_M, for each aircraft after each phase is listed in Table 26-4. The average CLIMAT corrosivity of 1.69% and the wash interval was 1 month. The 95% confidence intervals for the average k_M are 21 – 40, 40 – 55 and 36 – 51 man-hours' for Phases 2, 3 and 4 respectively.

Table 26-4: Estimates for Time Averaged k_M Based on Periodic Inspection and Repair Records in Table 26-3 and Equation (3).

	Phase 2	Phase 3	Phase 4
Plane	**k_M, Man-Hours'**	**k_M, Man-Hours'**	**k_M, Man-Hours'**
1	20.6	44.5	33.4
2	21.3	52.9	59.2
3	96.2	43.7	49.8
4	24.5	55.3	38.8
5	20.9	45.5	28.2
6	27.9	32.8	
7	22.4	41.1	33.8
8	35.6	103.3	35.3
9	17.6	46.3	30.6
10	19.3	25.2	
11	23.2	37.4	51.8
12	20.1	43.8	
13	36.2	50.2	55.2
14	51.6	60.1	80.1
15	44.0	51.2	
16	32.6	49.9	
17	10.4	39.6	28.2
18	22.6	37.3	
Average	30.4	47.8	43.7
Std Deviation	19.3	16.2	15.8
95% Confidence	21.3 – 39.5	40.1 – 55.4	36.2 – 51.1

*Also included are the average, standard deviation and 95% confidence interval for the average.

The maintenance factor for another fleet was calculated from a different but limited set of data. This fleet was stationed at an inland base at Trenton, Ontario. The average yearly corrosivity as measured by CLIMAT coupons was 0.3%. The average number of man-hours at a DLIR after a phase of 66 months from three aircraft was 4473 man-hours for corrosion related maintenance. Given an average wash interval of 13 months, the maintenance factor was 50 man-hours'. The closeness of this value to that for the marine patrol fleet, even with much different values for corrosivity and wash interval, hints that this range of values for k_M may have some general applicability.

In order to develop a model for calculating an optimal wash interval, the cost of corrosion-related maintenance over a DLIR phase may be formulated in equation (5):

$$C_T = \frac{N_M}{T_{wash}}[C_W + C_U] + r_M k_M c T_{wash} N_M^{0.75} \tag{5}$$

where:

C_T = total cost of washes and DLIR maintenance

T_{wash} = wash interval, months

C_W = cost per wash

C_U = cost of aircraft unavailability during washes

r_M = charge rate for maintenance work, dollars/hour

N_m = number of months between DLIR

The first term in equation (5) is the cost of washes during the DLIR phase and the second term is the cost of corrosion-related maintenance during DLIR. The wash interval that minimizes the total cost, T_{min}, can be obtained by differentiating equation (5) with respect to T_{wash}, setting dC_T/dT_{wash} to zero and solving for T_{wash}. The wash period, T_{Min}, that minimizes the total cost is expressed in equation (6):

$$T_{\min} = \sqrt{\frac{N_M^{.25}(C_W + C_U)}{r_M k_M c}} \tag{6}$$

Figure 26-11 shows the optimal wash interval, according to equation (6), as a function of atmospheric corrosivity within reasonable limits for k_M (i.e., 25 to 55 man-hours'). The values for the other parameters used in this equation were typical for a marine patrol fleet in North America, i.e., C_W = \$4000, C_U = \$1000, r_M = \$85/hour and N_M = 55 months. It is obvious then that the uncertainty in k_M produces uncertainty in estimating T_{min}, which is about 1 month at the lower end of corrosivity (0.5% CLIMAT mass loss) and about 0.4 months at the upper end of corrosivity (4% CLIMAT mass loss).

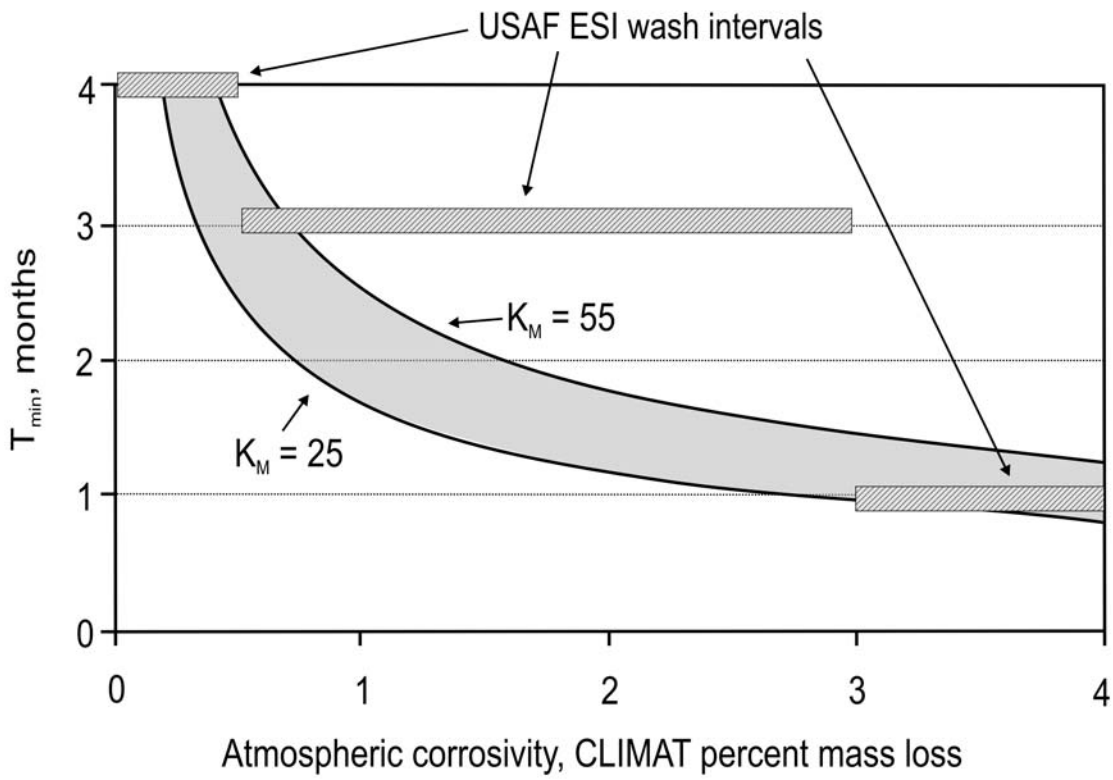


Figure 26-11: Predicted Wash Interval as Function of Corrosivity as Measured by CLIMATs Within Reasonable Limits for k_M (i.e., 25 – 55 man-hours') – Other parameters were: C_W = \$4000, C_U = \$1000, r_M = \$85/h, N_M = 55 months.

These results indicate that the optimal wash interval for the maritime patrol fleet is 1 – 1.4 months during the winter and 2.7 – 4.0 months during the summer. Given that the current practice at CFB Greenwood is to wash marine patrol aircraft once per month, stretching out the wash interval during three seasons, i.e., spring, summer, and fall, will result in significant savings on a fleet-wide basis.

Also shown in Figure 26-11 are the wash intervals recommended by the new USAF ESI algorithm after correcting for the differences in the atmospheric corrosivity scales between the USAF ESI and ISO 9223. A mildly corrosive environment would therefore correspond to a CLIMAT mass loss of less than about 0.5%, a severely corrosive environment to a CLIMAT mass loss greater than about 3% and a moderately corrosive environment with a value between 0.5% and 3%. The USAF algorithm and T_{min} according to equation 5 are similar for the mild and severe environments but differ significantly for the moderate environments.

26.4 SUMMARY

The USAF ESI algorithm for setting wash intervals is based on an environmental severity rating and an implied set of economic assumptions. A maintenance factor approach was introduced for setting wash intervals based on corrosion maintenance records, an atmospheric corrosion model and an explicit set of economic parameters. The maintenance records required are the number of man hours required to repair corrosion related damage and the number of months since the last repair. The atmospheric corrosion model assumed a bilogarithmic or power law relationship between cumulative damage and exposure time. It was also assumed that atmospheric severity increases corrosion damage whereas washing decreases it. The economic parameters are the cost per wash, the cost of aircraft unavailability during a wash and the

charge-out rate for aircraft maintenance. This approach requires a measure of atmospheric corrosivity that is not restricted to any particular method as long as one processes the maintenance data and calculates the optimal wash interval with the same method.

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