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THE USAF CORROSION TESTING PROGRAM AND A CORROSION SEVERITY INDEX ALGORITHM

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INTRODUCTION

Several studies have centered on the total costs of corrosion prevention and control within the past few years (1-5). Direct costs of corrosion maintenance for major aircraft systems have been estimated to be in excess of $750 million per year, and total corrosion costs, including those for facilities, are estimated to be in excess of $1 billion per year (4). A key factor in controlling costs is the ability to optimize corrosion repairs based upon need. The current program of fixed time interval depot maintenance of aircraft does not correspond to the actual corrosion damage level of individual units (6). The scheduling of depot maintenance could be based on the cumulative exposure to corrosion risk if the risk factors were quantified and relations between exposure and damage were known.

One approach to quantifying risk is to classify the environmental severity according to the nature and intensity of ambient corrosive factors. It has been acknowledged that some environments are more corrosive than others, and environments are commonly classified as industrial, urban, or marine, thus indicating their approximate severity (7,8). It is also established that certain environmental constituents, e.g., sea salt and sulfur dioxide, increase the relative aggressiveness of the environment (9, 10). An environmental classifiecation, based on the atmospheric constituents present, might be used as a guide in establishing maintenance schedules for aircraft.

1. THE CORROSION SEVERITY CLASSIFICATION SYSTEM

1.1 Environmental Variability

The variability of environmental corrosion severity has been well established by atmospheric testing programs (8, 11-14). Relative severity is commonly indicated by designating an environment as rural, urban, industrial, marine, or an appropriate combination of these terms. Moreover, many studies (7, 9) have shown that certain environmental factors, e.g., moisture, salt, and pollutants, are responsible for rapid corrosion observed in environments containing them. Consequently an environmental rating scale which takes into account those factors could provide a useful indication of relative severity.

It would be difficult to devise a rating system which would predict corrosion damage to every metal. Different metals display widely diverse behavior in a given environment. Some alloys are more resistant in marine locations than industrial, and the reverse is true of others. Several factors which influence corrosion are present in a unique combination for a given site, and precise information relating the corrodibility of a specific alloy to every environmental factor is not available. In the case of aircraft, the concern is with a limited number of alloys, a few each of aluminum, steel, titanium, and magnesium.* A precise rating scale is not needed for logistic decisions, but merely a relative rating. It is commonly known that aircraft corrode more severely in some environments than others. Finally, since military aircraft spend most of their lifetime on the ground at the home airbase (6), a system for classifying the severity of airbase environments is reasonable.

1.2 Atmospheric Corrosion in Aircraft

Tomashov (7) distinguishes the following types of atmospheric corrosion:

(1) "Wet atmospheric corrosion" caused by visible droplets of condensed moisture on the surface. Such moisture may result from dew, frost, rain, snow, or spray;

(2) "Moist atmospheric corrosion," which occurs at relative humidity less than 100%, and proceeds under a very thin, invisible layer of electrolyte formed on the surface by capillary action, physical, or chemical adsorption;

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* The scope of this study is restricted to corrosion of structural alloys, excluding engines and avionics. Materials of these latter systems, however, probably will respond to environmental corrosive factors in a similar way (6).

Both wet and moist atmospheric corrosion occur in aircraft. Water accumulates on metal surfaces as condensation (dew, fog, from humid air on cold post-flight surfaces), rainfall on exterior surfaces and through open hatches, and various inadvertent spills.

Thus the range of corrosion problems in aircraft may be categorized as:

(1) Wet and moist corrosion of bare unprotected metal surfaces;

(2) Wet and moist corrosion of protected metal surfaces subsequent to failure of protective coatings. Protective coatings fail because of solar radiation, atmospheric contaminants (mainly ozone and other oxidants, particulates, fuel, and exhaust gases), high speed air ablation, and mechanical abrasion and flexure;

(3) Corrosion caused by contaminants of human origin including spilled beverages, human waste, hydraulic fluids, and battery acids.

The first and second categories of corrosion may be related to environmental factors which accelerate corrosion of metals or degradation of protective coatings, hence an environmental rating system would be relevant to them. The third category is a housekeeping problem. Although it should be relatively easy to control and prevent such damage, it is in fact a serious problem in USAF aircraft.

1.3 Factors Affecting the Rate of Corrosion

The rate of metallic corrosion in the atmosphere is determined by three sets of variables:

(1) Weather conditions, especially those relating to moisture;

(2) Atmosphere pollutants, both natural and anthropogenic;

(3) The nature of the metal.

The relationship of weather and pollutants to the corrosion of aircraft alloys of interest in PACER LIME will be discussed in some detail.

1.3.1 Weather

Weather parameters include temperature, precipitation, solar radiation, wind direction, wind speed, relative humidity, dew point, cloud cover, and fog (10). All can affect the rate of corrosion, but water (and therefore those parameters related to water) will produce the largest influence. Vernon (17, 18) has shown that a given metal corrodes rapidly when the relative humidity exceeds a critical value, but corrodes slowly or not at lower humidity. The value of the critical humidity varies from one metal to another, and the presence of various pollutants can change the value as well as the corrosion rate. The critical humidity for ferrous alloys is about 70% in the absence of other factors; in the presence of sulfur dioxide, however, it is reduced to about 60%. Similarly in the presence of SO_2, the critical RH is about 70% for aluminum. Unfortunately very few data are available for other metals.

A film of moisture will deposit from humid air on metal surfaces of aircraft (19) under several conditions: if the metal is colder than the air (immediately following high altitude flights), if hygroscopic salts (corrosion products, pollutant deposits) are present, or through simple chemisorption. The film thickness, from 2 or 3 to several hundred molecular layers, will be determined by the humidity value as well as the nature of the adsorption process (7). Consequently, relative humidity alone is not sufficient to determine relative corrosivity, but it can provide a good first approximation.

Dew, fog, and rain, on the other hand, we exposed surfaces immediately. Dew condensation occurs when air cools to its dew point temperature, corresponding to 100% RH. The air itself need not cool to this point before moisture accumulates. The requirement is that the metal surface be sufficiently cooler than the surrounding air. At 80% RH, for example, the surface must be only 6°F cooler than the air (19).

There has been much discussion (10) on the effects of rainfall. Rain is thought to promote corrosion by providing moisture and washing away soluble corrosion products. It is also believed to retard corrosion by washing away pollutant deposits. Thus light rain would be harmful, but heavy rain would be beneficial.

The beneficial effects appear to be unimportant to aircraft corrosion, because, generally, paint protects aircraft surfaces exposed to the washing effects of rain, whereas corrosion occurs underneath the paint at cracks, etc., where the washing is ineffective. Interior surfaces carelessly exposed to rain, however, are wetted and not washed, and water is harmful to the less well protected surfaces. Accordingly, rain should be considered a harmful source of moisture.

Air temperature, humidity, solar radiation, cloud cover, and wind speed affect the rate of water evaporation. Temperature strongly influences the rate of corrosion reactions, thus corrosion rates would be expected to increase as the temperature rises. But oxygen, dissolved in the water electrolyte, is required for most corrosion reactions and the solubility of gases decreases with increasing temperature.

Rozedfeld (9) considers in some detail the interaction of temperature and moisture, and points out that the time of wetness will vary with temperature. Thus corrosion rates are greater in northern regions, where temperatures are low, than in warmer southern regions because moisture remains on metal surfaces longer at the cooler northern temperatures. A combination of high temperature with prolonged moisture contact, however, will result in severe corrosion. For example, corrosion of marine pilings in summer is rapid near the water surface where they are wetted by rain. It remains difficult to predict the effect of temperature on corrosion processes in the atmosphere.

1.3.2 Pollutants

Atmospheric pollutants are natural and anthropogenic airborne substances present at harmful concentrations. These substances usually are described as follows (20), including only those known to contribute to corrosion (21):

(1) "Particulates" includes both solid and liquid material in particle size from 0.1 to 100 µm. Dust, grit, fly ash, and visible smoke particulates larger than 20 µm settle to the ground somewhat quickly. Smaller particles remain suspended much longer and may be dispersed over

extremely wide areas. Thus large particulates potentially might cause corrosion problems close to the source (sea salt-spray is a special case), whereas small particulates can be important factors at great distances from their source.

Particulates vary in chemical composition. They generally are classified according to the source (22): (1) salts from sea spray and salt flats; (2) dust from agricultural lands; (3) soots from the incineration of agricultural wastes the burning of fuels; (4) agricultural and industrial dusts. Ninety per cent of airborne particulates originate from natural sources. Very few monitoring stations report the chemical compositions of particulates, but provide only total concentrations. Thus, although the corrosiveness of various particulates may vary widely, there is no way to take account of the differences, because data are not available. Geographical proximity to salt, however, is a notable exception. The corrosivity of salt is well established, but for other particulates, there exist only a few studies (22) which show corrosion to be more severe in industrialized areas with high particulate concentrations. These studies are ambiguous, however, because other corrosive factors are present.

The presence of salt greatly increases corrosion rates for nearly all metals (7, 9), hence the proximity of salt sources will be of much concern. Environments where airborne salt concentrations are high will be high risk environments. When soluble salts, e.g., sodium chloride or ammonium sulfate, are present, corrosion products usually are water soluble and readily removable. Corrosion products which form in the presence of water only, however, usually are weakly soluble, thus not readily removed, and serve a protective function to the underlying metal. In addition, many anions remove primary oxide films or displace oxygen layers which are passivating (9).

There is a synergistic effect between salt deposits and the atmospheric water content. The deliquescent salts undergo a phase transformation from dry crystal to a solution droplet when the ambient water vapor pressure exceeds that of a saturated solution of the highest hydrate (7). The relative humidities at which this transformation occurs for ammonium sulfate, sodium chloride, and ammonium nitrate are 80, 86, 75, and 62 percent, respectively. Thus salt deposits both attract moisture to metal surfaces and provide the electrolyte solution required for corrosion.

(2) Sulfur enters the atmosphere in a variety of forms, including sulfur dioxide, SO_2, hydrogen sulfide, H_2S, and sulfate salt particulates (23). About two thirds of all atmospheric sulfur comes from natural sources, mainly as H_2S from bacterial action which later is converted to sulfur dioxide.

Sulfur dioxide initially is oxidized photochemically to sulfur trioxide, which then combines with water to form sulfuric acid. The primary oxidation process may follow several different paths and can proceed rapidly in polluted atmospheres. In air containing nitrogen dioxide and certain hydrocarbons, sulfur dioxide is oxidized in a photochemical reaction process that produces aerosols containing sulfuric acid. Also, sulfur dioxide can be oxidized in water droplets that contain ammonia, the end product being ammonium sulfate aerosol. Both sulfuric acid and sulfate salts thus formed are removed by precipitation and, to a lesser extent, by gravitational settling.

Hydrogen sulfide is emitted by some industrial operations and by catalytic converter-equipped automobiles. Hydrogen sulfide, like sulfur dioxide, is oxidized in the air and eventually converted to sulfur dioxide, sulfuric acid, and sulfate salts.

On a local or regional basis, the mechanisms by which sulfur compounds are removed from the air may produce significant effects. In the 1960's as the concentration of sulfur compounds in the air over Europe began to rise, so did the acidity of precipitation (24). Both phenomena are attributed to increased use of sulfur-containing fuels.

Many materials, in addition to metals, deteriorate in the presence of atmospheric sulfur in one form or another (23). Ferrous alloys, in particular, corrode more rapidly in the presence of SO_2, the effect apparently being synergistic with moisture.

In the U.S., ambient SO_2 levels have decreased in recent years because of reduced usage of coal and enforcent of "environmental protection" legislation (25). It appears likely, however, that energy consideration will force the U.S. to use more coal, and SO_2 concentration probably will reach levels no lower than they are today and may even increase.

(3) Hydrocarbons (26) mostly come from natural decomposition of organic matter. Anthropogenic sources are important, however, because they may be highly concentrated geographically where they are not rapidly dispersed. The most notable example is the Los Angeles basin, where the sources are automobile engines. The fate of the hydrocarbon pollutants involves the reaction with oxides of nitrogen to form photochemical smog, which include a variety of secondary pollutants such as ozone, nitrogen dioxide, and peroxyacetyl nitrates. Hydrocarbons themselves are not damaging either to metals or protective coatings, but photochemical oxidants are harmful to both (27).

(4) Nitrogen oxides (28), NO_x, arise from both natural and anthropogenic sources. The former mainly are organic decomposition, the latter the internal combustion engine. Internal combustion initially yields nitric oxide, NO, which by itself is relatively harmless. In the atmosphere, however, NO oxidizes to nitrogen dioxide, NO_2 which is harmful both directly as an irritant and indirectly in the formation of photochemical smog. The chemical reactions occuring in the presence of NO_2, hydrocarbons, and sunlight are complex but yield an atmsophere which is aggressive in the destruction of organic materials such as paint films and protective coatings.

The corrosive effects of NO_x and photochemical oxidants (27, 28) probably are indirect. These pollutants may decompose protective finishes on aircraft resulting in premature failure of the coating and exposure of underlying metal. It should be remembered that the nature of local pollutants is relevant to the type of aircraft corrosion problems to be expected. In the industrial eastern U.S., smog containing SO_2 will produce direct metal corrosion to the interior and exposed metal parts of an aircraft, whereas a Los Angeles photochemical-type smog will damage finishes and seals, followed by corrosion of underlying metal.

1.4 Establishing Environmental Quality Standards for Corrosion

Corrosion accelerates when the following environmental factors are present:

(1) Humidity, rainfall, and solar radiation;

(2) Proximity to the sea or other salt sources; and

(3) Pollutants, mainly sulfur oxides, particulates, photochemical oxidants, and nitrogen dioxide.

The prevalance of these environmental factors varies widely from one geographical location to another even within relatively small areas (29). Moreover, there is much evidence to show that environmental corrosivity becomes increasingly severe as these factors increase. Thus, it is reasonable to assume the existence of a critical value for each factor, either alone or in combinations, which could be used to establish environmental severity. The critical value may sharply divide slow and rapid corrosion, such as for iron and aluminum in the presence of SO_2 versus humidity (cf. Rozenfeld (9), pp. 106 and 109). Alternately, the variation of damage with the environmental parameter may be gradual, such as the repainting of houses vs. particulate concentration (cf. Stoker and Seager (30), p. 98). Where such critical values are known, they can be utilized directly as environmental quality standards.

Unfortunately, data are nearly nonexistent for all environmental factors except humidity. Most laboratory studies of pollutant effects on corrosion have used concentrations much higher than any found in even the most polluted environments. Much effort (22, 23, 26-28) has been devoted to establishing critical concentration levels with respect to human health, plant, and animal welfare which form the basis of ambient air quality standards. A critical concentration for materials damage, however, may be higher or lower than these.

A set of working environmental corrosion standards (WECS) might be developed by consideration of the following:

(1) The range of values for the several ambient parameters, which will establish limits of environmental exposure, if not the damage to be expected. Such data include maxima, minima, medians, and percentiles for the measured parameter. Since the acutal environments are known to vary

in corrosion severity, it follows that critical concentrations for practical use must be within the range of ambient levels, perhaps near the median values or higher.

(2) Ambient air quality standards established by the Environmental Protection Agency are concerned primarily with human health, as noted above. Nevertheless, they do summarize careful consideration of all available evidence by a host of scholars and bureaucrats. The values represent the highest levels believed safe for human health and comfort.

(3) Experimental studies which relate corrosion damage with pollutant concentrations and weather variables may provide information for establishing WECS.

1.4.1 Ranges of Ambient Parameters

Within the United States, a number of air quality parameters are measured by several agencies. Weather data are collected by the National Weather Service, the USAF Environmental Technical Applications Center (ETAC), and others. Weather data most commonly are measured at aerodromes because weather is a critical factor in aircraft operational safety. Air quality data - measurements of a limited number of pollutants - are collected by federal, state, municipal, and private air monitoring stations, the results are compiled by state agencies and, nationally, by the U.S. Environmental Protection Agency. Many monitoring stations - especially private ones - were established to track specific pollution sources, e.g., certain manufacturing operations, thus their data may reflect highly localized conditions. Despite these limitations, the national data as compiled by EPA are the only data available to assess the range of exposure.

Graedel and Schwartz (31) analyzed ambient atmospheric conditions and quality based on National Weather Service and EPA data. Weather data spanned 30 years from more than 200 measuring sites, and air quality data, mostly from CY 1973, represented as few as 82 to as many as 3760 measuring sites for several pollutants. Graedel and Schwartz's objective was to determine the range of environmental parameters to which materials are exposed in the U.S. and thus establish "bench marks" for laboratory or field testing. Weather data analyzed by the authors were mean annual temperature and mean annual absolute humidity. Pollutant data were the annual median of hourly averaged continuous data for each measuring site.

We note three results of Graedel and Schwartz for each atmospheric parameter: The median of the 50th percentiles, the median of the 99th percentiles, and the maximum value reported (Table 1). The 50th percentile median represents "average of averages" values reported, whereas the 99th percentile median is the level exceeded at only 1% of all air quality sites. Graedel and Schwartz define the 99th percentile median as Atmospheric Upper Limit Values, AULV, or "mean high water marks" which may be used for design purposes with the expectation that 99% of the applications will encounter levels below the AULV. The maximum value was the highest mean reported.

The distribution of means as shown by Graedel and Schwartz is more-or-less Poisson-like for all factors except ozone and SO_2. For ozone, a large number of sites reported values below 20 $\mu g/m^3$ and a substantial number were grouped between 30 and 60 $\mu g/m^3$. Nevertheless, the median, 36 $\mu g/m^3$, probably is a valid demarcation between high and low concentrations. Sulfur dioxide data from 447 monitoring sites were highly skewed toward low values. Indeed, the maximum number of sites reported values at the median and mean value of 43 $\mu g/m^3$, and only 17% of monitoring stations reported means greater than 53 $\mu g/m^3$. Because of this, the significance of the median value of SO_2 is placed in a different light than for the other parameters. This is especially unfortunate because of the peculiar role of SO_2 in corrosion.

Critical levels of atmospheric factors probably lie between the median values and the worst-case maxima or even the AULV's. Clearly the AULV's represent the most hostile environments for individual atmospheric factors in the CONUS, and this worst 10% level would be inappropriate to use in a practical environmental rating scale. It may be noted that the list of monitoring stations (their Table 2) which exceed the AULV's includes San Bernadino, CA only once (for nitrate ion particulates), whereas Travis, CA and Charleston, SC are not mentioned. All three of these have been shown to be severe environments, the first for paint degradation and the latter two for metallic corrosion (6. 32).*

1.4.2 Proximity to the Sea and Other Sources of Salt

Several studies (8, 11, 13, 33, 34) have shown that accelerated atmospheric corrosion near the seashore is correlated with airborne sea salt. Establishing a critical distance from the shore, however, is difficult because there is little quantitative information relating corrosion to atmospheric salt concentrations, or even relating salt concentrations to distance from the shore.

The study of atmospheric aerosols (36) has centered mostly on the distribution of particle sizes, rather than the mass of aerosol per unit volume, i.e., micrograms per cubic meter of particulate, as measured at air monitoring stations. The upper limit of aerosol particle size is determined by sedimentation processes. Particles larger than 20 μm radius remain airborne for a short time and are found only in the vicinity of their source. Hence, an atmospheric aerosol by definition consists of particles between 0.1 μm and 20 μm radius. Aerosol particles commonly are classified as "Aitken" particles, $\leq$ 0.1 μm radius, "large" particles, 0.1 - 1.0 μm radius, and "giant" particles 1 μm radius in size. Larger particles settle from the air rapidly whereas smaller particles persist in the atmosphere for long times and travel large distances, and serve as condensation points for rainwater precipitation. Thus measurements of sodium chloride particulates vs. distance from the sea may suggest values for the critical distance.

1.4.2.1 Salt in Rainwater

The concentration of sodium chloride in rainwater is high near and over the ocean, but diminishes inland (35). Concentrations over the sea are 8.0 μg/l, and over land in the central U.S. are 0.1 μg/l (35). The concentration decreases logarithmically with distance from the sea up to 500 km in the U.S., and is constant at greater distances.

*The corrosive severity of Travis and Charleston has been attributed primarily to their proximity to salt water, which in turn should indicate high concentration of seal salt. Graedel and Schwartz's list does include several sites near the ocean which exceed their particulate AULV.

It is unlikely, however, that chloride in rainwater is relevant to aircraft corrosion. The exterior surfaces of aircraft exposed to rain are protected by paint, whereas, most interior surfaces are not exposed to rain. Moreover, the decrease of chloride in rainwater occurs over large distances, whereas the decrease in corrosion damage is quite abrupt (9, 11). Corrosion rates 10 km from the shore are approximately the same as corrosion rates far inland. Consequently, the critical proximity should not be determined from rainwater chloride concentrations.

1.4.2.2 Particulate Sodium Chloride

Duce et al. (37) have measured the concentration of sodium chloride and other ions in the air at various elevations and distances from the sea-shore on Hawaii Island, HI. All measuring sites were downwind of off-shore trade winds. Their results show chloride concentrations at all sites varying widely with ambient weather conditions. Their primary interest was the variation of chloride and other ionic components vs. elevation above sea level, rather than distance from shore. Nevertheless, the results show a consistent, monotonic decrease in chloride concentration with increasing distance from the shore.

Also included are two additional reported values for giant particle chloride concentrations, one over the ocean and one near the shore in Massachusetts. The over-ocean values should be compared with Junge's summary (36) (p. 162) of salt concentration vs. wind velocity measurements, which illustrate the wide variability of such data.

Hudson and Stanner (34) found in Nigeria that sodium chloride concentration in the air varies within wide limits and depends strongly on the distance from the shore. The sodium chloride content in the air is about .22 milligrams per cubic meter. The amount of salt that settles out on the surface under these conditions reaches values from 10 to 1000 milligrams per square meter per year. Corrosion tests were conducted at various distances from the shore with simultaneous determination of airborne salt concentration. The relationship between salt deposits and distance from the sea as well as corrosion rates vs. distance from the sea are calculated.

Available evidence shows that giant particle chloride concentrations in the atmosphere are reduced by about 1 order of magnitude at a distance of 3/4 km from breaking surf. At distances of about 15 km the concentration reaches a value which remains nearly constant further inland.

Junge (36) (p. 176) has drawn together the available data on giant salt particulates vs. distance from sea. Values of 5 $\mu g/m^3$ at distant point inland.

The available data on atmospheric corrosion near marine environments suggests that the decrease in corrosion rate parallels this decrease in giant salt particulates, and "marine atmospheres are aggressive in direct proportion to concentration of (airborne) NaCl particles" (Rozenfeld (9)).

Most studies suggest a critical distance of less than 1.5 km for sites where strong off-shore winds are not prevalent. Allowing for the variability of weather, however, it seem prudent to extend this to 4.5 km.

1.4.3 U.S. National Ambient Air Quality Standards (NAAQS)

The Federal Clean Act (Public Law 91-640) directed the Environmental Protection Agency (EPA)

> " to publish proposed national primary and secondary ambient air quality standards based upon air quality criteria, (also issued by EPA). Primary ambient air quality standards define levels of air quality which (the EPA judges) necessary, based on air quality criteria and allowing an adequate margin of safety, to protect the public health. Secondary ambient air quality standards define levels of air quality which (EPA) judges necessary, based on the air quality criteria to protect the public welfare from any known or anticipated adverse effects of an air pollutant." (40)

Air quality criteria published by EPA summarize the scientific knowledge relating pollutant concentrations and their adverse effects. They were issued to assist the development of air quality standards. In developing criteria many factors were considered, including the chemical and physical characteristics of the pollutants, the techniques available for measuring them, exposure time, relative humidity, and other conditions of the environment. The criteria attempted to consider the contribution of all variables to the effect of air pollution on human health, agriculture, materials, visibility, and climate. Air Quality Standards on the other hand legislate pollutant concentrations that the government determines should not be exceeded in a specific geographic area. Primary standards were intended to protect public health, whereas secondary standards were intended to protect public welfare. In the case of some pollutants, the primary and secondary standards are the same, whereas for others, notable sulfur oxides and particulates, the secondary standards are lower. These standards are listed in Table 2.

It is difficult to determine how EPA based the NAAQS on the respective Air Quality Criteria (22, 23, 26-28). Comments submitted to EPA, subsequent to the first publication of standards, "reflected divergences of opinion among interested and informed persons as to the proper interpretation of available data on the public health and welfare effects of the six pollutamts . . ." (41), suggesting that others could not follow the logic used in developing standards.

"Current scientific knowledge of the health and welfare hazards of these air pollutants is imperfect." (41) Indeed! The Clean Air Act, however, required the promulgation of standards by a specific data. Using the available scientific evidence, any standard value could be established within a wide range.

In responding to comments on the initial standards, EPA did state the basis for setting several of the standards. The standard for carbon monoxide

"was based on evidence that low levels of carboxyhemoglobin in human blood may be associated with impairment of ability to discriminate time intervals . . . In the comments, serious questions were raised about the soundness of this evidence (and) extensive consideration was given to this matter. The conclusions reached were that the evidence regarding impaired time-interval discrimination have not been refuted and that a less restrictive national standard for carbon monoxide would therefore not provide the margin of safety which may be needed to protect the health of persons especially sensitive to the effects of elevated carboxyhemoglobin levels.

The only change made in the national standards for carbon monoxide was a modification of the 1-hour value. The revised standard affords protection from the same low levels of blood carboxyhemoglobin as a result of short-term exposure. The national standards for carbon monoxide, as set forth below, are intended to protect against the occurrence of carboxyhemoglobin levels above 2%.

"National standards for photochemical oxidants have also been revised. The revised national primary standard of 160 micrograms per cubic meter is based on evidence of increased frequency of asthma attacks in some asthmatic subjects on days when estimated hourly average concentration of photochemical oxidant reached 200 micrograms per cubic meter. A number of comments raised serious questions about the validity of data used to suggest impairment of athletic performance at lower oxidant concentrations. The revised primary standard includes a margin of safety which is substantially below the most likely threshold level suggested by this data.

"National standards for hydrocarbons have been revised to make these standards consistent with the above modifications of the national standard for photochemical oxidants. Hydrocarbons are a precursor of photochemical oxidants. The sole purpose of providing a hydrocarbon standard is to control photochemical oxidants. Accordingly the above described revision of the national standards for photochemical oxidants necessitated a corresponding revision of the hydrocarbon standards.

"National standards for nitrogen dioxide have been revised to eliminate the proposed 24-hour average value. No adverse effects of public welfare have been associated with short term exposure to nitrogen dioxide at levels which have been observed to occur in the ambient air. Attainment of the annual average will, in the judgement of the EPA, provide an adequate safety margin for the protection of public health and will protect against known and anticipated adverse effects on public welfare."

We conclude that the NAAQS are of little relevance to corrosion in aircraft.

1.4.4 Experimental Studies Relating Corrosion to Environment

Several studies have attempted to develop quantitative relations between corrosion and environmental parameters. These will be discussed as possible indications of critical values.

Upham (42) conducted atmospheric exposure studies at established air monitoring sites in St. Louis and Chicago. His results showed approximately linear relationships between corrosion rates and SO_2, TSP, and surface sulfation rates for low-carbon, low-copper mild steel panels. Mansfield (43, 44) has extended this work to a wider variety of materials at St. Louis sites, but analysis of the results is not complete.

Guttman (21) conducted a long term exposure program using zinc at a single site and compared the results with environmental conditions. He showed that the most important factors are time of wetness and atmospheric concentration of SO_2, and, further, that the time of wetness is a consequence of ambient relative humidity. He found temperature not to be important. Using a curve-fitting technique, Guttman obtained an empirical equation

$$y = 0.00546A^{0.815} \quad (B + 0.0289),$$

where

y = corrosion loss, mg/3x5-in panel,
A = time of wetness, hr., and
B = SO_2 concentration during the time panels were wet, ppm.

This equation suggests a linear dependence of corrosion damage on SO_2 concentration, which would imply that there is no critical concentration. Guttman did not relate time of wetness to weather parameters, thus it doesn't help this study.

Haynie and Upham (45), in an extension of Guttman's work with zinc, assumed a linear dependence of corrosion on mean relative humidity and mean SO_2 concentration. Zinc specimens were exposed at a number of U.S. Public Health Service Continuous Air Monitoring Program (CAMP) sites. Corrosion damage to the samples was compared with CAMP pollutant data and weather data from the nearest weather station. Statistical analysis yielded

$$y = 0.00104\ (RH - 49.2)\ SO_2 - 0.00664\ (RH - 76.5)$$

where

y = zinc corrosion rate, μm/yr.,
RH = mean relative humidity, %, and
SO_2 = mean SO_2 concentration, μg/m^3.

This equation suggests that zinc will not be wet below RH of 76.5% in the absence of SO_2 and, furthermore, increasing humidity above that point inhibits corrosion. Haynie and Upham view this as consistent with the formation of a protective carbonate film. In the presence of SO_2, however, their equation indicates a linear dependence on the product of RH with SO_2 and a linear dependence on SO_2. Again, critical values of each parameter are not indicated.

Equations such as these can be used to predict the useful life of galvanized iron products which are scrapped when the zinc coating is perforated. Haynie and Upham have made such predictions for various environments and their results compare well with experience.

Haynie and Upham (46) conducted a more extensive study of the corrosion of enameling steel and atmospheric factors. Specimens were exposed at 56 sites on the National Air Specimens Network (NASN) coordinated by the EPA. Weight loss data were obtained at one year and two years and were correlated with mean weather data (RH and temperature) and pollutant concentrations (SO_2, TSP, sulfate ion $SO_4^=$, and nitrate ion NO_3^-). Correlation analysis identified the variable set which was used in multiple regression analysis. Haynie and Upham found that corrosion of steel is a function primarily of $SO_4^=$, NO_3^-, RH, and time. Temperature, TSP, and SO_2 appeared to be insignificant. Because of an observed covariance between $SO_4^=$, and SO_2^-, together with many other studies which had shown a relation between corrosion and SO_2, Haynie and Upham suggested that $SO_4^=$ may be merely a "proxy" variable for SO_2. When $SO_4^=$ data were excluded from their analysis, the empirical fit was nearly as good with SO_2 as with $SO_4^=$.

The relation between corrosion for this steel and the environmental factors considered was best expressed as

$$\text{corr.} = 183.5\sqrt{t}\exp(0.0642\,\text{Sul} - 163.2/\text{RH}),$$

where

t = time, yr.,

Sul = mean concentration $SO_4^=$ or SO_2, $\mu g/m^3$, and

RH = relative humidity, percent.

By transposing the time factor to the left hand side, Haynie and Upham show the dependence of "pseudocorrosion rate," $\text{corr.}/\sqrt{t}$, on SO_2 concentration and relative humidity.

Environments where RH and SO_2 are high should be more corrosive and maintenance to equipment will be required more frequently. The frequency of a given maintenance operation would be inversely proportional to the time required for corrosion to reach a specified depth. Thus a crude estimate of the ratio of maintenance frequency in a SO_2 polluted environment to that in a cleaner environment is given by Haynie and Upham as

$$\text{MFR} = \exp(.006\,SO_2),$$

or

$$\text{MFR} = \exp.\,[.006\,(SO_{2a} - SO_{2b})],$$

where MFR - maintenance frequency ratio, and a, b refer to two different environments.

Haynie, Spence, and Upham (47) have studied the corrosion of weathering steel and galvanized steel in a laboratory chamber with various combinations of humidity, radiation, and pollutants. Experiments were conducted in atmospheres containing SO_2, NO_2, O_3, and water vapor, each at two different concentrations as listed in Table 3, and the results were compared with corrosion rates in clean humid air. This two-level factorial arrangement was selected to identify environmental factors statistically. It may be noted from Table 3 that the three "low" pollutant concentrations are essentially equal to the primary NAAQS values, and considerably higher than the 50th percentiles of Graedel and Schwartz (31). Absolute humidities are very high compared with the ambient 50th percentiles. The "high" values of the several factors are many times greater than the extreme values of the U.S.

Analyzing the results, Haynie et. al. conclude that only SO_2, humidity, and their interaction are significant factors in the corrosion of weathering steel. For galvanized steel, only the direct effects of the two were of importance. Thus, they view NO_2 and O_3 as having little or no effect on the corrosion of these alloys.

Their corrosion rate results, reproduced in part in Table 4 however, suggest otherwise. (We must admit we do not have access to their complete analysis). Corrosion rates, the largest increase being for SO_2. From these data, it appears that NO_2 and O_3 do accelerate corrosion rates, although not as much as SO_2.

1.4.4 Working Environmental Corrosion Standards (WECS)

After considering the existing literature on materials degradation and environmental factors, we conclude that there are no firm guidelines for setting WECS, with the exception of humidity. Metallic corrosion is definitely accelerated in the presence of SO_2 and high humidity, and probably accelerated by NO_2, oxidants, and many particulates. Organic protective finishes are deteriorated by solar radiation, oxidants, some particulates, and possibly by NO_x and SO_2. Published research does not tell us, however, at what level these factors become significantly damaging.

Accordingly, we adopt the view that critical values lie within the range of ambient values, because accelerated corrosion has been observed in existing environments. We adopt two sets of WECS based on the analysis of Graedel and Schwartz (31). The first set are their 50th percentile values plus 20 percent of the difference between the 99th and 50th percentiles. These are listed in Table 5. The values for proximity to salt or sea are based on the analysis presented earlier. The solar radiation values are based on the mean (July) values for the continental U.S.

These WECS have been used in the Corrosion Severity Index Algorithms (described in a subsequent section) and the results compared with experimental environmental ratings. The agreement is sufficiently good that the values of Table 5 together with the Algorithms may be used to compute accurate relative environmental severity for corrosion in aircraft.

1.5 Environmental Severity Algorithms for Aircraft Corrosion

We propose a set of algorithms, based on locally-measured environmental factors which rely in part on maintenance experience as contained in AFM 66-1 records. A feature of this approach is that the authority to set maintenance intervals is left in the hands of local management. These decisions would be based on locally measured meteorlogical and pollutant conditions and would be subject to change dictated by local experience.

1.5.1 Corrosion Maintenance in Aircraft

Excluding housekeeping, corrosion maintenance involves

(1) washing of exterior surfaces,
(2) repair of replacement of protective coatings and sealants, and
(3) treatment and repair of corroded components.

Environment elements which corrode metal are not necessarily the same as those which deteriorate paint and sealants.

Consequently, no single algorithm can classify an environment with respect to all three corrosion problems. Instead three decision algorithms are required to determine intervals for:

- aircraft washing
- complete repainting, and
- corrosion inspection/maintenance.

Each algorithm would assess the level of local contaminants and, via a decision-map process, lead to recommended intervals for each maintenance cycle.

1.5.1.1 Aircraft Washing

Aircraft are washed both to maintain appearance and to remove soil deposits which may damage the paint. There are several sources of soil: engine exhausts, fuels, and lubricants; airborne particulates; and the workers' shoesoles during maintenance and servicing operations. Soil deposits will attract and retain moisture from humid air and gaseous pollutants, particularly SO_2. Thus, the damaging effects of soil are compounded by high humidity and pollutant concentrations. It is not likely that surface soils accelerate paint degredation by sunlight or gaseous oxidants, but there is no evidence to support this view. Thus, aircraft washing intervals selected to protect the paint and exposed metal should be related to particulates (and proximity to the sea), SO_2, (possibly) NO_2, and humidity. USAF recommended washing intervals, for several years, have been 45, 60, and 90 days, depending on local conditions. Practical washing intervals, which are consistent both with environmental risk factors and rigorous climates, are 30, 60, and 120 days. We designate these as A, B, and C, respectively.

The Washing Algorithm (Figure 3) first determines if the distance to the sea is less than the WECS distance. If it is, washing interval A is recommended; if not, particulate concentrations are compared with WECS. If the ambient level exceeds the standard, then the ambient SO_2 concentration is checked. If SO_2 is higher than WECS, interval A is recommended; if lower, interval B.

If particulates are below the standard, SO_2 concentration again is queried: If high, interval B is recommended; if low, moisture factors are considered. High moisture values -- either RH or rainfall greater than WECS -- lead to interval B recommendation; low values yield interval C.

1.5.1.2 Painting

Aircraft are painted primarily to protect metal surfaces. Protective finish maintenance is effected at three levels: (a) minor touchup; (b) major touchup; and (c) complete strip-repaint. Minor and major touchup are effected at field or intermediate level maintenance, whereas complete repaint is authorized only at depot-level for large aircraft (52). The need for touchup painting must be determined at field-level inspection: an environment-based algorithm should not be used. The following paint-interval algorithm refers to complete strip/repaint maintenance.

As before, three intervals, A, B, and C, are recommended. Paint systems currently in use -- epoxy or polysulfide primers and polyurethane finish coat -- should provide a service life of 10+ years in the mildest environments (53). Consequently, the A, B, and C intervals may be equated to 36, 72, and 120 months, respectively. These intervals may not correspond to the PDM intervals for a particular aircraft system. For example, C-141A aircraft currently are on a 42 month cycle, and B-52's are on 48 months. If 120 months is the maximum expected service life for the paint finish, and the PDM interval is y months, then y should be compared with the intervals recommended by the Repaint Algorithm, i.e., 36, 72, or 120 months. The interval closest to the PDM interval should be selected.

Environmental factors which deteriorate paint are, in order of severity, solar radiation, oxidants, and sulfur dioxide absorbed on soil deposits. Soil deposits themselves might be included, but there is insufficient information to relate repaint schedules to the nature of the soils. Thus, only sunlight, oxidants, and SO_2 are considered. The repaint algorithms (Figure 2) compares the solar radiation level, ozone and sulfur dioxide concentrations with the WECS values. High values for all three result in the A interval recommendation, whereas low values for all three lead to the C interval. Various combinations of high values lead to the B interval.

1.5.1.4 Corrosion Damage

The Corrosion Damage algorithm (CDA) is of a different nature than those for washing and repainting, which recommend maintenance intervals appropriate to the environment. Corrosion repairs routinely are effected simultaneously with phased and isochronal maintenance efforts, and it would be both undesirable and difficult to impact their scheduling.

Accordingly, the CDA is intended as a guide for anticipating the extent of corrosion damage and for planning the personnel complement and time required to effect their repairs.

The Algorithm (Figure 1) considers first distance to salt water (or salt flats), leading either to the very severe (AA) rating or a consideration of moisture factors. After moisture factors, pollutant concentrations are compared with WECS either for SO_2, TSP, or O_3. High values for any one of the three pollutants together with a high moisture factor leads to the (AA) rating, but if all are low, together with a high moisture factor, the severe (A) rating results. Low moisture factors with a high pollutant value result in the moderate (B) rating, whereas if all are low, rating (C) results.

1.5.1.5 Use of Environment Algorithms

The above algorithms are readily compared with the appropriate local environmental parameters to yield corrosion maintenance ratings; the use of a computer obviously is not necessary. The algorithms could be used in a modified for within the base-level computer system and , with appropriate automatic data input, can provide monthly revisions for maintenance needs recommendations.

1.5.1.6 Environmental Applications

Environmental Severity Algorithms have been used to establish preliminary ratings for most airbases of interest to USAF. These ratings are listed in Appendix 3[*]. These ratings are based essentially on comparisons of the Working Environmental Corrosion Standards with local geographical and environmental data. Modifications to the algorithms were necessary in order to use the available data format, but the results are not significantly affected. No responsibility is assumed for the accuracy of the data, particularly with respect to its relevance to a specific airbase, since the monitoring site may have been located at some distance from the airbase in question. If more accurate and reliable data should become available, they may be used to compute more appropriate ratings.

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[*] Available from the authors.

1.5.1.7 Environmental Data

The following environmental data were collected for USAF, AFRES, and ANG airbases, from the sources indicated.

(1) Mean annual relative humidity, mean annual temperature, mean annual rainfall. Source: USAF Environmental Technical Applications Center, "Worldwide Airfield Climatic Data," Vols. I-VIII, 1970. (54)

(2) Mean solar radiation for July. Source: Baldwin, J. L., "Climates of the United States," U.S. Department of Commerce, Washington D. C., 1973. (55)

(3) Ambient concentrations of SO_2 particulates, NO_2, and O_3. Source: U.S. Environmental Protection Agency, "Air Quality Data -- 1976 Annual Statistics," March 1978, EPA-450/2-78-009. (56)

(4) Distance to salt water or other salt source and prevalent wind direction with respect to the nearest urban/industrial area. Source: U.S. Department of Commerce, "Sectional Aeronautical Charts," Washington, D. C., 1979. (57)

Additional discussion of some of these points is required. Data were collected only for continental US airbases because pollutant data were available only for them. The algorithms could be used in abbreviated form with only weather and geographical data. In some case this would lead to useful results. For example, Anderson AFB, Guam would receive A, (probably) B, and AA ratings for washing, repaint, and corrosion severity, respectively, based only on these parameters. Ratings for less unique environments, however, would be ambiguous, and we chose not to compute them.

Weather data reported by ETAC are variable-year averages of hourly measurements and were obtained by weather stations located at the specific airbase in question. These stations did not report solar radiation measurements, hence the source listed in item (3) was used. These latter data are mean values for wide geographical regions and were computed from US Weather Bureau measurements. Values for July are used because these are near the maximum for the northern hemisphere. July values would be inappropriate elsewhere. Mean annual RH and temperature were used to compute mean annual absolute humidity.

Sulfur dioxide and particulate concentrations were available in the cited EPA documents as mean annual values and thus are directly compared with WECS. In the case of the NO_2 and O_3, however, available data frequently provided only first and second hourly maxima, which cannot be compared with the WECS annual mean values. Accordingly, we have substituted for these pollutants a secondary WECS equal to the 50th percentile of Graedel and Schwartz (29) plus 0.8 of the difference between their 99th and 50th percentiles. The modified algorithm compares this secondary WECS with the reported hourly maximum.

Unlike the ETAC data, EPA's pollutant data were not measured at the airbase in question. We have selected data from the nearest EPA monitoring station and upwind of the airbase wherever possible. In the data listings (Appendix 3#), latitude and longitude of both the relevant monitoring station and the airbase are included, together with the wind direction from the airbase.

2. PACER LIME -- Atmospheric Corrosion Testing

2.1 OBJECTIVE

The experimental phase of PACER LIME was intended to provide a calibration for the corrosion severity index (CSI) algorithm. Corrosion of selected alloys would be used to compare environmental corrosivity at several airbases selected to span the range of actual environments. Comparative evaluation of the alloys tested was not a consideration.

2.2 THE TESTING PROGRAM

2.2.1 TESTING SITES

Warner-Robins AMA, in 1971, selected eleven test sites, seven CONUS, two USAFE and two PACAF airbases. Close consideration, however, reduced the number of overseas test sites to two. Test sites were selected on the basis of the Interim CSI algorithm, represented a wide range of environmental severities, but most "moderate," two were "severe" and one "very mild." Unfortunately, no useful data were obtained from the "severe" locations. Mild sites included Davis-Monthan AZ, and F. E. Warren WY. Moderate locations chosen were Andrews DC, Barksdale LA, Hickman HI,

Available from the authors.

Norton CA, Robins GA, Tinker OK, and Wright-Patterson OH. Severe sites were MacDill FL. and RAF Lakenheath England.

Exposure sites were a few hundred yards distance from operational areas unusual environmental factors were rare, e.g., a wash rack at 200 yards (Barksdale), fuel depot at 100 yards (Norton), and fuel depot and sewage treatment plant at 300 yards (Robins). Stand location details are not available for Andrews, Hickman, MacDill, and F. E. Warren.

2.2.2 TEST METHODS AND MATERIALS

Test stands (ASTM G 50-76. (1)) Fastened test panels by means of poreclain insulators at 30° to the horizontal and facing prevailing winds. Stand installation was accomplished at eight sites in March 1972, two more in September 1973, and the last one in late summer 1975.

Six alloys* were tested in three different configurations. Three aluminum alloys 2024 T3 (clad) 7075 T6 and 7079 T6 (clad), steel 4340, magnesium AZ31B and titanium Ti 6AL 4V. An assembly made from one panel of each aluminum alloy was also exposed. The assemblies were riveted with four cadmium plated rivets. Panel sizes were 12.7 x 14.3 cm for all materials. In addition 12.7 x 29.8 cm panels were provided for 2024 T3, 7075 T6 and magnesium. Thus, corrosion should represent the behavior of aircraft.

Initial setup and specimen handling followed ASTM G 1-72 and G 50-76 (1).

At six month intervals, panels were removed, scrubbed with a rubber stopper under flowing water, acetone-rinsed, dried and weighed.

2.3 PROBLEMS

The setup procedure was too flexible, but since test stands were set up by personnel from Warner-Robins, this does not seem to have been a difficulty. There is evidence (e.g., weights recorded to the nearest 0.0001) that care was taken at every step of the program.

*From hindsight, it is unfortunate that a low carbon steep and perhaps zinc were not included, since these metals are so common in published corrosion tests.

The decision to remove, clean, and weigh every panel at six month intervals was unfortunate. The task of multiple weighings results in a greater chance of error on the part of the laboratory personnel.

The cleaning procedure was selected to avoid the hazards of chemical cleaning methods. Chemical methods remove corrosion products more effectively than the stopper-rubbing technique, hence yield more accurate weight loss measurements. Since many actual weight changes were quite small, the resultant errors are probably significant.

In addition to these problems, the program was plagued with numerous difficulties from the onset. At most locations the required equipment (balance) or personnel were lacking, hence panel weighings could not be done locally. Only Robins, Tinker, Wright-Patterson, and Lakenheath possessed the needed capability. Specimens from other sites were removed, packaged, and shipped to Robins or to Tinker for measurements.

In 1974 all data from MacDill were lost* because of personnel changes. A new set of panels was installed, but the test stand soon was destroyed by weather* and testing was discontinued. The late-installed stand at Lakenheath was destroyed by weather and testing was discontinued after only six months. This was especially unfortunate because both Lakenheath and MacDill were believed to be severe environments.

Steel panels were found to corrode so rapidly that the surface-marked identifications were obliterated; a new marking method was developed. Finally, when an attempt was made in 1975 to analyze the data it was discovered that no initial weights had been recorded for most panel sets.

3. RESULTS

3.1 DATA REDUCTION

Data were tabulated, keypunched and entered into a CDC 6500 Computer. Mass change per unit area vs. time was computed. Anomalous values were noted and checks were made to determine whether they resulted from tabulation or keypunch errors, and corrections made. In addition a subroutine calculated

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*Not uncommon occurrences even in programs operated by the most experienced workers, cf. References 3, 4. 5.

mean mass change and rejected data more than three standard deviations from the mean.

A curve-fitting algorithm plotted mass change for all panels for each alloy and each base, and corrosion rates were computed.

4. DISCUSSION

Compared with the amount of data this study might have yielded, useful information actually obtained is meager. Panels tested number 1089. As noted, experimental values for each panel type were averaged for each test site, thus reducing potential corrosion rate values to 110. Only 33 apparently valid corrosion rates, in fact, could be computed. We also have pointed out the difficulty of taking such data seriously when they are surrounded by obviously-invalid data measured simultaneously by the same personnel. But for evaluative purposes, the results must be accepted at face value and compared with measurements by other workers and with the environmental ratings of the corrosion severity algorithms.

4.1 OTHER RESULTS

Carter (6) reported weight loss measurements on aluminum alloys exposed to industrial, rural, and marine environments. The alloys studies were identical to none in this study, but one contained copper and had a nominal composition similar to that of 2024. His corrosion rates were 70×10^{-6} and 5×10^{-6} kg/m^2-dat for severe industrial and rural environments, respectively. Marine and rural environments produce quite similar results and were relatively non-corrosive. Environmental pollutants -- mainly SO_2 -- increased pitting attack, rather than general corrosion.

Pearlstein and Teitell (7) reported four year weight loss data for 2024 T3 and AZ31B exposed at three different sites in the Panama Canal Zone. Highest corrosion rates for both alloys were observed at the marine site and lowest in a rain forest. Weight losses in 2024 T3 were negligible in the latter environment. Pearlstein and Teitell comment, however, that weight loss measurement may not be meaningful because 2024 exhibited extensive blistering and exfoliation corrosion without substantial weight loss. Their results for both alloys are about an order of magnitude larger than our highest corrosion rates.

McGeary et al. (3) report seven year weight loss data for several aluminum alloys exposed at four sites (Kure Beach NC, Point Reyes CA and State College PA). Lowest corrosion rates were observed at the rural site for all alloys, and except for 7075 T6, highest rates were found at the moderately severe industrial environment. For 7075 T6, the highest rate occurred at the 80-foot Kure Beach NC site. Corrosion rates at marine and industrial sites are quite similar, however, and reported difference may not be significant, in contrast with Carteris (6) findings for a copper-containing aluminum alloy.

Additional data for aluminum alloys are shown in Tables 7-9. Industrial environments were the most severe, whereas marine environments were somewhat milder. Ailor's seven year values (8) are in good agreement with those of McGeary et al. (3). Ailor notes that intergranular and exfoliation corrosion were more dominant in marine environments, whereas weight loss and pitting corrosion were prevalent at industrial sites.

4.2 CORROSION RATES COMPARED WITH ENVIRONMENT

Sufficient PACER LIME data are available for environmental comparisons for AZ31B, 2024 and 7075 alloys only. In the case of 4043 and the aluminum assembly, there are but four data values each. For 7079 there also are only four values, but there are literature corrosion rates which warrant environmental comparison.

For each site, the CDA yields a two-letter scale, viz., BB, AB, etc. The first rating is derived from less-tolerant threshold values for environmental parameters, and the second from a more-tolerant set. Thus a second-letter "A" indicates a more severe environment than does a first letter "A." Ratings range from mildest "C" through "B" and "A" to the most severe "AA." For data plotting, these letters are assigned a numerical scale 1 to 4 for C to AA, and the two-letter values are summed. Thus, an "AB" environment yields the sum of 5, and "AA, AA" yields 8.

Data for the magnesium alloy, Figure 1, shows a remarkable good correlation with the CDA rating, with one or two discrepancies. ASTM data for State College PA and Newark NJ are high for their environmental ratings. The PACER LIME data, however, are consistent.

In the case of 2024 T3 Alcald, Table 8 nearly all the results are consistent, with the exception of the ASTM McCook IL and Richmond VA values. The data for 7075 T6, Table 7 are similar to those of 2024 T3. The four PACER LIME 7079 T6 data points are plotted with ASTM results, and are consistent with the CDA ratings.

5. CONCLUSION

The experimental phase of PACER LIME was designed to calibrate the Corrosion Factor Equation by measuring weight losses of panels exposed at several airbases. The results are less useful than expected:

(1) Although alloys tested were typical aircraft alloys, they were not especially suitable for measuring environmental corrosivity by weight-loss methods. The aluminum alloys are relatively resistant to general corrosion, weight losses were small, and potential experimental errors large. The titanium alloy did not corrode and yielded no data.

(2) Test sites which yielded data were quite similar and more-or-less, whereas the mild and severe test sites were unproductive.

(3) Experimental methods were flawed:

(a) Rubber-stopper rubbing to remove corrosion products is not reproducible and not effective.

(b) Removing cleaning, and weighing all panels at six-month intervals was unfortunate because information was lost and technicians were overburdened.

(4) This was a complex program, with significant potential for expanding knowledge or corrosion. Resources committed to it, however, were inadequate.

(5) Although misfortune can be expected, PACER LIME received more than its share.

With these facts, together with scant data from the experiment, it is difficult to give serious weight to the apparent relative corrosivity of each test site. Despite flaws in the experiment, however, the results are consistent with those of other workers, the results agree with USAF maintenance experience, and the results confirm environmental ratings from the Corrosion Damage Algorithm.

We conclude that the experimental phase of PACER LIME was successful in supporting a priori environmental corrosion severity ratings. Its success did not extend far enough, however, to provide a basis for a more accurate rating system.

TABLES AND FIGURES

Table 1. Ranges of Environmental Ambient Parameters, Continental U.S.[19]

	50th Percentile	99th Percentile	Maximum Reported
Total Sustended Particulates, $\mu g/m^3$	61	185	500
Sulfur Dioxide, $\mu g/m^3$	43	186	410
Photochemical Oxidants, as ozone, $\mu g/m^3$	36	90	110
Nitrogen Oxides			
as NO, $\mu g/m^3$	25	88	98
as NO_2, $\mu g/m^3$	72	135	150
Temperature, °C	11.8	23.3	25.7
Humidity, absolute, g/m^3	7.1	16.5	18.3

Table 2. National Ambient Air Quality Standards [8,9]

	Primary	Secondary[a]	
Sulfur dioxide	80	60	$\mu g/m^3$, annual arithmetic mean
	365	260[b]	$\mu g/m^3$, 24-hour maximum
		1300[c]	$\mu g/m^3$, 3-hour maximum
Particulate matter	75	60	$\mu g/m^3$, annual geometric mean
	260	150	$\mu g/m^3$, 24-hour maximum
Carbon monoxide	10	10	mg/m^3, 8-hour maximum
	40	40	mg/m^3, 1-hour maximum
Photochemical oxidants	160	160	$\mu g/m^3$, 1-hour maximum
Hydrocarbons	160	160	$\mu g/m^3$, 6 to 9 AM maximum
Nitrogen dioxide	100	100	$\mu g/m^3$, annual arithmetic mean

[a] Maximum values are not to be exceeded more than once per year.

[b] ". . . as a guide to be used in assessing implementation plans to achieve the annual standard."

[c] ". . . as a guide to be used in assessing implementation plans to achieve the 24-hour standard."

Table 3. Working Environmental Corrosion Standards (WECS)

	Annual Mean	
	I	II
Suspended Particulates, $\mu g/m^3$	61	86
Sulfur dioxide, $\mu g/m^3$	43	72
Ozone, $\mu g/m^3$	36	47
Nitrogen dioxide, $\mu g/m^3$	64	78
Absolute humidity,* g/m^3	7.1	9.0
Proximity to sea or salt source, km	4.5	2
Solar radiation, July (Langleys)	600	650
Rainfall, cm total	125	150

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*Absolute humidity is the product of relative humidity and the mass of water in one cubic meter of water-saturated air at a given temperature.

Table 4. Environmental Ratings for Selected Test Sites

Site	Test Type	Corrosion Damage Algorithm Rating
Altus AFB OK	C-141A base	A,B
Andrews AFB MD	PACER LIME	A,B
Barksdale AFB LA	PACER LIME	A,B
Charleston AFB SC	C-141A base	AA,B
Corpus Christi TX	Other	AA,AA
Davis Monthan AFB AZ	PACER LIME	B,C
F.E. Warren AFB WY	PACER LIME	C,C
Kure Beach NC:	Other	
80 ft		AA,AA
800 ft		AA,A
McCook IL	Other	A,B
McChord AFB WA	C-141A base	A,C
McGuire AFB NJ	C-141A base	B,C
Newark NJ	Other	A,B
Norton AFB CA	C-141A base	A,A
Panama Canal Zone:	Other	
Marine*		AA,AA
Open Field*		AA,AA
Rain Forest*		AA,AA
Point Reyes CA	Other	AA,A
Richmond VA	Other	A,B
Robins AFB GA	PACER LIME	A,B
State College PA	Other	B,B
Tinker AFB OK	PACER LIME	B,C
Travis AFB CA	C-141A base	AA,A
Wright-Patterson AFB OH	PACER LIME	A,B

*Reported corrosion rates [35] suggest a higher rating than AA,AA.

Table 5. Materials Tested in PACER LIME Program

Code	Number of Panels	Size	Materials
01	12 ea	12.7 x 14.3 cm	2024 T3 (clad)
03	12 ea	12.7 x 14.3 cm	7075 T6
05	12 ea	12.7 x 14.3 cm	7079 T6 (clad)
07	12 ea	12.7 x 14.3 cm	4340
09	12 assemblies	12.7 x 14.3 cm	*
11	12 ea	12.7 x 14.3 cm	Mg AZ31B-0
13	12 ea	12.7 x 14.3 cm	Ti 6Al 4V
15	5 ea	12.7 x 29.8 cm	2024 T3 (clad)
17	5 ea	12.7 x 29.8 cm	7075 T6
21	5 ea	12.7 x 29.8 cm	Mg AZ31B-0

99 Total panels for each test stand.

*The assemblies were made from one panel each of

(clad) 2024 T3
7075 T6
(clad) 7079 T6

each panel was 12.7 x 6.4 cm. The assemblies were riveted with 4 cadmium plated rivets and assembled as shown in Figure 2.

Table 6. Corrosion Rates For Four Year Exposure in the Panama Canal Zone (afer Pearlstein and Teitell [35]).

	Marine	Openfield	Rain Forest
2024 T3	9.75×10^{-5}	8.9×10^{-6}	negligible
AZ31B-0	4.8×10^{-4}	2.2×10^{-4}	$1.3. \times 10^{-4}$

kg/m^2-day

Table 7. Corrosion Rates for Seven-year Exposure at Several Test Sites (after McGeary et al [36]).

	Kure Beach 80-foot (E. Coast Marine)	Newark NJ (moderately severe industrial)	Point Reyes CA (W. Coast marine-1900 ft)	State College PA (rural)
2024 T3 Alclad	1.62×10^{-6}	2.04×10^{-6}	0.76×10^{-6}	0.34×10^{-6}
2024 T3 bare	3.77×10^{-6}	4.28×10^{-6}	2.97×10^{-6}	0.52×10^{-6}
7075 T6	5.67×10^{-6}	4.90×10^{-6}	4.61×10^{-6}	0.66×10^{-6}
7079 T6 Alclad	1.98×10^{-6}	2.96×10^{-6}	(lost)	0.43×10^{-6}

Kg/m^2-day

Table 8. Corrosion Rates for Seven-year Exposure of 2024 T3 Aluminum at Several Test Sites (after Ailor [37]).

	Kure Beach NC 800-ft (E. Coast Marine)	Corpus Chisti TX 150-ft (Gulfcoast Marine)	Richmond VA (moderate industrial)	McCook IL (industrial)
1 year	7.62×10^{-6}	14.5×10^{-6}	23.6×10^{-6}	52.9×10^{-6}
2 years	1.89	5.92	18.0	33.2
7 years	2.17	2.57	4.40	7.14

kg/m^2-day

Table 9. **Corrosion Rates for One-year, Two-year, and Seven-year Exposure of Aluminum and Magnesium Alloys (after Copson [39], Pettibone [40,41], and Coburn [42].**

	Kure Beach NC 80 ft lot	Newark NJ	Point Reyes CA	State College PA
	Corrosion rate x 10^6	kg/m^2-day		
2024 T3 Alclad				
1 year	2.40	2.77	1.73	0.60
2 years	1.74	2.25	1.43	0.52
7 years	1.62	2.04	0.76	0.34
7075 T6				
1 year	9.87	5.77	7.75	1.18
2 years	6.85	4.34	6.33	0.90
7 years	2.46	3.29	1.15	0.42
7079 T6 Alclad				
1 year	1.28	2.63	0.99	0.60
2 years	2.26	2.68	2.28	0.60
7 years	*	4.85	*	0.49
*** data considered unreliable**				
AZ31B-H24				
2 years	86.7	134	71.1	90.3
7 years	71.6	129	55.5	68.1

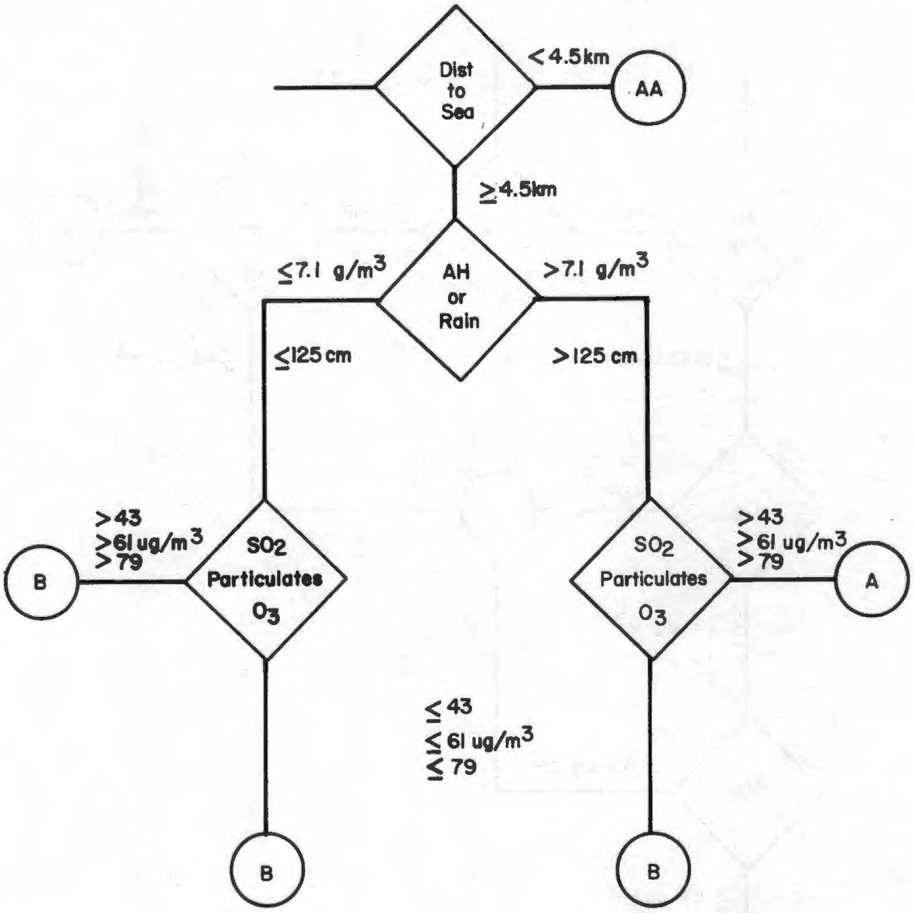

Figure 1. Corrosion Damage Algorithm for aircraft using set I of Working Environmental Corrosion Standards (Table 3).

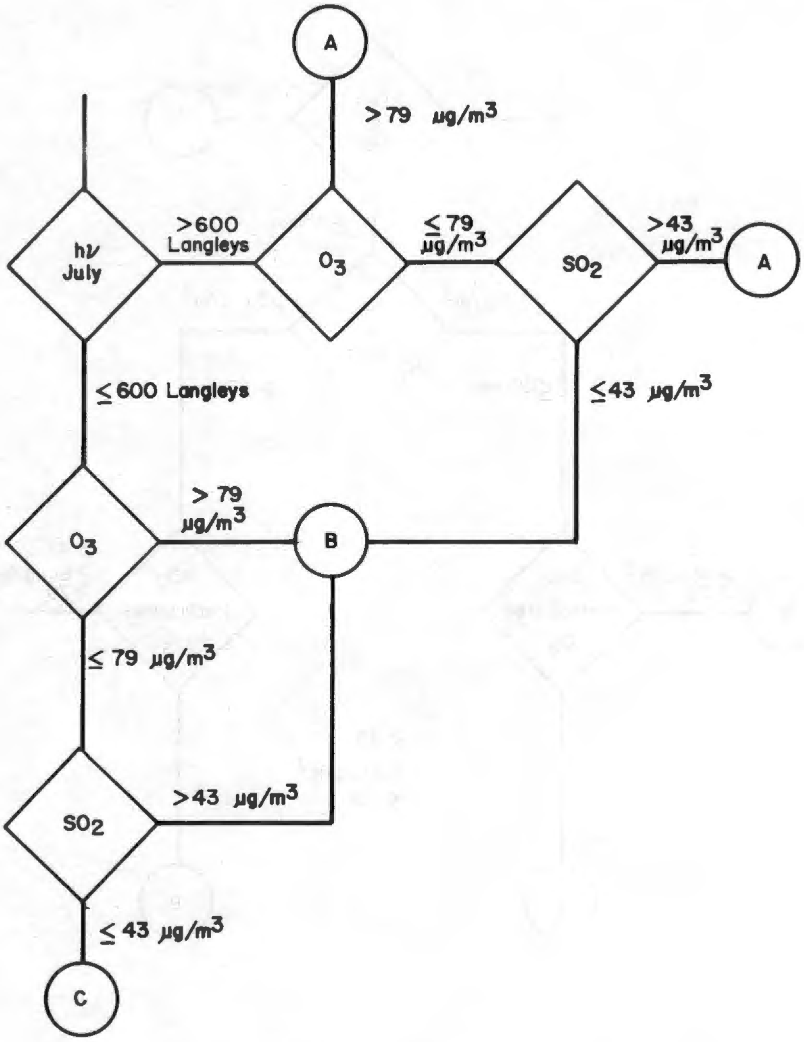

Figure 2. Aircraft Complete Repaint Algorithm.

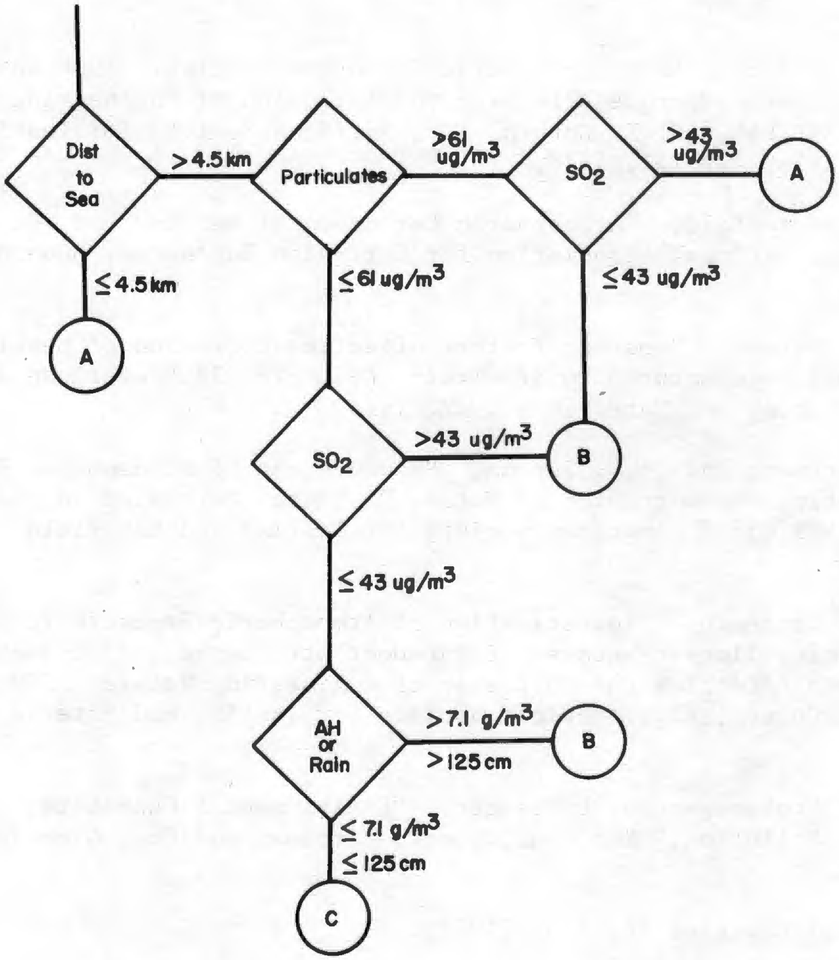

Figure 3. Aircraft Washing Interval Algorithm.

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