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Measuring Rates and Impact of Corrosion on DOD Equipment

Sean Morefield, Susan Drozdz, Vincent Hock

Engineer Research and Development Center, Construction Engineering Research Laboratory,
2902 Newmark Drive, Champaign, IL 61822-1076,

and

William Abbott

BATTELLE, 505 King Avenue, Columbus, OH 43201-2693, USA

Sean.Morefield@erdc.usace.army.mil, Susan.A.Dorzdz@erdc.usace.army.mil,
Vincent.F.Hock@erdc.usace.army.mil, wabbott@battelle.com

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Abstract. A large scale atmospheric corrosion monitoring test was undertaken for the purpose of characterizing environmental severity. This work was conducted at ground based Army, Navy, Coast Guard, and Air Force sites. At present over 73 sites are in operation. This work adds to the existing worldwide databases to include new military and/or related sites not previously monitored. In addition and to the extent that such data are available, relevant weather data was collected from public or military sources in order to test existing corrosion algorithms for each site. Many of the 1 year exposures have been successfully completed. However, all of the exposures currently in progress will not be completed until early 2008. Sample analyses are in progress. New data have

been obtained to show the important effects of sheltering on reducing corrosion rates. Data from Daytona Beach and Tyndall AFB show that even a relatively simple open structure/sunshade can reduce corrosion rates by factors of 2 or 3. New data are being reported on corrosion vs. distance from ocean. Data were also collected for the comparison of corrosion severity among commonly used test sites and within selected sites (multiple locations within a base.)

Introduction

Throughout the world, corrosion maintenance is most often based on finding and repairing the damage prior to its becoming a structural or safety concern. DoD has identified this approach as inadequate to meet mission criticality, e.g. equipment and facilities availability to support deployment, training, and readiness. There has been little emphasis on the development of engineering tools needed for the management of this corrosion and the associated maintenance and repair actions. The benefits and longevity of corrosion prevention and control measures have not been quantified so optimization of these actions has not been possible. As the DoD fleets and facilities have aged, the life limiting degradation mechanisms have shifted from those associated with usage to those associated with time. The costs of corrosion maintenance have risen drastically. Furthermore, the concerns for corrosion, which previously had centered around cost, have now begun to include structural integrity and safety. This shift has dictated a change to a prediction and management approach beyond just simply finding and repairing. For convenience, the reader is referred to a table of acronyms common to this paper, Table 1.

Table 1. Common Acronyms

Acronyms	**Description**
NSF	National Science Foundation
VAFB	Vandenburg Air Force Base
KSC	Kennedy Space Centre
DoD	Department of Defense (USA)
CG	Coast Guard ship

The original plan was to conduct sampling at a minimum of 40 sites distributed worldwide. This number has been increased several times and the current distribution among the Services follows in table 2.

Table 2. Distribution of Monitoring sites.

Army	18
Air Force	19
Coast Guard	14
Navy	6
NASA	8
NSF	2
Other	6

The goal of the study was to collect atmospheric corrosion data on uncoated metal samples for the purpose of characterizing environmental severity. Of particular interest were the atmospheric corrosion rates observed at locations within 16 km (10 miles) of ocean coastline. Eventually data collected in this study will feed into a corrosion prediction algorithm and corrosion severity index system.

Experimental Procedure

The plan was to distribute a small, "standard" test rack to each location containing a single test card holding the uncoated metal coupons. This card was replaced every 3 months over the course of 1 year. The exception to this was for any sites outside the continental US (OCONUS) in which cases a larger rack with 4 cards was sent up front for Quarterly removals.

Each test card contained silver, copper, and 1010 steel coupons, and three aluminum alloys (2024 T3, 6061 T6, and 7075 T6). The silver is rather unique and represents a Battelle development/procedure for getting a measure of atmospheric chlorides.

The coupons were placed on polymer panels and placed uncovered in a number of Department of Defense facilities. The test coupons were placed in primarily uncovered positions, and a select number of covered positions for comparison.

This effort covered a broad geographic scope. The final site count for this work exceeded 73 installations requiring separate test racks. Samples were placed at select locations at Kennedy Space Center and Vandenburg Air Force Base to examine the relationships between corrosive severity and distance-from the ocean. Sample returns were analyzed for mass loss in accordance with ASTM G1 [1] and chlorides in accordance with ASTM B825 [2].

The data directly collected in this study measures the general atmospheric corrosion rate, not the pitting rate. However, since there is also chloride deposition and weather data, it may be possible to estimate pitting potential using other models.

Results

Results for the tests to determine the relationship between corrosion rate and distance from the ocean are shown in Fig. 1-6. The data in Figures 1 through 3 represents nine months of exposure, and Figures 4 through 6 represents twelve months. The plots show data at zero distance from the coast. These points represent data from racks located approximately 10-meters from the high-tide mark.

Several features are very clear from these data. First, is the fact that chlorides and particularly corrosion rates vary greatly as a function of distance. The message from such data is that when coastal corrosion rates are presented it is very important that distance from the ocean also be given. These data also illustrate the very important effect that positioning of equipment/aircraft/etc: in relation to the coast can have on corrosion. The data in Fig. 2 and 3 indicate that position within even the first 0.4 km or less can be critical.

A second feature in these recent data would now indicate very similar relationships for distance effects at Kennedy Space Center (KSC) and Vandenberg Air Force Base (VAFB). Both locations rate as very severe and similar. In fact, beyond the 1.6-3.2 km (1-2 mile range) inland both locations are nearly the same.

These data indicate that VAFB is one of the more severe locations in this study at less than 1.6-3.2 km from the shore. In fact, for similar distances it appears to be more severe than KSC. This difference may be due to the very high atmospheric chloride levels found at VAFB and which persist for greater distances inland. These data confirm that there is a sharp decrease in severity with distance from ocean. This is shown at both in Fig. 2 and 3 for the corrosion of two metals at KSC and VAFB. The sharpest portion of that decrease is well within the first 1.6 km. Attenuation factors are in the range of 7-8 to 1.

There are, however, some surprising results in these data. The first is the high overall corrosion severity at VAFB and particularly as compared to KSC. This was, at least, surprising to Battelle since in spite of extensive worldwide monitoring at military bases worldwide it is surprising to see values this high particularly on the West Coast. In this respect, VAFB ranks near the top of our worldwide severity scale. Initially we expected to see a higher corrosivity near coastlines compared to inland areas, but did not expect to see a significant difference between the east and west coastal monitoring sites.

The severity levels at VAFB appear to be due mainly to the high atmospheric salt/halogen content in the environment and at levels that appear to remain unusually high for a long distance inland. In other words, they do not appear to decrease at the rate "expected" from earlier work at coastal sites. The reasons for these unique features are not yet known but may be due to unique, prevailing wind patterns at VAFB. This will be studied further.

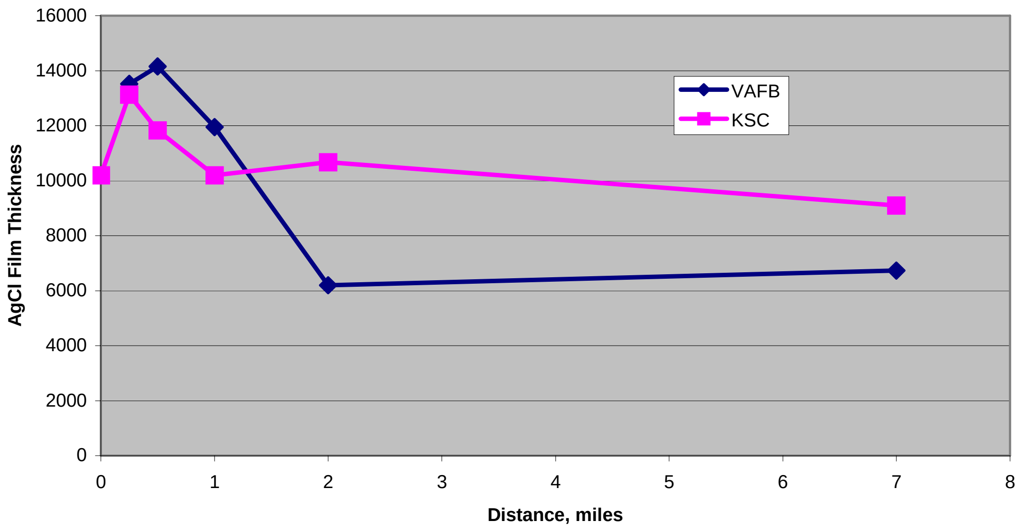

Fig. 1. Chloride (From Battelle Silver Sensors) vs. Distance at KSC and VAFB; 9 Month Data

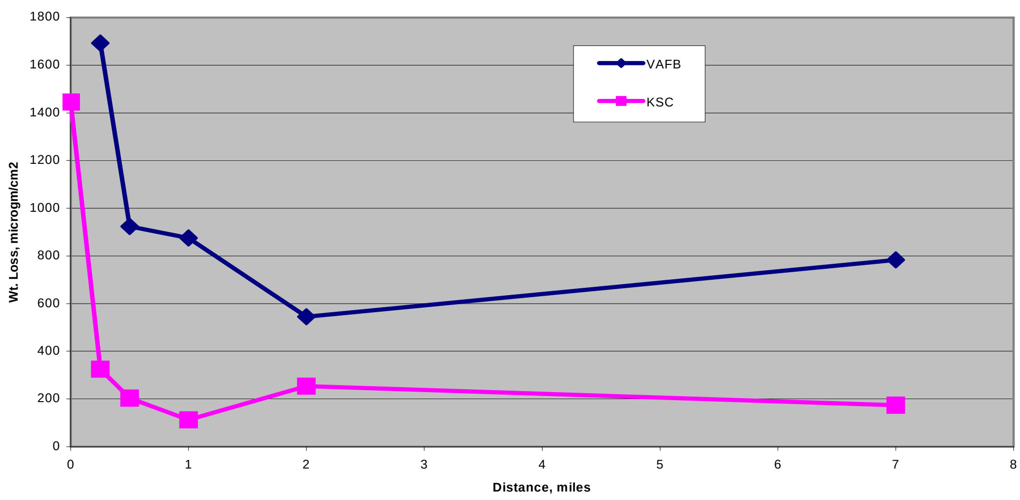

Fig. 2. Corrosion of 2024 T3 Aluminum At KSC and VAFB; 9 Month Data

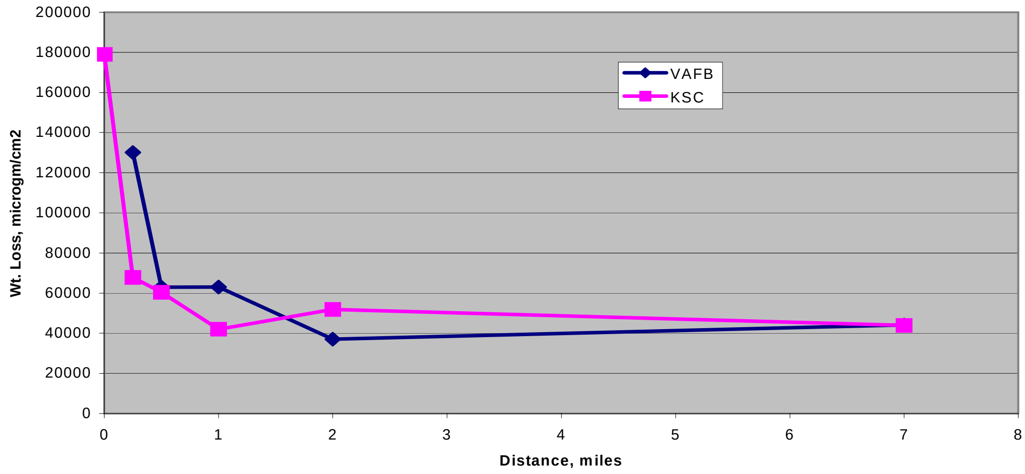

Fig. 3. Corrosion of 1010 Steel At KSC and VAFB; 9 Month Data

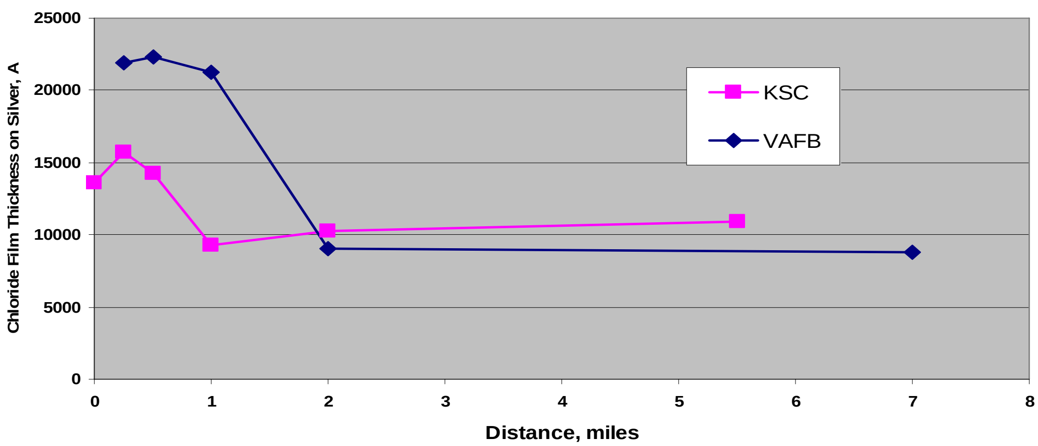

Fig. 4. Atmospheric Chloride vs. Distance from Ocean at KSC and VAFB; 1 Year Values

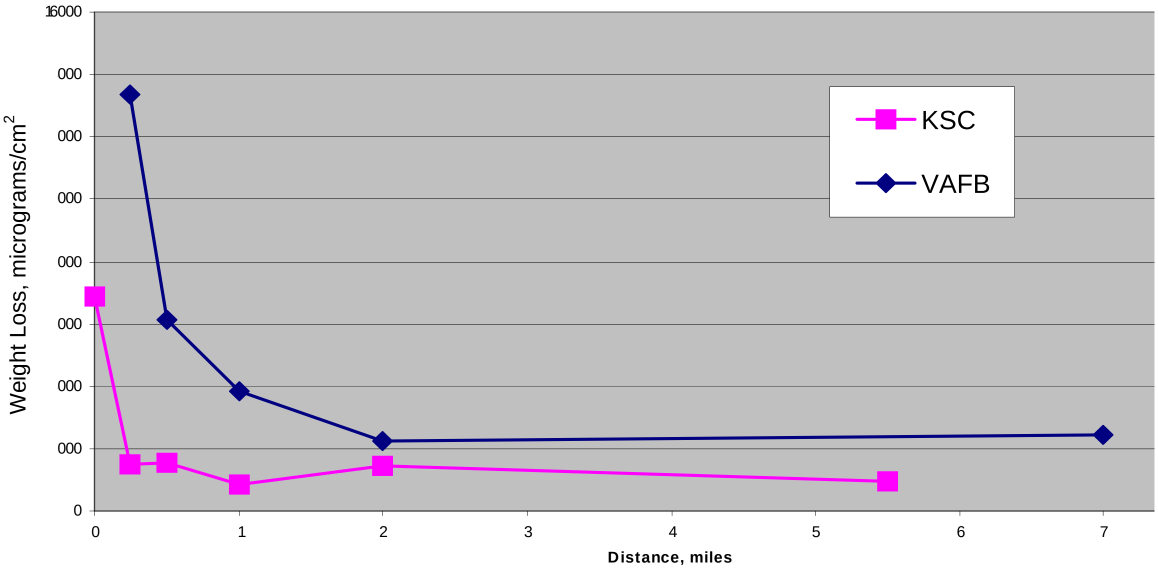

Fig. 5. Corrosion of 2024 T3 Aluminum At KSC and VAFB vs. Distance; 1 Year Values

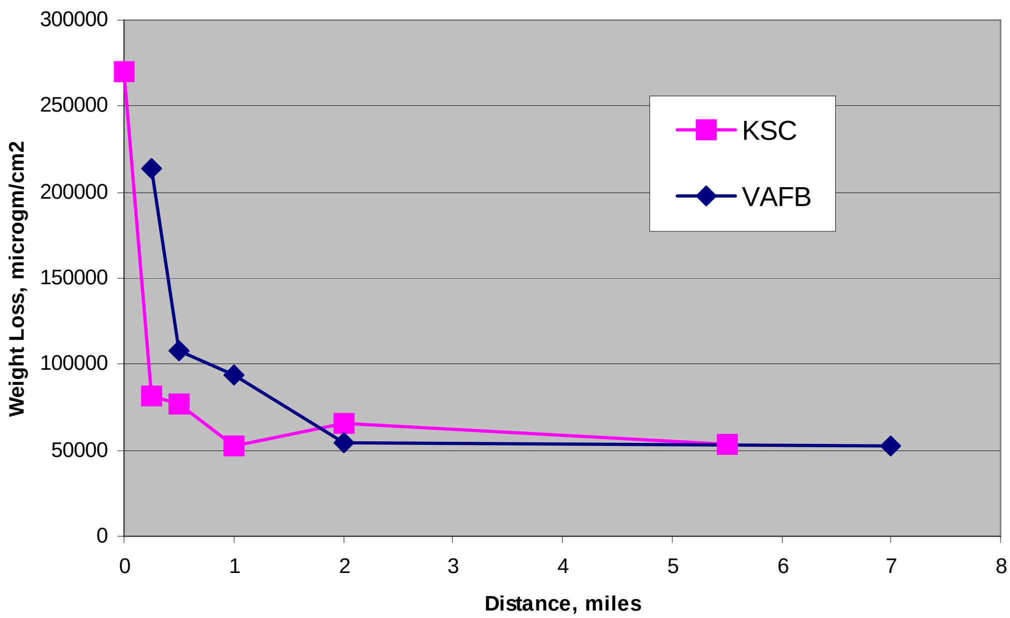

Fig. 6. Corrosion of 1010 Steel at KSC and VAFB vs. Distance; 1 Year Values

Initial analyses have been made for several of the test sites that have historically been used for corrosion exposures. These include KSC, Pt. Judith, Battelle Daytona, and Key West. Vandenberg has been added to this list as a matter of interest and contrast as the only West Coast site. Samples are now in place at LaQue and it is likely that data will be obtained over at least 9 months before this site closes.

Kinetic Chloride results for these sites are shown in Fig. 7. One important point to note concerning these data is the necessity to clearly define where the samples are being exposed in relation to distance-from-ocean. This was shown in Fig. 1-6. It is also shown for Pt. Judith where there is a large difference between the Front and Back of the test lot. Some of these details are not yet available but it will be our intent to define locations for each of these sites. Again, it should be emphasized that these are early results, and it will be of particular interest to see how the data develop over a full year of study.

These early data show measurable differences among atmospheric chloride levels but Fig. 8 and 9 show far greater differences in corrosion rates. Coupons from KSC show lower levels of Chlorides demonstrate higher levels of corrosion rate. Additionally, coupons from Key West show higher chloride levels and lower corrosion rates compared to KSC. Attempts have not yet been made to examine these results against current corrosion models. However, if these models hold true, the corrosion rate differences would have to be accounted for by significant differences in relative humidity, Time of Wetness and to a lesser extent rainfall.

These new data show very similar annual chloride levels among these particular sites. However, as shown in Fig. 8 and 9 the chloride levels alone do not account for the large differences in corrosion rates among the same sites/locations as there is not a sufficiently strong correlation between the chloride concentrations and the corrosion rates.

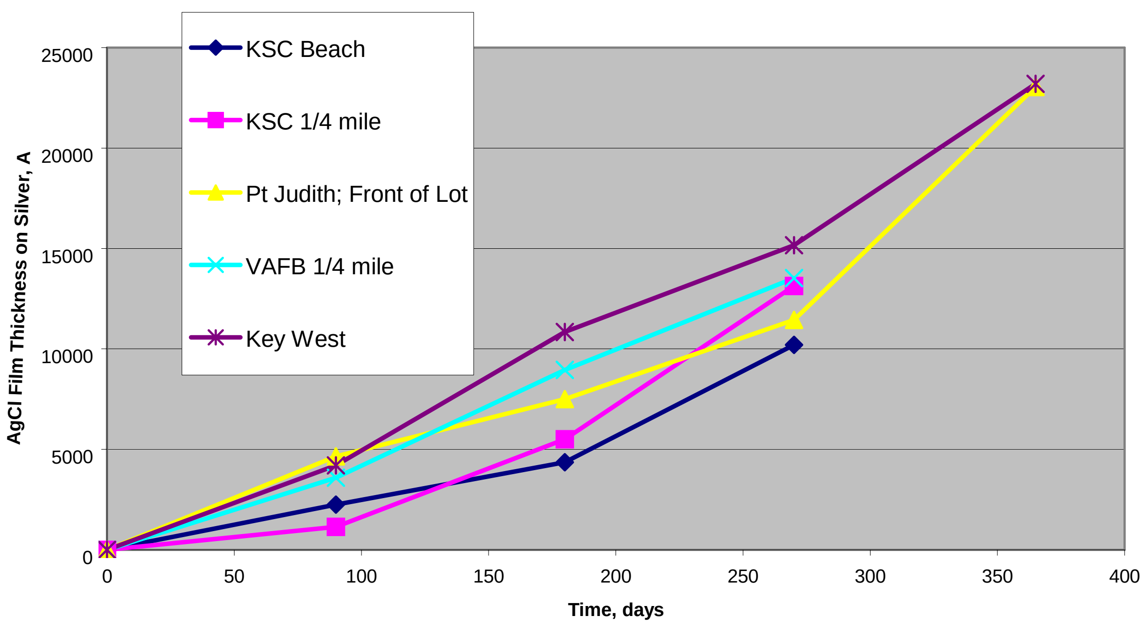

Fig. 7. Site Comparisons for Atmospheric Chlorides from Silver Sensors

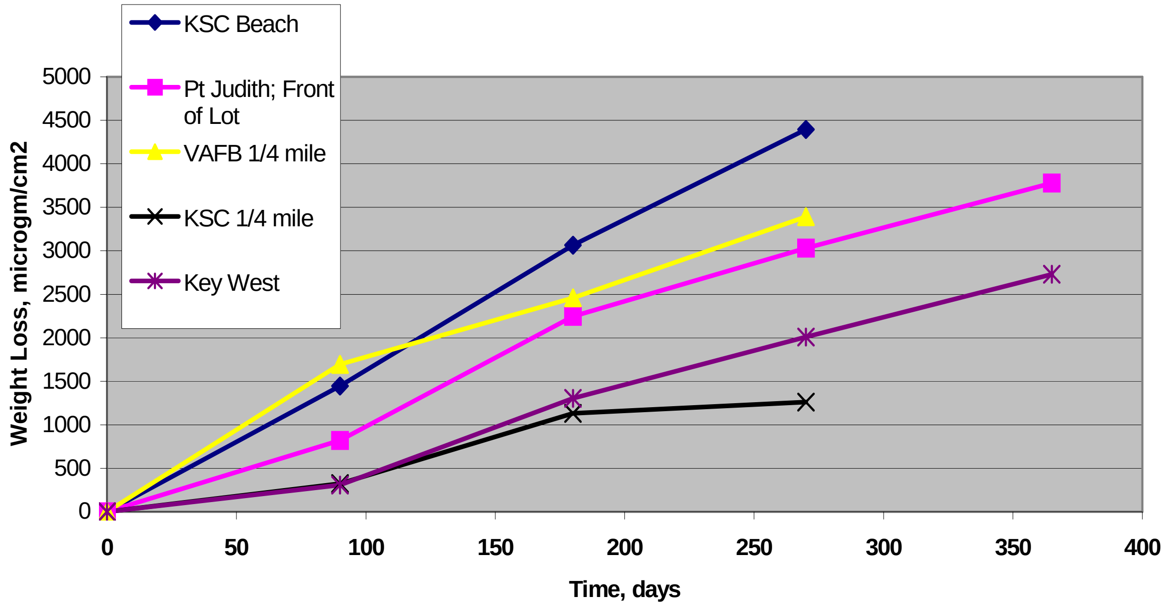

Fig. 8. Comparison of Test Sites; Corrosion of 2024 T3 Aluminum

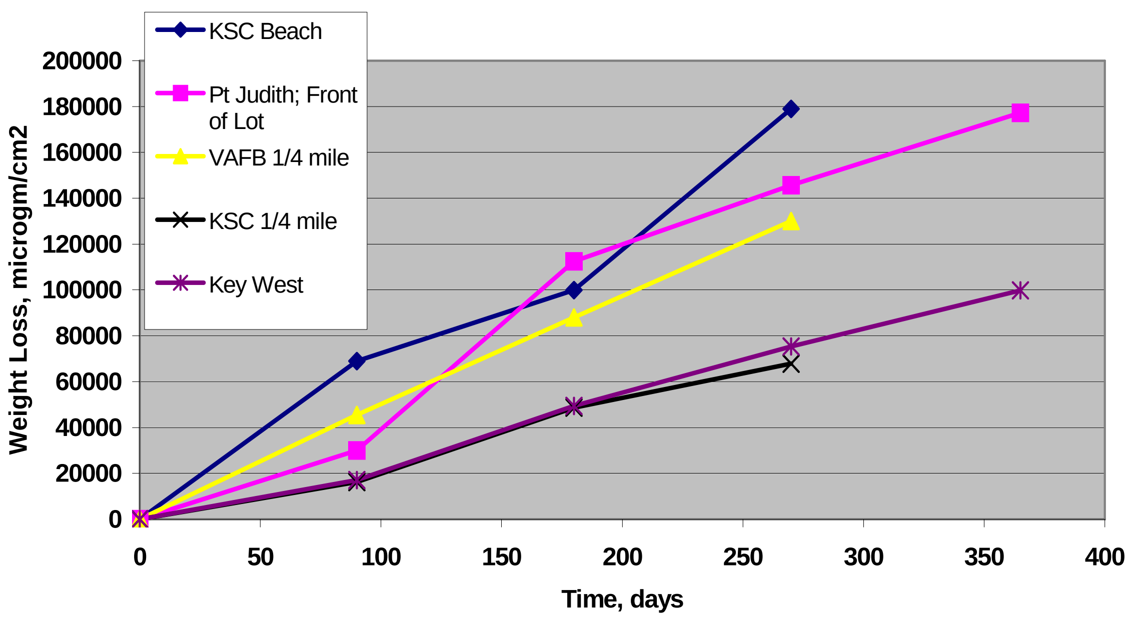

Fig. 9. Test Site Comparisons; Corrosion of 1010 Steel

The data for KSC are particularly important to illustrate some of the effects already discussed concerning distance effects and the synergistic effects of chlorides and humidity. The KSC beach site is one of the most severe. For test purposes this may be an important result. However, that high level of severity is not descriptive of overall conditions at KSC due to the distance effects. For example, 0.4 km (¼ mile) inland (and possibly less) shows results far less severe than at VAFB and most other of these relatively severe sites. These dramatic differences are most likely due to time of wetting (TOW) levels due to the close proximity to the surf.

Some early results for effect of sheltering on corrosion rates are expressed as the chloride film thickness on silver sensors is shown in Tables 3 and 4:

Table 3. Tyndall AFB, 105 days exposure

Exposure	**Material**	**Result**
Outside	2024 aluminum	215 microgm/cm^2
Inside	2024 aluminum	48 microgm/cm^2
Outside	6061 aluminum	98 microgm/cm^2
Inside	6061 aluminum	41 microgm/cm^2
Outside	7075 aluminum	234 microgm/cm^2
Inside	7075 aluminum	71 microgm/cm^2
Outside	1010 Steel	12680 microgm/cm^2
Inside	1010 Steel	8157 microgm/cm
Outside shelter	Chloride sensor	2370 A; chloride
inside shelter	Chloride sensor	1460 A; chloride

Table 4. Coast Guard Ship Harriett Lane, 90 days exposure:

Exposure	**Material**	**Result**
outside	2024 aluminum	1829 microgm/cm^2
inside	2024 aluminum	30 microgm/cm^2
outside	6061 aluminum	708 microgm/cm^2
inside	6061 aluminum	18 microgm/cm^2
outside	7075 aluminum	1003 microgm/cm^2
inside	7075 aluminum	22 microgm/cm^2
outside	1010 Steel	48496 microgm/cm^2
inside	1010 Steel	3349 microgm/cm
above deck	Chloride sensor	12316 A; chloride
Hangar Bay –	Chloride sensor	253 A; chloride

The data presented in table 4 are highly significant for several reasons. The reactive chlorides represent a major factor in atmospheric corrosion rate. These data do not represent the total picture of the corrosion drivers, yet they are very important. This is particularly significant for both locations since it is expected that reduced rainfall and probably reduced time of wetness (TOW) will lower corrosion rate results even more than what is implied by these chloride values. These results continue the trends found in all earlier work to indicate how even simple sheltering procedures may have a large effect on corrosion.

The results for Tyndall are in the “expected” range in Battelle’s experience for earlier results from shelters. However, the implied sheltering effects/attenuation ratios for the Coast Guard ship appear far too high. Questions have been asked to the Coast Guard about the exact location and conditions surrounding the samples placed in the “Hangar Bay”. It appears that while this location may be called a Hangar Bay, it is not used for this purpose. Furthermore, present indications are that the door to this location is usually closed or only partly open in contrast to the situation associated with aircraft shelters and even the Hangar Bays on the aircraft carriers. Therefore, these attenuation factors for the Coast Guard ship are believed to be unrealistically high. At the same time, the data do indicate how small changes in the conditions surrounding items that may corrode can be affected by nearby structure.

Analyses have been made of the chloride levels (Battelle silver sensor method) obtained during recent deployments on Navy and Coast Guard ships. These particular samples were located above and below deck. In most cases, data will be available below deck as now shown in Fig. 10.

It is of no surprise that these values are quite high. However, it is again noted that these data represent only one important part of the corrosion equation.

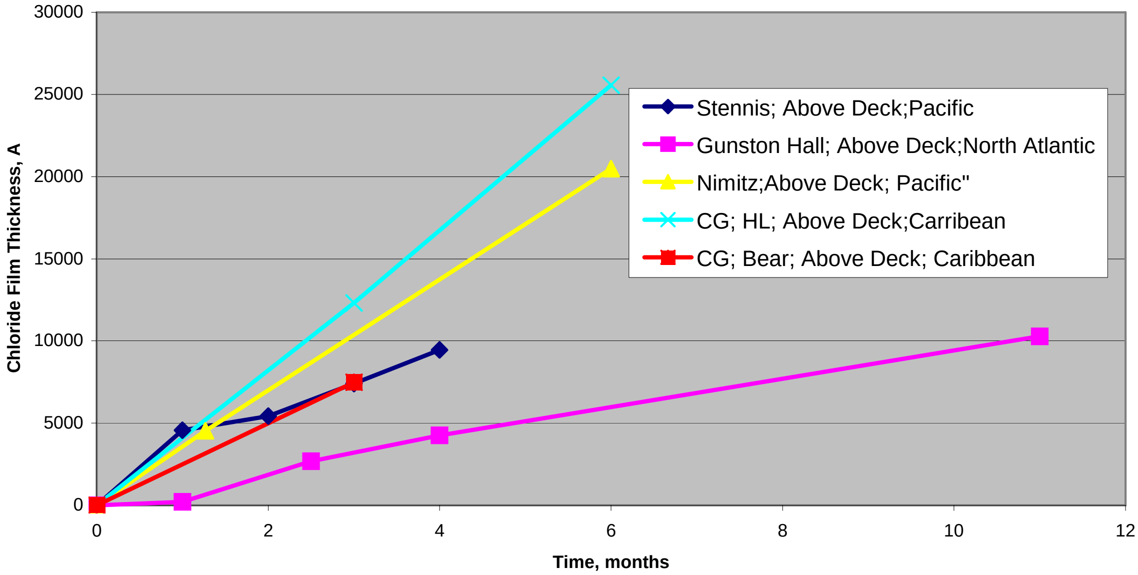

Fig. 10. Reactive Chloride Kinetics Above Deck for Several Ships at Sea

Fig. 11 presents a summary of all of the atmospheric chloride data available to date for ships-at-sea. There is little question that at sea and above deck the atmospheric chloride values are well above the extremes found on land even in coastal regions. As important as these data may be, they do not tell the entire story, since they do not address either corrosion or the very important effect of sheltering.

With regard to the latter, it is evident that very large differences exist between the above-deck locations and any of the more enclosed Bays on the ships. This argument will be developed further as corrosion data are developed. However, it also provides a good introduction to the need for gaining a further understanding of sheltering effects both on land and sea. Fig. 12 summarizes some of the first corrosion data from the same locations at sea.

The corrosion data confirm the general conclusions reached from the chloride data. Specifically, the corrosion rates found above deck are higher than land values but not to the same degree. Also, the sheltering effects remain large but highly variable. The latter was quite evident between the two carrier deployments into the Pacific. We can only speculate that the differences were not due to small differences in geographic regions. It is more likely that any differences were due to operating practices such as the amount of time Bay doors were open and/or any other practices that would have affected air transport and/or humidity levels in Bay 3.

The results of sheltering on the CG ships are worth noting in view of the apparent very high attenuation factors. In these 2 cases, it is understood that what is called the Hangar Bays are typically not used for aircraft storage. This means that the Bay door may not be open or at least to the degree found on the carriers. If this is correct these data show how possibly small differences in operating practices can have a large effect on sheltering/corrosion.

Analyses of most of the 1 year data at a number of Coast Guard land bases have been completed. These results are summarized in Fig. 13 – 15. As expected these results show a wide range of severity levels. Information is being obtained from these locations regarding distance from ocean for the point of sample placement in an attempt to understand these differences.

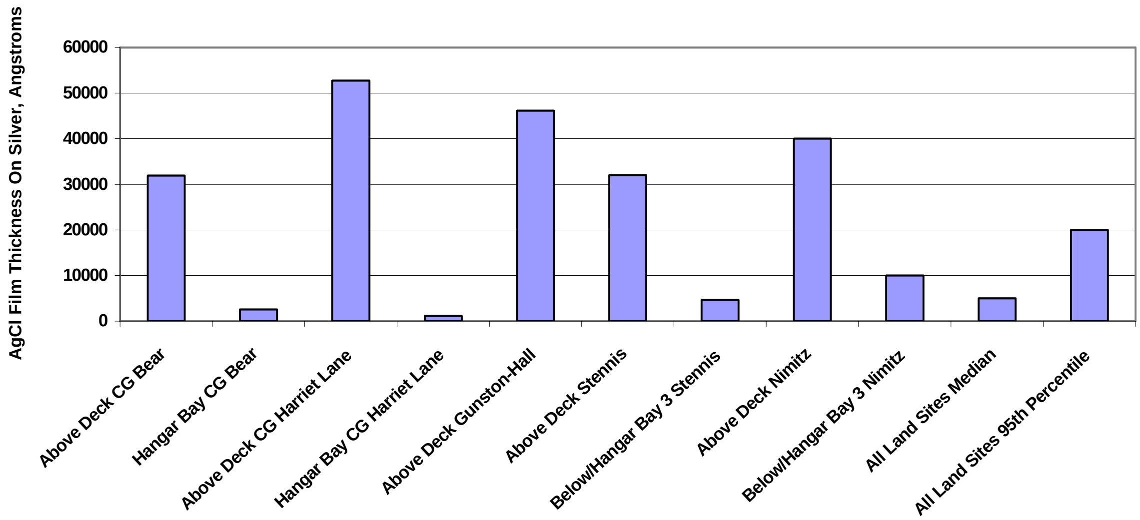

Fig. 11. Atmospheric Chlorides; Comparison of Land vs Ship Data; Projected 1 Year Values

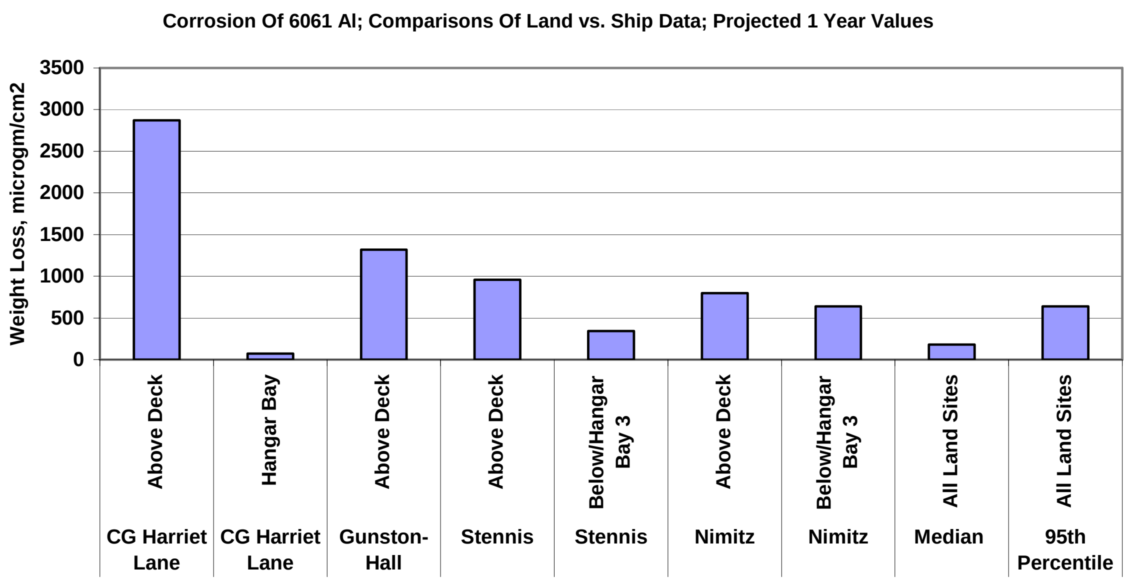

Fig. 12. Corrosion of 6061 T6 Al; Comparison of Land vs. Ship Data; projected 1 Year Values

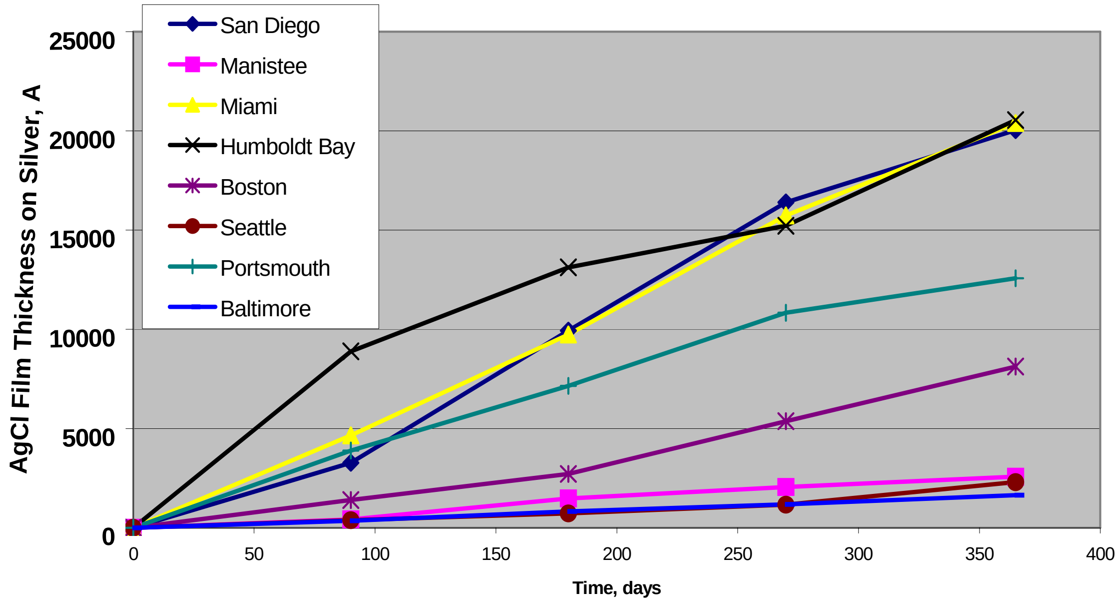

Fig. 13. Chloride Kinetics On Silver Sensors At Coast Guard Stations

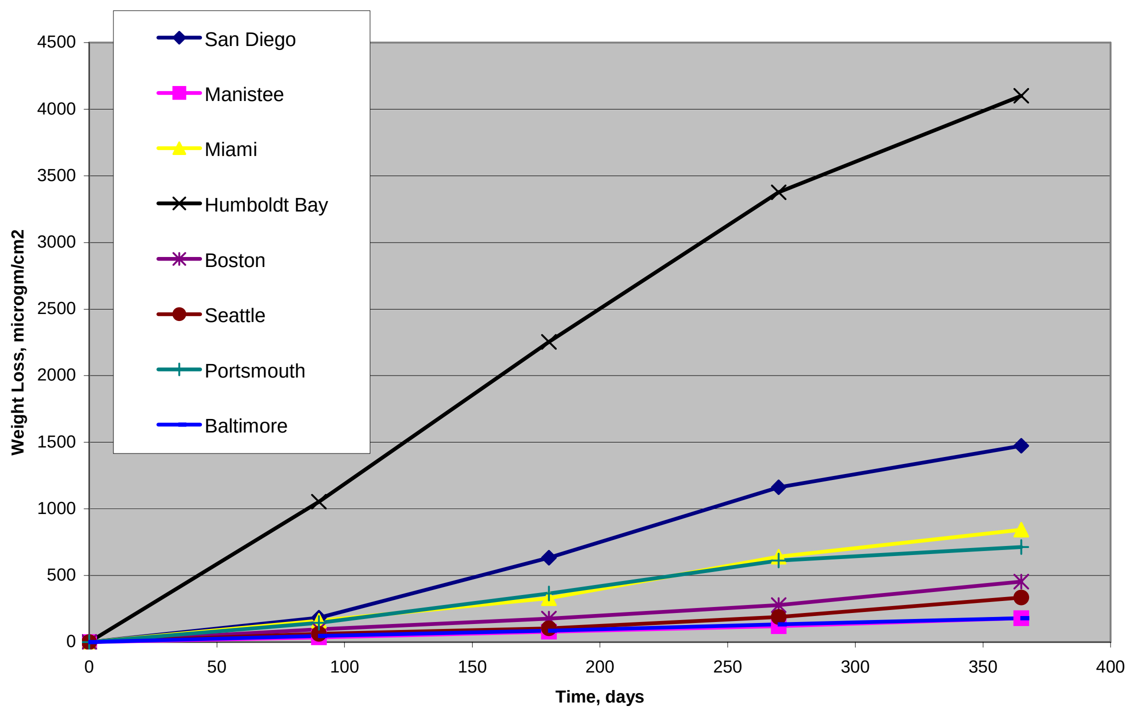

Fig. 14. Corrosion of 2024 T3 Aluminum At Coast Guard Sites

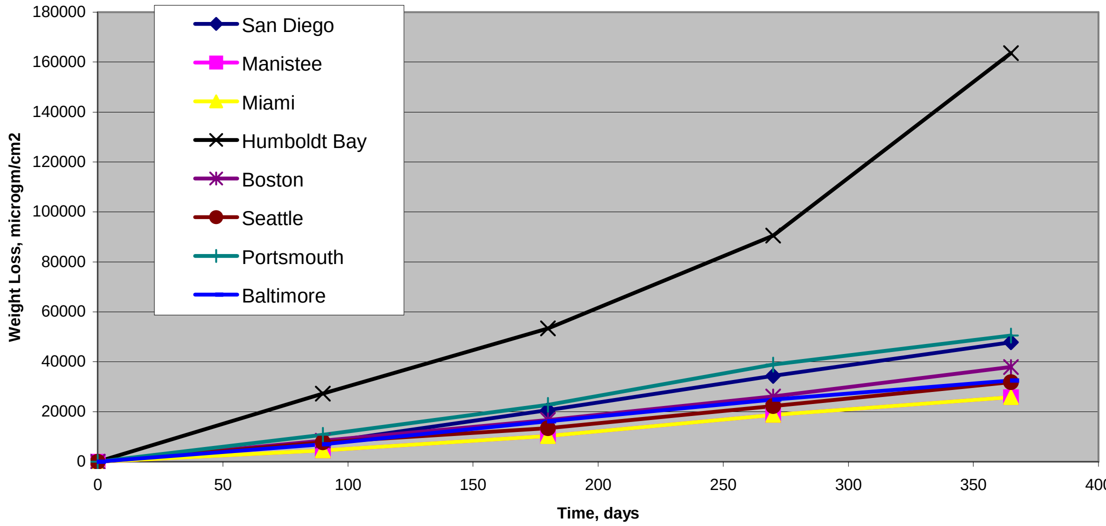

Fig. 15. Corrosion of 1010 Steel At Coast Guard Stations

Data have already been presented to illustrate that there is a very substantial benefit in terms of reduced corrosion rates even from simple sheltering by structure. Most of these data were from ships at sea comparing above vs. below deck conditions. New data are being obtained on land from structures that could be described as open aircraft shelters/hangars/tents/etc: The following discussion shows some early data from a broad range of severity levels at Daytona Beach, Tyndall, AFB (FL) , and China Lake (CA).

Fig. 16 and 17 show results for Daytona. For the data inside the structure reference is made to High and Low. This refers to samples located at 2 elevations. One was about 0.6 m (2 ft) below the peak of the tent; the other was about 1.8 m (6 ft) below the peak or about half way below the peak and ground level.

Fig. 18 and 19 show comparable data at Tyndall. Fig. 20 and 21 were obtained for an aircraft shelter at the Navy's China Lake facility.

It is clear that at Tyndall and the inland Daytona sites, corrosion attenuation is being demonstrated. Both Tyndall and inland Daytona are relatively severe sites with Tyndall actually showing higher ESI values. This is somewhat significant since these data are suggesting that the greatest benefits may actually occur in those environments where they are most needed. For example if we compare corrosion at 200 days, we find an attenuation factor of about 3.5:1 at Tyndall, 2.5:1 and at inland Daytona. For the benign location at China Lake, there is no apparent benefit.

Recently, the first (90 day) data were obtained from a metal hangar (CAP shelter, open both ends only at Wheeler AAF, HI. Here, the outside ESI values were slightly lower than the inland Daytona values, yet the corrosion attenuation for 2024 T3 was approaching 5:1. It is too early to reach any definitive conclusions of whether the shelter structure is giving the higher attenuation.

At this time, the more important conclusion concerns the consistent observation of corrosion attenuation by structure, particularly in the more severe environments.

Among the diverse and numerous sites being studied in this work there are several that have historically been used for corrosion exposures. Specifically, Point Judith, Key West FL, Kennedy Space Center beach site, Battelle OH, and Vandenberg AFB. It was considered useful to develop a comparison among these sites for monitoring conducted in a consistent manner.

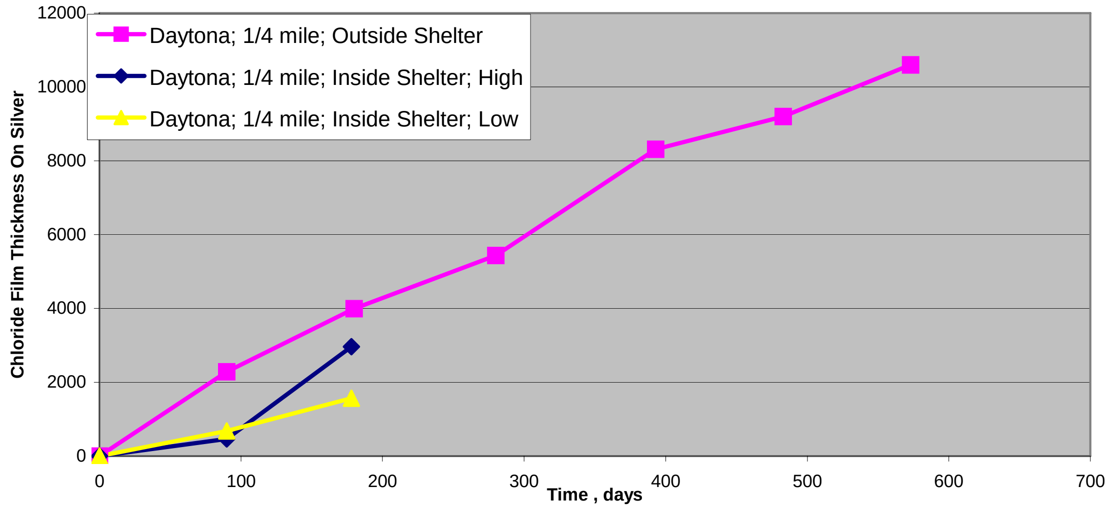

Fig. 16. Chloride Reaction Kinetics on Silver Sensors Inside and Outside Open Tent Structure at Daytona Beach; 0.4 km Inland

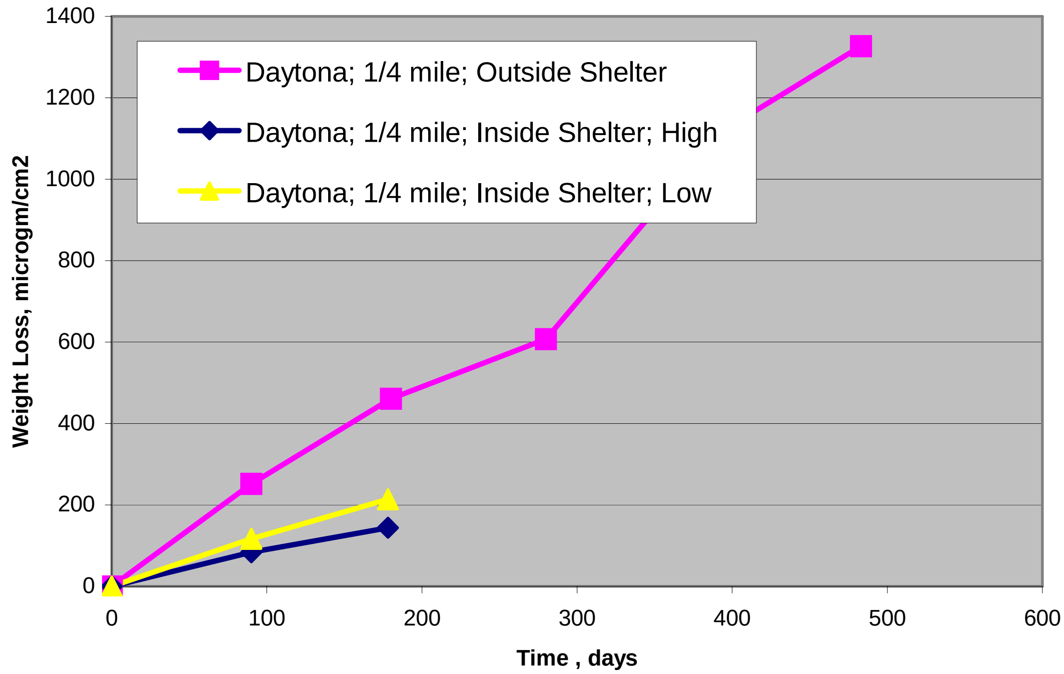

Fig. 17. Corrosion of 2024 T3 Aluminum Inside and Outside Open Tent Structure at Daytona Beach; 0.4 km Inland

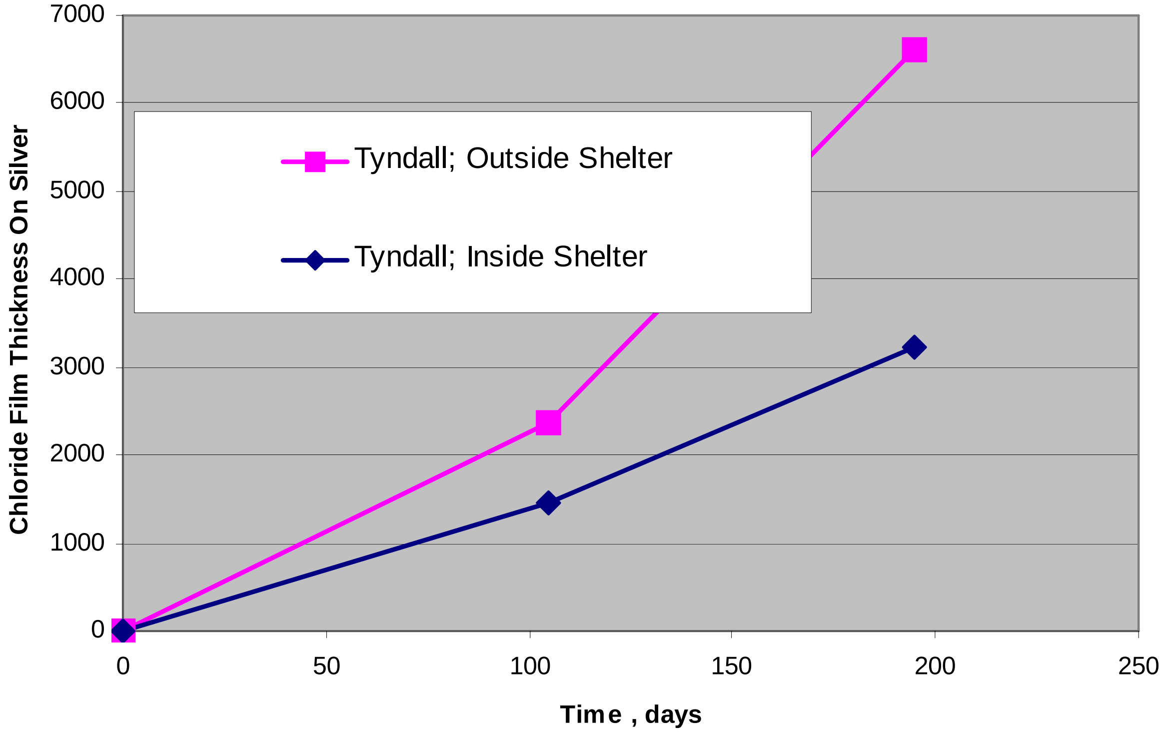

Fig. 18. Chloride Reaction Kinetics on Silver Sensors Inside and Outside Open Aircraft Shelter At Tyndall AFB

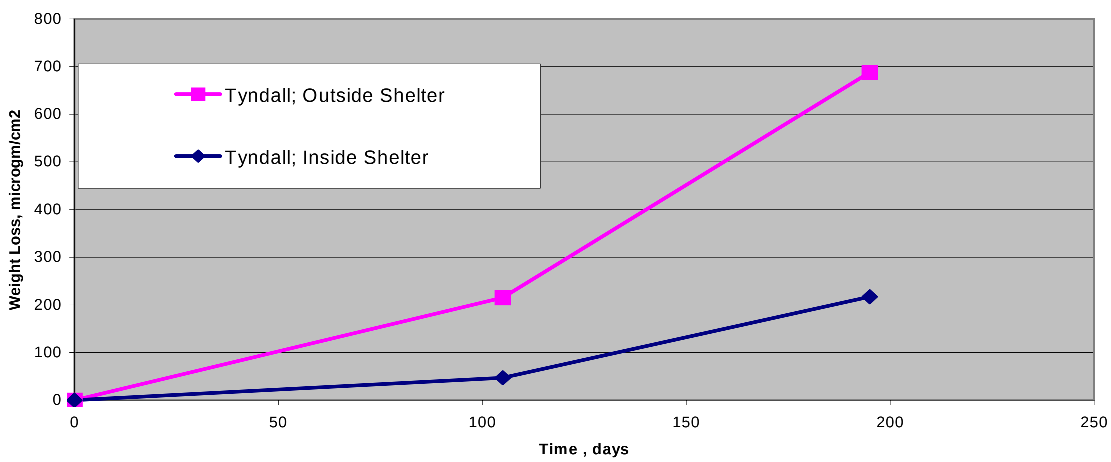

Fig. 19. Corrosion of 2024 T3 Aluminum Inside and Outside Open Aircraft Shelter at Tyndall AFB

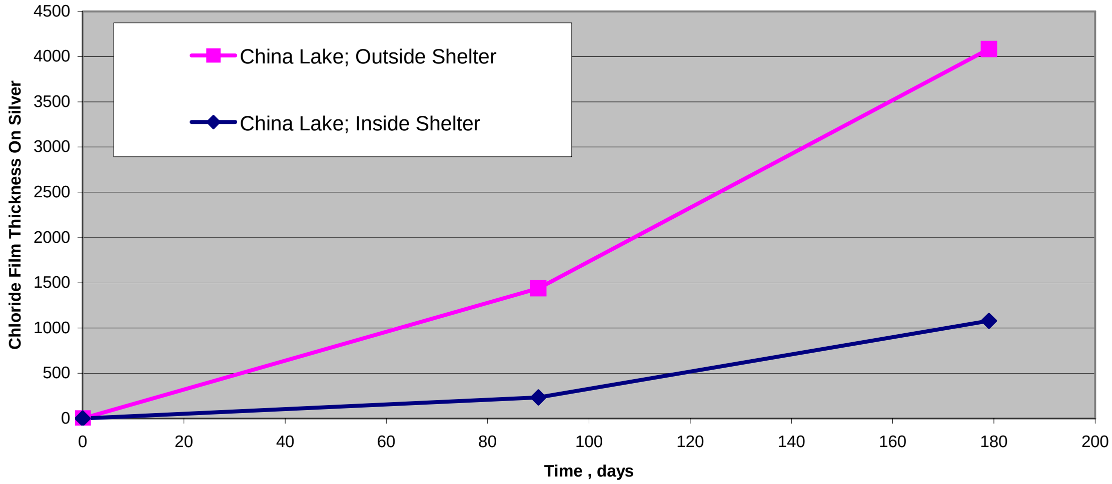

Fig. 20. Chloride Reaction Kinetics On Silver Sensors Inside and Outside Open Aircraft Shelter at Navy China Lake Facility

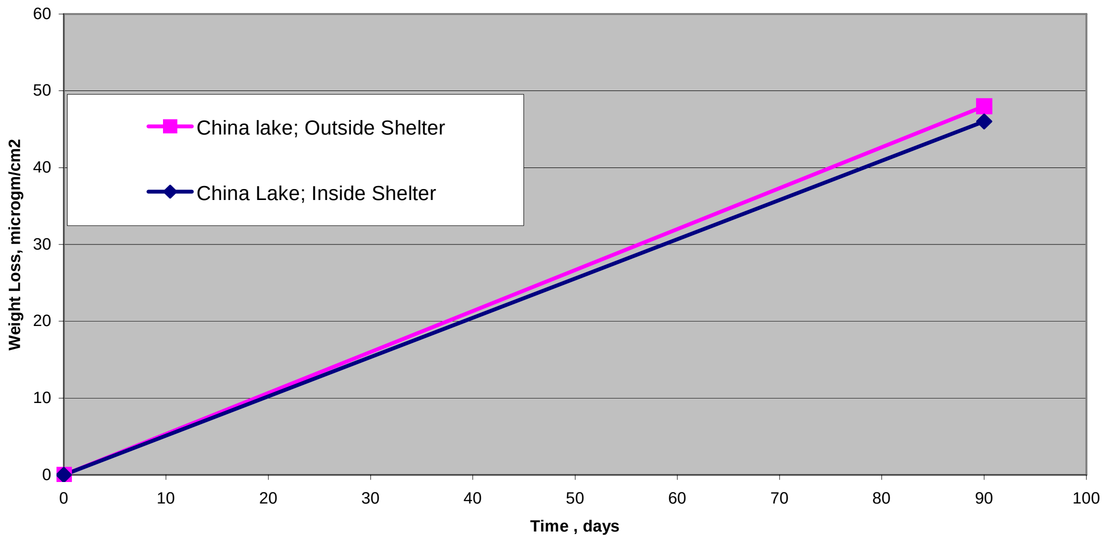

Fig. 21. Corrosion of 2024 T3 Aluminum Inside and Outside Open Aircraft Shelter at Navy China Lake Facility

Army Sites

Some of the data for Army sites are shown in this paper regarding Chlorides are shown in Fig. 22 along with steel corrosion rate data in Fig. 23.

This particular work represents one of the few times where monitoring has been done around a given base. This was done as a result of an interest expressed by Ft. Irwin personnel.

The data in Fig. 22 show what we judge to be a small but real variation in atmospheric chlorides around the base. Battelle monitoring has shown that chlorides detected in this manner on silver sensors can be found at virtually any location in the world.

It is known that chlorides detected in this manner play a major role in the corrosion of metals. Several points should be noted, however. First, there is no intent to describe or determine what the source(s) or nature of the chlorides may be. There is a natural tendency to believe the form to be NaCl but we question this for coastal locations.

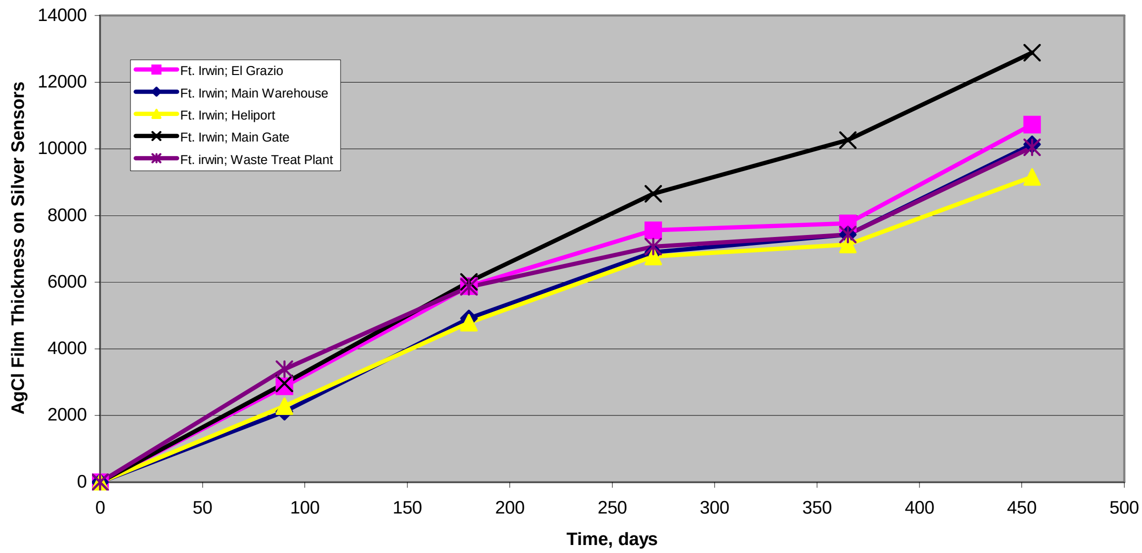

Fig. 22. Atmospheric Chlorides at Various Locations Around Ft. Irwin

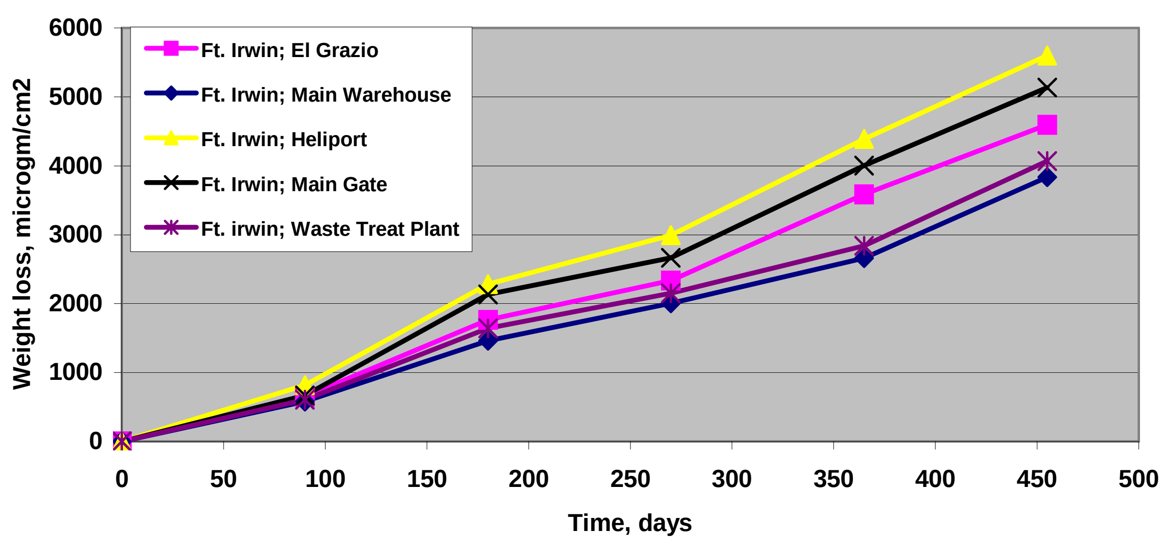

Fig. 23. Corrosion of 1010 Steel Around Ft. Irwin

Fig. 23 shows the corrosion rates on steel. The conclusions from these data are that 1) the data are relatively well ordered, and 2) there are what we consider small variations around the base. These variations can be considered as due to variations in critical variables and any small experimental instrument errors.

Fig. 24 shows chloride film thickness data observed for 5 inland Army sites in comparison to a truly severe site at KSC. These data show the following. First, among the sites surveyed, there is an expected/natural distribution of severity levels for Army sites. Among these, Wheeler will qualify as one of if not the most severe. Second, compared to the other Services, Army sites are likely to qualify as low to moderate severity. This does not conclude in any way that corrosion is not an issue at Army sites. However, it is an attempt to place the atmospheric corrosion issues in proper perspective.

Corrosion data for the Army sites are shown in Fig. 25 and in Fig. 26 is compared to the KSC site. This shows that Army site corrosion data for inland locations are significantly lower than any exposure tests run at KSC.

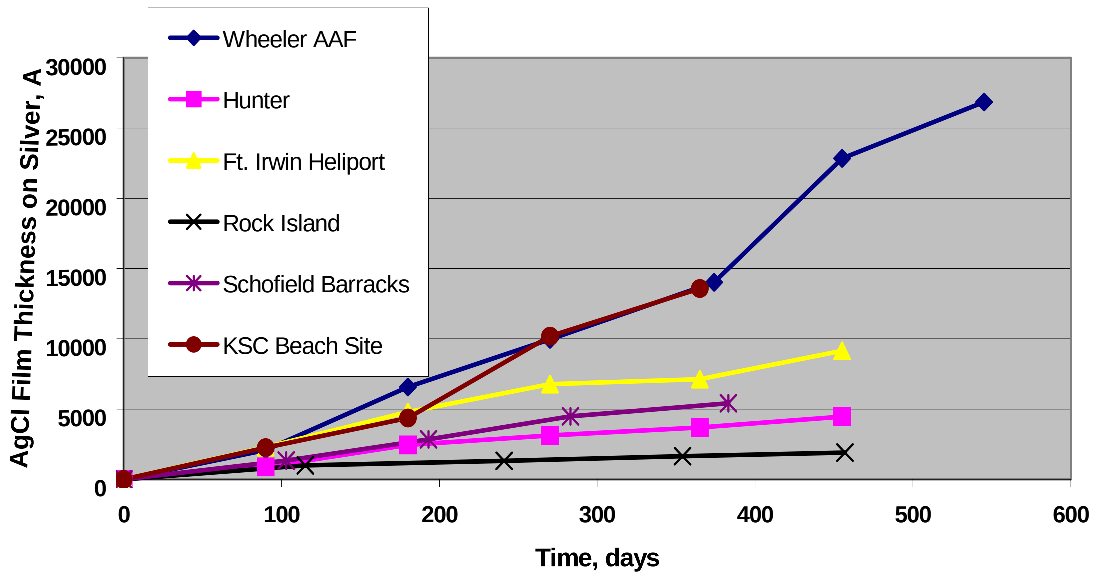

Fig. 24. Atmospheric Chlorides at Army Sites Compared to Severe Atlantic Coastal Site

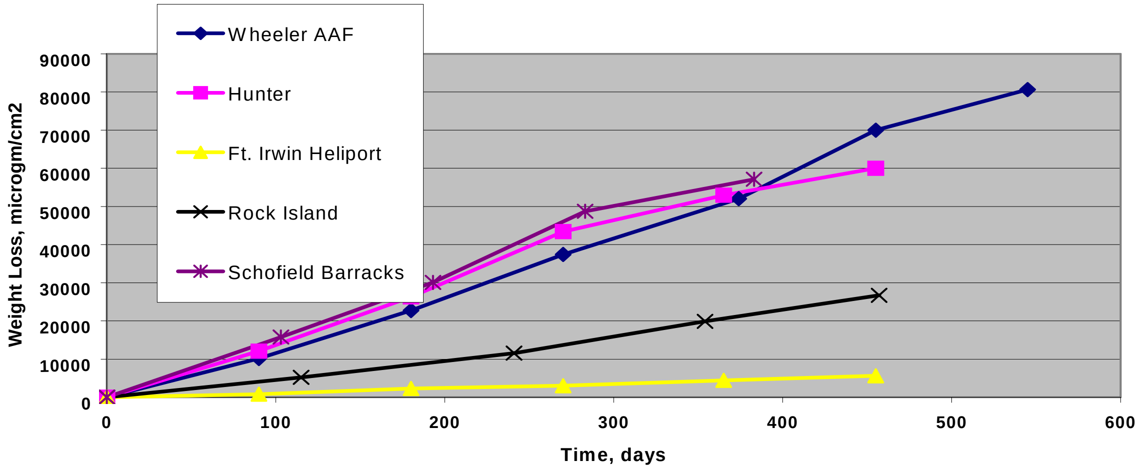

Fig. 25. Atmospheric Corrosion Of 1010 Steel At Army Sites

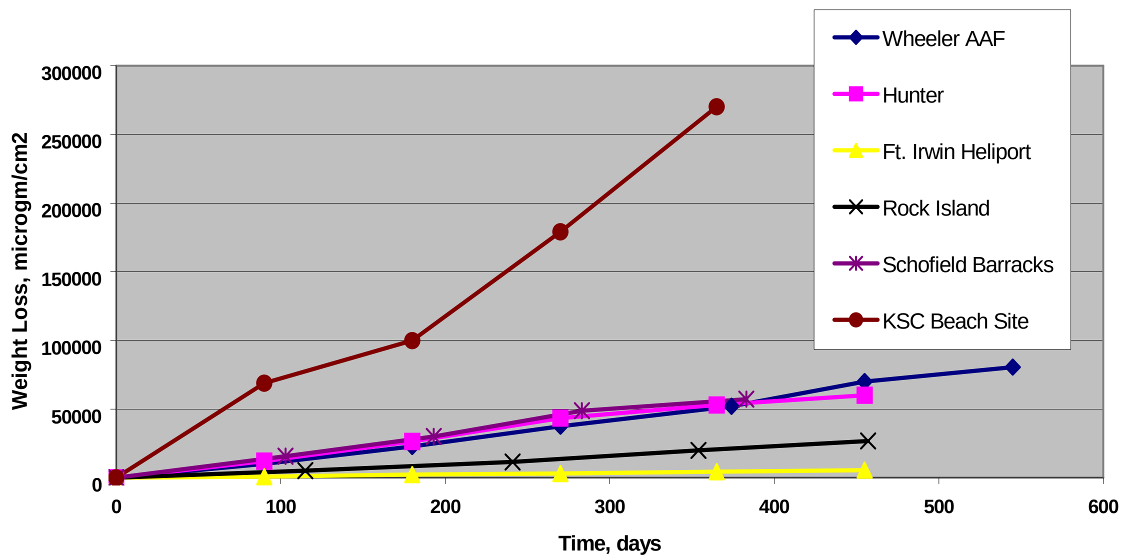

Fig. 26. Atmospheric Corrosion Of 1010 Steel at Army Sites Compared to Severe Atlantic Coastal Site

Conclusions

The chloride contribution to corrosion is an important factor in atmospheric corrosion rate, but it should be recognized that this is only one part of a complex, synergistic relationship between chlorides and other critical environmental variables. In particular, various measures of moisture in the atmosphere play a very important role. High time of wetting in combination with high Chloride concentration produces a higher corrosion rate than would be expected from either effect individually.

There was a marked correlation between chloride concentration and corrosion rate as a function of distance from the ocean. For measurements taken at various distances from the ocean, early data shows strong differences among atmospheric chloride levels but far greater differences in corrosion rates. These results have been observed, but not yet explained using current corrosion models. However, if these models hold true, the corrosion differences have to be accounted for by significant differences in relative humidity / time of wetness and to a lesser extent rainfall.

The observed corrosion rates varied strongly with the degree of sheltering the coupons were exposed under.

References

[1] ASTM G1 Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.

[2] ASTM B825 Standard Test Method for Coulometric Reduction of Surface Films on Metallic Test Samples.