ATMOSPHERIC CHLORIDE DEPOSITION RATE FOR CORROSION PREDICTION ON OAHU

FINAL PROJECT REPORT
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Prepared in cooperation with the:

State of Hawaii
Department of Transportation
Harbors Division
and
U.S. Department of Transportation
Federal Highway Administration

UNIVERSITY OF HAWAII
COLLEGE OF ENGINEERING

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

Research Report UHM/CEE/11-02

May 2011

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
Atmospheric Chloride Deposition Rate for Corrosion Prediction on Oahu	May 2011
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Kyle Suzuki and Ian N. Robertson	UHM/CEE/11-02
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Department of Civil and Environmental Engineering University of Hawaii at Manoa 2540 Dole St. Holmes Hall 383 Honolulu, HI 96822	HWY-L-2005-02
	11. Contract or Grant No. 53634
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Hawaii Department of Transportation Highways Division 869 Punchbowl Street Honolulu, HI 96813	Final
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

This report describes a study to quantify the amount of atmospheric chloride deposited on the exterior of built infrastructure. Data were collected between October 2010 and March 2011, at various locations on the island of Oahu. This study was conducted for the Department of Transportation for use in life cycle analysis programs such as Pontis, an AASHTO bridge and highway management system, and LIFE-365 Corrosion Prediction model.

A preliminary data collection method was proposed using the ISO 9225:1993 (E) sheltered wet wick system which collects chlorides present in the atmosphere. This method provides deposition rate in $mg/m^2/day$ averaged over the period between sampling. Unfortunately agreement was not reached with the City and County of Honolulu as to suitable locations for the 50 testing stations proposed for this study.

An alternative data collection system was implemented using single chloride content measurements from roof beams of city bus shelters. One hundred and twenty six (126) sheltered bus stops were carefully selected around the island for testing. Site locations were selected ranging from the coast to inland in approximately one (1) mile radii. Each site was only tested once and prior research studies were used to normalize the results.

Equations were developed for extreme values and design values of the chloride deposition rate. These equations are functions of the bus stop distance to the nearest shoreline in kilometers. A chloride deposition rate map was produced based on the collected data. This map can be used to estimate likely chloride deposition rates around Oahu. As additional data become available, they can be added to this study and updated maps produced.

17. Key Word	18. Distribution Statement
Chloride Deposition, Corrosion	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	65	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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ACKNOWLEDGEMENTS

This report is based on a Masters Plan B report prepared by Kyle Suzuki under the direction of Dr. Ian Robertson. The authors wish to thank Drs. David Ma and H. Ronald Riggs for their assistance in reviewing this report. The authors also wish to thank Paul Santo of the Hawaii Department of Transportation Bridge Division who was instrumental in the initiation of this project.

This project was funded by a grant from the State of Hawaii Department of Transportation. This funding is gratefully acknowledged.

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of Hawaii, Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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1 INTRODUCTION

1.1 PROJECT OUTLINE

A study was performed to quantify the atmospheric chloride deposition on the exterior of built infrastructure. This study was conducted for the Hawaii Department of Transportation for use in life cycle analysis programs such as Pontis, an AASHTO bridge and highway management system, and LIFE-365 Corrosion Prediction model.

This project was initiated by the Hawaii Department of Transportation on August 1, 2005. Initial efforts to establish monitoring sites for the chloride deposition rate were designed to utilize the International Organization for Standardization 9225 (ISO 9225:1992 (E)) (wet wick candle system) (Malalis and Robertson, 2006). Malalis and Robertson (2006) proposed locating ISO 9225 monitoring stations on street light poles at 50 locations on Oahu. The City and County of Honolulu denied all requests to locate the testing stations on city property.

Ultimately an alternate method was used to determine the distribution of chloride deposition on Oahu. A total of one hundred and twenty six (126) bus stops were strategically selected as testing sites in place of the ISO 9225 candle system. Each site was tested once. Chloride deposition rate averages were then normalized based on prior chloride deposition rate research.

The two prior research projects were: 1) University of Hawaii's department of Civil and Environmental Engineering's study of the Corrosion of Galvanized Fasteners used

in Cold–Formed steel framing, and 2) Pacific Rim Corrosion Research Project (PRCRP) on the Corrosion of Advanced Metallic Composites.

This research formed the basis for developing a chloride deposition rate map for the island of Oahu.

1.2 OBJECTIVES

The objective of this research project was to generate a chloride deposition rate map for the island of Oahu. Inferences can be made for similar locations on the neighbor islands.

1.3 PROJECT SCOPE

To quantify the chloride deposited by the atmosphere on the built environment, one hundred and twenty six (126) bus stops were strategically selected over the island of Oahu. Surface chlorides were collected at each site and used to develop a deposition rate map using ArcGIS software. The chloride measurements were normalized using prior research projects that monitored chloride deposition rates using the ISO 9225 procedure at 10 sites on Oahu.

1.3.1 TEST STATION REQUIREMENTS

The following criteria were used to select suitable chloride measurement sites:

- The sites must not require city approval for use (public access)
- The sites must be in abundance over the island of Oahu for maximum coverage and to allow for the averaging of findings

- The sites must be located along the coastline and inland
- The sample collection site must be sheltered from the rain to ensure the accumulation of chloride would not be washed away

Without the permission to install monitoring stations, it was decided that city bus stops provided a suitable source for collecting data.

The selection of the test sites was based upon availability. This method of testing would permit a 180 degree of exposure, hence it was important to choose sites in relatively close proximity for averaging.

1.3.2 FACTORS AFFECTING THE CHLORIDE DEPOSITION RATE

Significant factors affecting the chloride deposition rate on the surface of built infrastructure include:

- Proximity to the ocean
- Topography between ocean and site
- Natural or man-made obstructions between ocean and site
- Predominant wind direction – on-shore or off-shore
- Coastal conditions – beach, fringing reef, rocky coastline, cliffs, etc.
- Average wave size – depending on seasonal swells
- Average wind speed and direction

2 LITERATURE REVIEW

2.1 IMPACT OF CORROSION ON INFRASTRUCTURE

The premature corrosion and deterioration of embedded reinforcing steel in concrete is primarily due to the penetration of chlorides from deicing salts, groundwater, or seawater. In the United States alone, billions of dollars is spent each year to repair and/or to replace infrastructure damage caused by the effects of chloride penetration (Cady and Wayers, 1984). To put it in another prospective, of the 580,000 bridges in the US, 160,000 are structurally deficient and in need of repair (Cady and Wayers, 1984). This means over 25% of all the bridges around the U.S. are in need of some form of repair or replacement, and much of the damage is related to chloride induced corrosion.

It is widely known that the major initiator of corrosion of reinforcing steel is the penetration of chlorides through the cover concrete. Therefore, it is important to be able to quantify the status of deterioration of a reinforced concrete structure during its lifetime, to assess the need for repair, to assess the performance of protection mechanisms in existence, and to assess the need for application of protection methods. By taking into account the necessary life of the structure, together with initial cost versus maintenance cost considerations, different techniques of corrosion prevention can be evaluated as to their likely effect on the total life of the structure and their applicability to different situations.

2.2 COST OF CORROSION

According to a Highway Bridge report on the Costs of Corrosion by Yunovich and Lave (2006), the dollar impact of corrosion on highway bridges is quite considerable. It states that the annual direct cost of corrosion for highway bridges is estimated to be $6.43 billion to $10.15 billion, consisting of $3.79 billion to replace structurally deficient bridges over the next 10 years, $1.07 billion to $2.93 billion for maintenance and capital cost of concrete bridge decks, $1.07 billion to $2.93 billion for maintenance and capital cost of concrete substructures and superstructures (minus decks), and $0.50 billion for the maintenance painting cost for steel bridges. This gives an average annual cost of corrosion of $8.29 billion. Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of corrosion. In addition, it was estimated that employing “best maintenance practices” versus “average practices” can save 46 percent of the annual corrosion cost of a black steel rebar bridge deck, or $2,000 per bridge per year.

Yunovich and Lave (2006) also states that while there is a downward trend in the percentage of structurally deficient bridges (a decrease from 18 percent to 15 percent between 1995 to 1999), the costs to replace aging bridges increased by 12 percent during the same period. In addition, there has been a significant increase in the required maintenance of aging bridges. Although the vast majority of the approximately 108,000 prestressed concrete bridges have been built since 1960, many of these bridges will require maintenance in the next 10 to 30 years. Therefore, significant

maintenance, repair, rehabilitation, and replacement activities for the nation's highway bridge infrastructure are foreseen over the next few decades before current construction practices begin to reverse the trend.

2.3 CORROSION PROCESS

Chloride-induced corrosion of reinforcing steel in concrete structures is a well-known problem that has been extensively researched and studied since the early 1960's (Gibson 1987). ASTM G-15 defines corrosion as "the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties." Although much advancement in technology and research capabilities has been made, the basic principles of chloride-induced corrosion stay the same.

Rusting of the reinforcing steel is an electrochemical process and requires the flow of electrons in order to advance. This process occurs when the penetration of water and oxygen reach to the depth of the reinforcement. The driving force for the electrical current during this process is developed when reduction occurs and oxygen with water react to produce hydroxyl ions (OH-). The site at which this occurs is called the cathode. The opposing site where oxidation occurs in the steel (iron is the major component of reinforcing steel and will be referred to as iron interchangeably) is called the anode. These electrochemical reaction equations are:

Anodic Reaction:

$$Fe \leftrightarrow 2e^{-} + Fe^{2+} \quad (1)$$

Cathodic Reaction:

$$\tfrac{1}{2}\,O_2 + H_2O + 2e^- \leftrightarrow 2OH^- \quad (2)$$

In a cyclic motion, the hydroxyl ion then is retrieved by the Fe^{2+} and forms ferrous hydroxide.

$$Fe^{2+} + 2(OH)^- \rightarrow Fe(OH)_2 \quad (3)$$

The ferrous hydroxide then furthers a reaction with water and oxygen to form ferric oxide which is known commonly as rust.

$$2Fe(OH)_2 \xrightarrow{O_2,\ H_2O} 2Fe(OH)_3 \rightarrow Fe_2O_3 \bullet nH_2O \quad (4)$$

This is the general formation of rust in a microcell, shown in Figure 1.

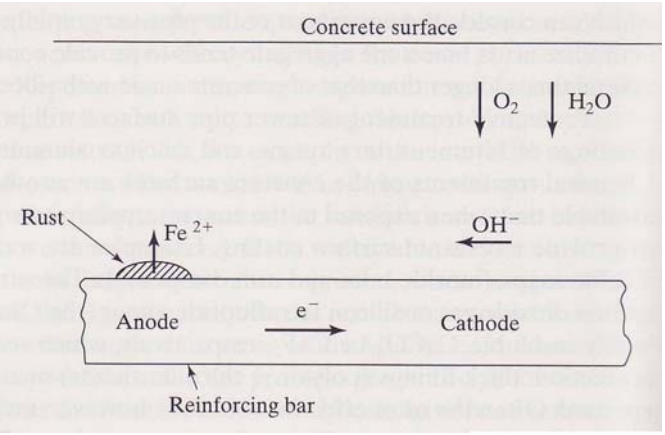

Figure 1 - Electrochemical Corrosion Cell

A microcell refers to the electrochemical process taking place on a single length of steel. In contrast, macro cells involve the process occurring with one piece of metal forming the cathode and another piece of metal forming the anode.

In a concrete with proper cover and with no foreign ions, corrosion will not occur. This is due to the high alkalinity of the surrounding concrete which protects the steel. With a pH of about 3, the ferrous hydroxide at the anode site is further oxidized to form a γ-ferric hydroxide shown in eqn. (5).

$$Fe(OH)_2 + O_2 \rightarrow \gamma\text{-}FeOOH + H_2O \quad (5)$$

γ-ferric hydroxide is a very tight adhering oxide film which forms on the steel and protects the surface from further corrosion. If the alkalinity of the concrete drops below 11.5, this initial oxide film breaks down and further oxidation to rust will occur.

It is in this aspect in which reinforcing steel is so susceptible to chloride ions. Chloride destroys the oxide film regardless of the high alkalinity and the following reaction takes place:

$$Fe^{2+} + Cl^- \rightarrow [FeCl\ complex]^+ \quad (6)$$

This cycle is further detrimental because the resulting iron chloride is highly soluble which allows a continuous attack of chlorides. The iron chloride then undergoes the following reaction:

$$[FeCl]^+ + 2OH^- \rightarrow Fe(OH)_2 + Cl^- \quad (7)$$

This reaction releases ferric hydroxide that will undergo more oxidation and form rust. The chloride ion is then available at the anode to induce further corrosion.

2.4 ENVIRONMENTAL EFFECTS

Environmental effects that influence the corrosion of reinforcing steel include temperature, humidity, and the extent of exposure to the material. Higher temperatures generally increase the rate of corrosion while colder temperatures slow down the rate of corrosion. The amount of moisture available and in contact with the material is also a key factor to the rate of corrosion because water serves as an electrolyte. In dry regions, corrosion may be slow compared to regions with above-average precipitation.

Exposure is important in assessing corrosion on a single structural member. Areas exposed to the wind or sun where drying occurs quickly and frequently are less prone to corrosion than sheltered areas where water or moisture can remain in contact with the material.

Impurities (such as chlorides) make water a more efficient electrolyte and accelerate the corrosion process. Because of this, structures in coastal areas – or those exposed to deicing salts – will corrode faster that structures not exposed to salts. Studies have shown corrosion rates up to 2.75 times higher when chloride is present than when it is not.

2.5 SOURCES OF CHLORIDES

Research has shown that corrosion of steel in concrete accelerates at a far greater rate when chloride-ions are present. Chlorides are made present through both the natural environment and the means and methods of mankind's everyday living. Most chlorides deposited on to the land, unfortunately, are unavoidable and will eventually come in to contact with metals, structural steel and concrete reinforcement. Below are a few examples of chloride sources produced by both nature and mankind.

- Exposure to sea water
- Salts used for de-Icing
- Salt spray from the ocean
- Sulphates from industrial sources
- Acidic rain

2.6 CHLORIDE MONITORING: ISO 9225:1993 (E)

A rain-protected wet textile surface, with a known area, is exposed during a specified time. The amount of chloride deposited is determined by chemical analysis. From the results of this analysis the chloride deposition rate is calculated, expressed in milligrams per square meter day [$mg/m^2/day$].

2.6.1 SAMPLING APPARATUS: WET CANDLE

The wet candle is formed of a wick inserted into a bottle. The wick consists of a central core of about 25 mm in diameter made of inert material (polyethylene). This material is stretched and/or wound to form a double layer of tubular surgical gauze or a band of surgical gauze. The surface of the wick exposed to the atmosphere shall be about 100 cm^2, which corresponds to a wick length of about 120 mm. The exposed area shall be accurately known.

One end of the wick is inserted into a rubber stopper. The stopper has two additional holes through which the free ends of the gauze pass (if tubular gauze is used, the lower end is cut along the length of the gauze until about 120 mm is left). The edges of the three holes are shaped into a funnel so that liquid running down the gauze drains through the stopper. The free ends of the gauze must be long enough to reach the bottom of the bottle.

The stopper is inserted into the neck of a bottle of polyethylene or another inert material, with a volume of about 500 ml. The bottle contains 200 mL of a glycerol and water solution [20 % (*V/V)*]. The solution is made up by mixing 200 mL of glycerol [$CHOH(CH_2OH)_2$] with distilled water to a volume of 1,000 ml.

2.6.2 EXPOSURE RACK

The wet candle is exposed on a rack under the center of a roof as shown in figure 5.1. The roof should be a square of 500 mm side, inert and opaque. The candle should be attached so that the distance from the roof to the top of the wick is 200 mm and so

that it is centered below the roof. The distance between the bottle and ground level should be at least one (1) meter. The candle should be exposed towards the sea or other chloride source.

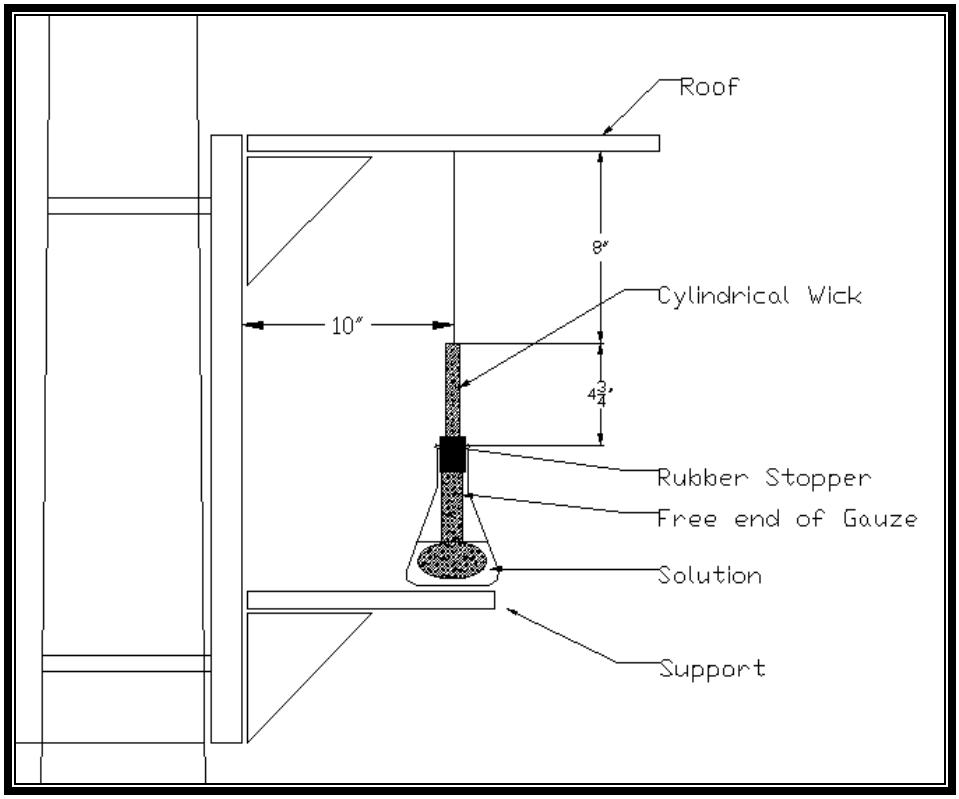

Figure 2 – ISO 9225 Apparatus Assembly

3 REMEDIAL MEASURES

Corrosion damage can often be avoided through the use of corrosion protection systems such as low-permeability (high-performance) concretes, corrosion-inhibiting admixtures, epoxy-coated steel reinforcement, corrosion-resistant steel or non-ferrous reinforcement, application of waterproofing membranes or sealants, cathodic protection, or combinations of the above methods and materials. Each of these strategies has scientific methods and means with expected costs. The challenge is to select the proper combination of protection methods, at an acceptable cost, to achieve the desired result.

3.1 IMPLEMENTING PONTIS

According to the Hawaii Department of Transportation (DOT), their mission is to facilitate the rapid, safe, and economical movement of people and goods in the State of Hawaii by providing and operating transportation facilities. They are also responsible for the planning, design, construction, operation and maintenance of State facilities in all modes of transportation: air, water, and land. At present, the Hawaii DOT has jurisdiction over the following facilities: Fifteen (15) airports; ten (10) commercial harbors and approximately 2,433 miles of highways (HDOT, 2011).

In order to keep up with the maintenance and repairs for their wide range of transportation facilities, the Hawaii DOT plans to implement Pontis, an AASHTO bridge management system, to manage the State bridge inventory. However, in order to

predict the likely onset of corrosion in both existing and new bridges, the Hawaii DOT Bridge Section is utilizing a recently developed LIFE-365 Corrosion Prediction model.

LIFE-365 considers numerous variables including the concrete material variables, the concrete material properties, use of admixtures and reinforcement coating, concrete cover thickness, and environmental exposure conditions. The most important environmental conditions are the ambient temperature and the Surface-Chloride-Concentration Profile. This profile indicates the rate at which chlorides accumulate on the surface of the concrete.

No information is currently available regarding the rate of chloride accumulation at various locations in Hawaii. This variable has a significant effect on the time to onset of corrosion and will greatly affect the output from the LIFE-365 computer model. Inaccurate predictions can lead to expensive mismanagement of the transportation infrastructure. If onset of corrosion can be predicted more accurately, relatively inexpensive remedial measures can be implemented so as to avoid more expensive repairs once concrete cracking and spalling occur.

3.2 CORROSION PREDICTION MODEL, LIFE-365

LIFE-365 is a standardized service life and life cycle cost model developed under the American Concrete Institute's Strategic Development Council. This program calculates the service life and life cycle costs of concrete structures exposed to different environmental and chemical influences.

LIFE-365 incorporates chloride threshold values for calcium nitrite and butyl oleate plus amine (OCI), and assumes a five-year window from the initiation of corrosion to

first repair based on the government's Strategic Highway Research Program (SHRP). When modeling the use of OCI, Life-365 model reduces chloride diffusivity by 10 percent (AASHTO, 2011).

3.3 IMPLEMENTATION AND BENEFITS

The advantage of incorporating LIFE-365 with Pontis will now provide designers and engineers a prediction of onset of corrosion and the time for corrosion to reach an unacceptable level. It can then estimate total costs over the entire design life of the structure, including initial construction costs and predicted repair costs. There are currently numerous strategies available for increasing the service life of reinforced structures exposed to chloride. Some of these include:

- Low permeability (high-performance) concrete
- Chemical corrosion inhibitors
- Protective coatings on steel reinforcement (e.g. epoxy coating or galvanizing)
- Corrosion-resistant steel
- Fiber reinforcement
- Waterproofing membranes or sealants
- Cathodic protection

LIFE-365 is being used more and more frequently to provide the means of computing total costs over the entire design life of a structure. Both initial construction costs and predicted future repair costs are included in the analysis. Therefore, although the implementation of a protection strategy may increase initial

costs, it may still reduce life cycle costs by reducing the extent and frequency of future repairs.

4 APPROACH

4.1 SITE SELECTION

The primary factors of consideration in selecting bus stops for testing are: 1) Land Topography, 2) Proximity to the Ocean, and 3) Proximity to Natural or Man-Made structures. City bus stops are placed where populations or 'demand' exist and (typically) in less than half-mile increments along bus routes. Over 2,000 bus stops were identified and considered for use in this research. For averaging purposes, this project selected one hundred and twenty six (126) bus stops ranging nearest to the ocean and furthest inland selecting bus stops with approximately one (1) mile radii from each other. Every bus stop on the island of Oahu was considered for maximum island coverage. The bus stops selected are shown in Figure 3.

Thousands of bus stops exist on the island of Oahu, and only a portion of them are sheltered. The newest type of sheltered bus stops (and most common) was the preferred type of selection. These bus stops are most distinguishable by their green painted metal roofing. These bus stops were predominantly chosen for sampling although other bus stop types were also used. The typical bus stops used is shown in Figure 4. These bus stops are sheltered, painted, and allowed air flow above and below the supporting roof beams.

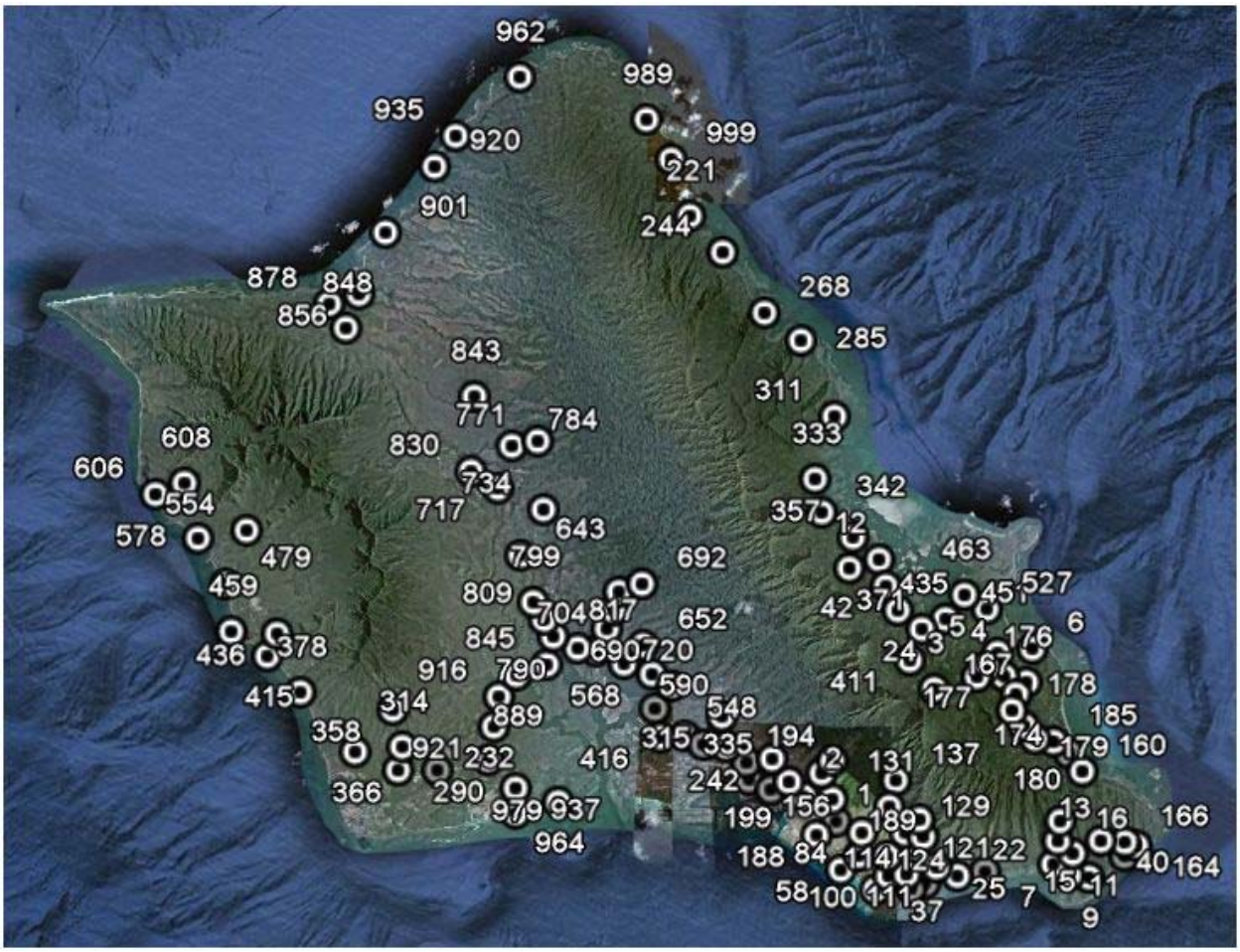

Figure 3 – Map of Selected Bus Stops

Bus stops which were not (or could not) be used in this study are shown in Figure 5. These bus stops were either not sheltered, did not have a suitable area for sampling, or did not allow proper air flow.

Figure 4 – Samples of Selected Bus Stops

Figure 5 – Unusable Bus Stop Designs

4.2 SAMPLE COLLECTION

For standardization, the lower roof supporting beam closest to the street was selected for testing on each bus stop, (Figure 6).

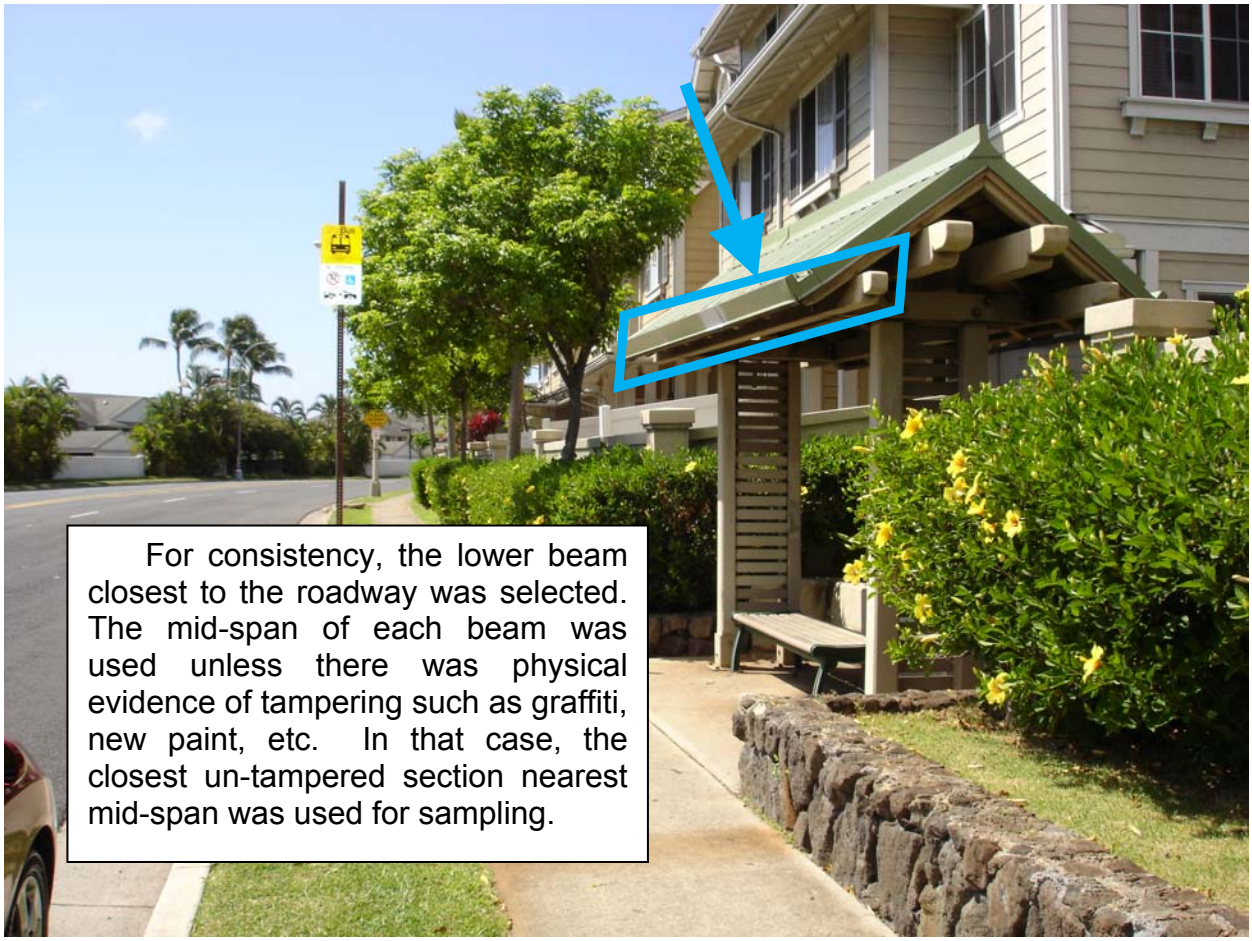

Figure 6 – Bus Stop Beam Tested

Samples were taken from both the vertical inner-face and vertical outer-face of the beam and combined for 180 degrees of exposure area. To measure the chloride concentrations accumulated on the beams, fixed areas were isolated using painters

tape. Measurements of the top-width, bottom-width, and height were recorded for area calculations.

The exposed beam areas were then wiped clean using two to three sterile pads and de-ionized water. A completed section is shown in Figure 7. The disturbed beam area surrounding the sample area in Figure 7 is from the removed painter's tape. The soiled pads were then stored in National Scientific Company 40 mL sample vials filled with de-ionized water. Each vial was labeled to track the collection location. GPS coordinates for each collection site were determined using a portable GPS locator. Photos were taken of each side of the beams completed sample area for later reference and documentation.

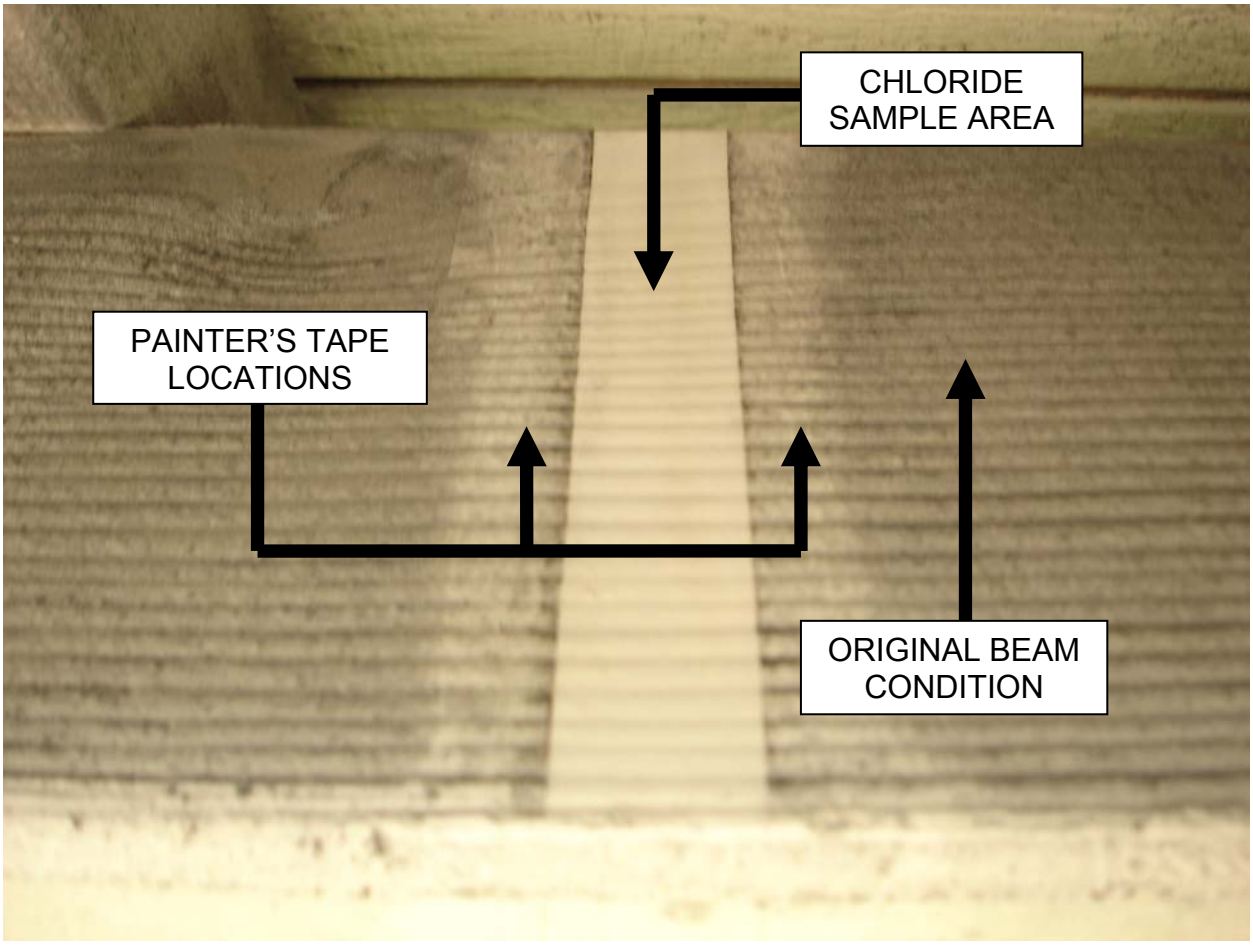

Figure 7 – Bus Stop Beam Area Isolation

4.3 SAMPLE TEST PROCEDURE

4.3.1 CHLORIDE TEST SYSTEM

Samples were analyzed for chloride anions using a Dionex DX-120 Ion Chromatograph equipped with a 4mm AS14A analytical column, a AG14A guard column, and an Ultra II anion self regenerating suppressor (ASRS). The flow rate of the 8.0mM sodium carbonate + 1.0mM sodium bicarbonate effluent was 1.0mL/min.

Samples were injected into the chromatograph by an AS40 auto-sampler utilizing Dionex filter cap vials that automatically filter the sample as it is loaded into the 25µL injection loop. The Dionex DX-120 and AS40 Autosampler setup is shown in Figure 8.

Data for each sample were collected and processed using Dionex PeakNet 5.11 software. A multi-component seven anion standard solution purchased from Dionex was use to calibrate the instrument. A six point calibration curve in the range of 1 to 100 ppm (1 mg/L) was prepared for most components (0.2 to 20 ppm for fluoride, 2 to 200ppm for phosphate).

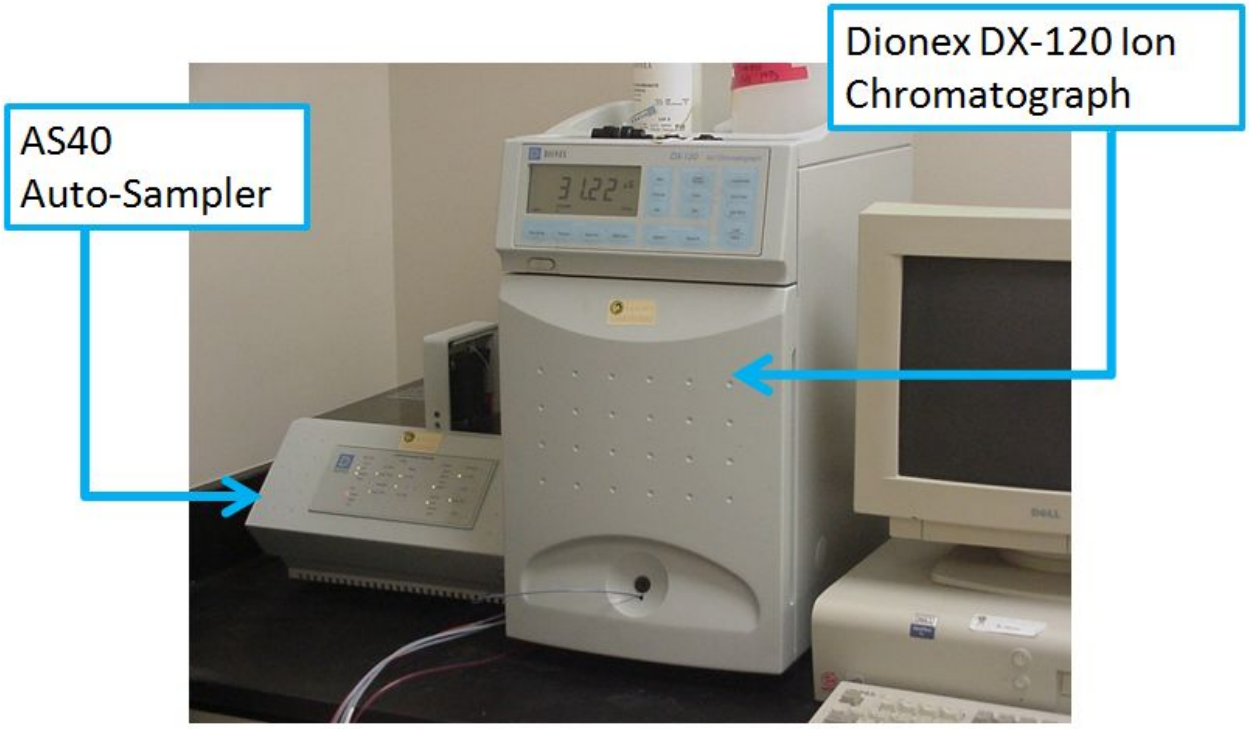

Figure 8 – Dionex DX-120 Ion Chromatograph and AS40 Auto Sampler

4.3.2 SAMPLE TESTING

Each sample collected was stored in an appropriately labeled National Scientific Company 40 mL sample vial. The Dionex DX-120 Ion Chromatograph utilizes an auto-sampler vial which tests approximately 1 mL of sample solution. The Dionex DX-120 continuously tests the sample solutions and exports the results into an excel file for data analysis. Each of the vials was filled to approximately 41 mL with de-ionized water. The cotton swabs used to wipe the surface displaced approximately 1 mL of de-ionized water in each of the vials. Therefore, each vial contained approximately 40 mL of sample solution.

The output data from the Dionex DX-120 gives the chloride content in 'parts-per-million' or (ppm). The chloride concentration in 'mg/mL' is determined by dividing the 'ppm' by 1,000. The mass of chloride extracted from each bus stop [mg] was calculated by multiplying the total volume of sample solution [40 mL] in each vial by the chloride concentration given by the Dionex DX-120 [mg/mL]. This was then divided by the bus stop sample area [m^2] from which the sample was taken for a chloride mass per unit area [mg/m^2]. This method of testing was unable to directly determine the duration of exposure. The duration of exposure was determined utilizing the two prior research projects described below.

- CONCENTRATION [ppm] / 1,000 = CONCENTRATION [mg/mL]
- CONCENTRATION [mg/mL] * VOLUME LIQUID [mL] = MASS [mg]
- MASS [mg] / AREA [m^2] = DEPOSITION [mg/m^2]
- DEPOSITION [mg/m^2] / EXPOSURE [days] = DEPOSITION RATE [mg/m^2/day]

4.4 CHLORIDE DEPOSITION RATE MAPPING

Two parallel research projects provide data pertaining to chloride deposition rates on the island of Oahu: 1) University of Hawaii's department of Civil and Environmental Engineering's study of the Corrosion of Galvanized Fasteners used in Cold-Formed Steel, and 2) Pacific Rim Corrosion Research Project (PRCRP) on the Corrosion of Advanced Metallic Composites.

4.4.1 PRELIMINARY RESULTS

4.4.1.1 CORROSION OF GALVANIZED FASTENERS USED IN COLD-FORMED STEEL FRAMING

This study was performed in 2004 and included five test sites on the island of Oahu. The five test sites used in this research were: 1) Marine Corps Base Inland, 2) Marine Corps Base Coastal, 3) Wheeler AAF, 4) Iroquois Point Inland, and 5) Iroquois Point Coastal. Figure 9 is a map of the five test sites.

Chloride deposition rates for each site were monitored for a period of six months while recording data in two week intervals. The data collected in this research project included measuring chloride deposition rates as well as implementing a full weather station which monitored wind speed and direction (Neville and Robertson, 2003).

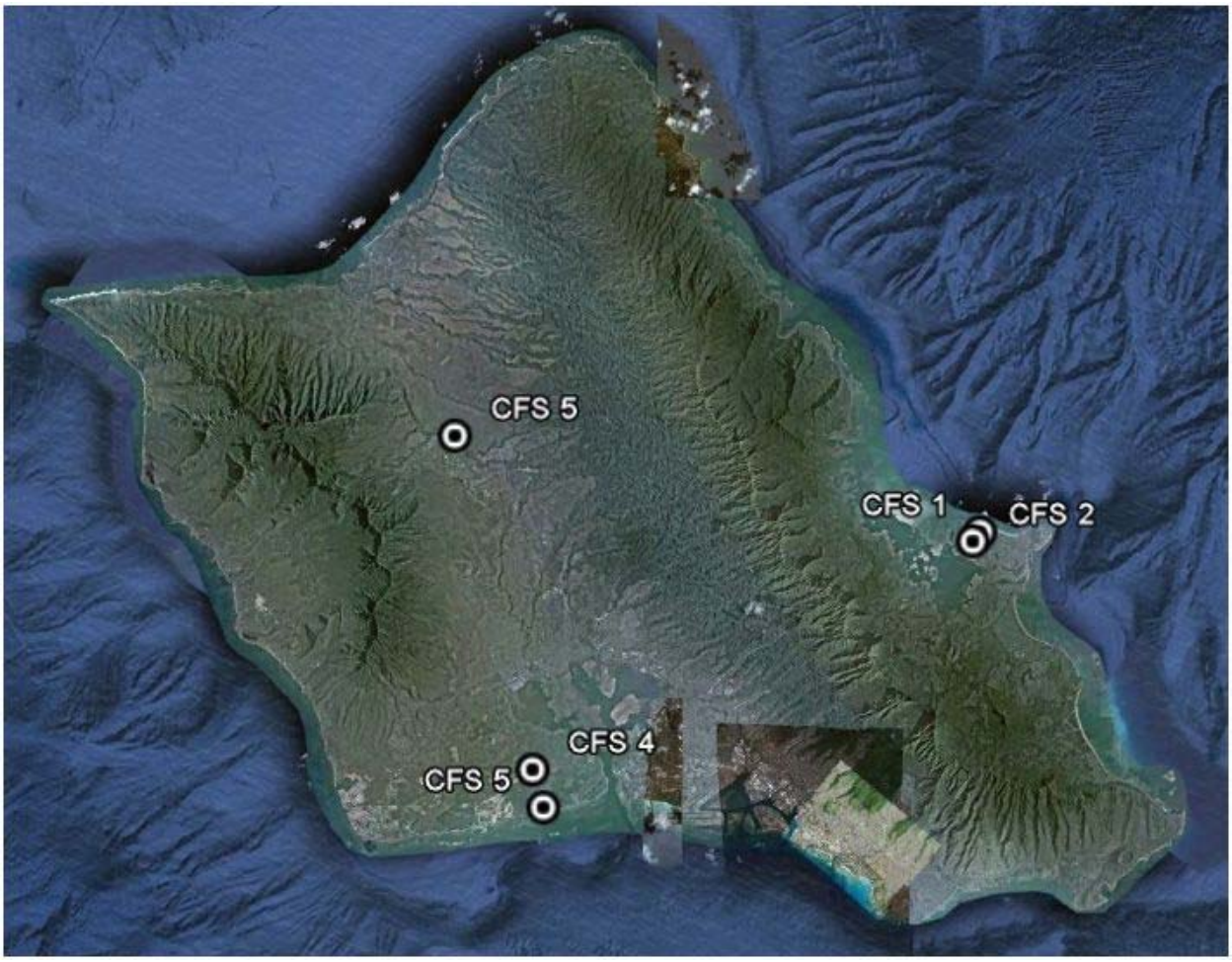

Figure 9 – Existing Site Locations for The Corrosion of Galvanized Fasteners used in Cold Formed Steel Framing Project

This study concluded that higher chloride values are typically present nearest the ocean and decrease inland. Short term inverse relations were attributed to differences in nearby vegetation and changing wind direction. Data collection over a longer period of time would be needed to ensure that the recorded chloride deposition rates aren't the result of any 'seasonal' or temporary site attributes.

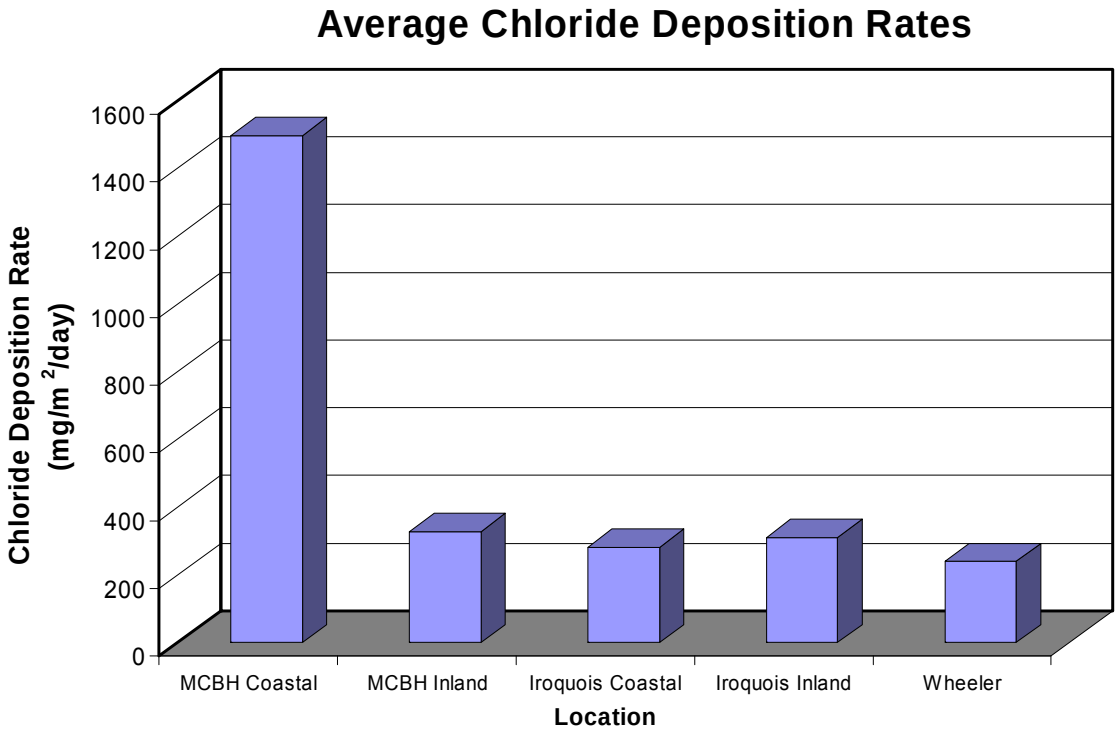

Figure 10 – Corrosion of Galvanized Fasteners used in Cold-Formed Steel Framing Project Average Chloride Deposition Rate

Much higher chloride deposition rates were concluded in this project resulting from improper water purification methods. The water used in this research project was purified using a reverse osmosis method instead of using de-ionized water. Reverse osmosis does not remove all of the chloride present in the initial water source. Therefore, an unknown portion of the chloride measured in this project was contributed to the chloride present prior to sample collection. The data from this research project was primarily used as reference.

4.4.1.2 PACIFIC RIM CORROSION RESEARCH PROGRAM

The Pacific Rim Corrosion Research Program encompassed six (6) test sites over the island of Oahu. The six (6) test sites were: 1) Campbell Industrial Park, 2) Coconut Island, 3) Ewa Beach Inland, 4) Kahuku, 5) Waipahu and 6) Manoa Valley.

Data have been recorded monthly from July 2003 to January 2006. The conclusion of this report showed that although monthly deposition rates may vary drastically, the average annual deposition rates were very similar. Figure 12 shows a comparison of average chloride deposition rates for 2004 and 2005. It also concluded that a one-year observation would be sufficient to create a yearly map for the island of Oahu.

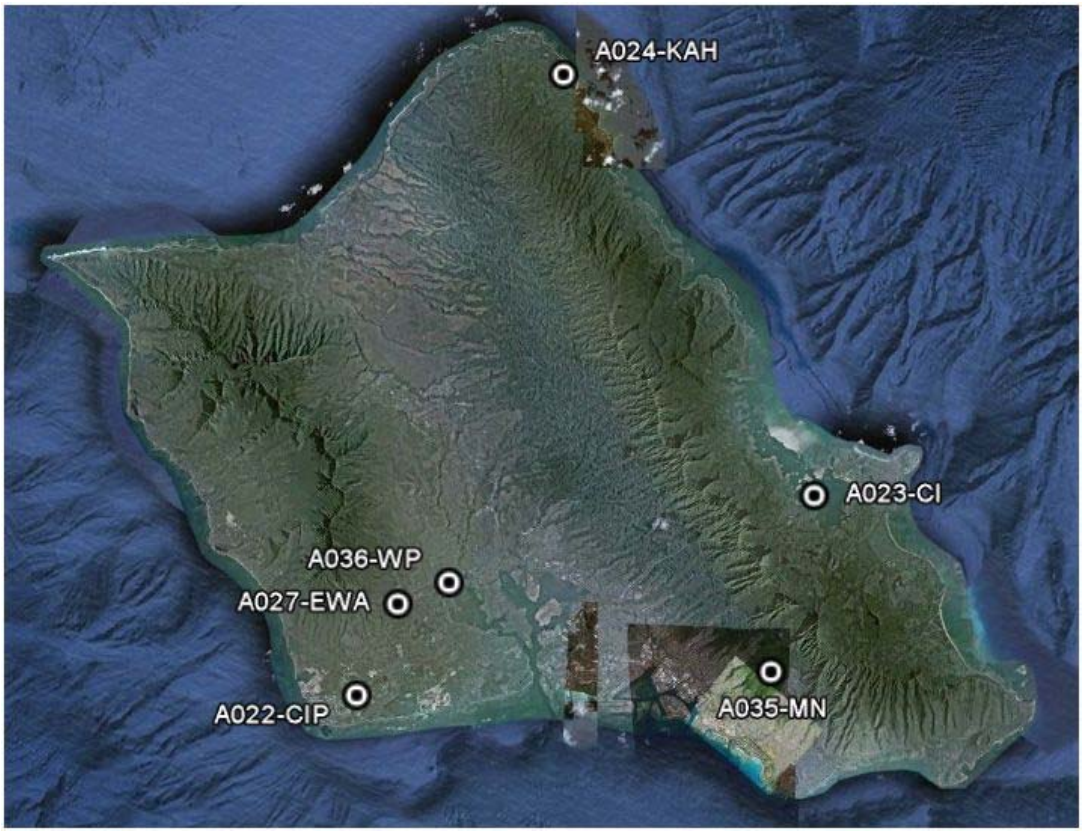

Figure 11 –Site Locations of the Pacific Rim Corrosion Research Program

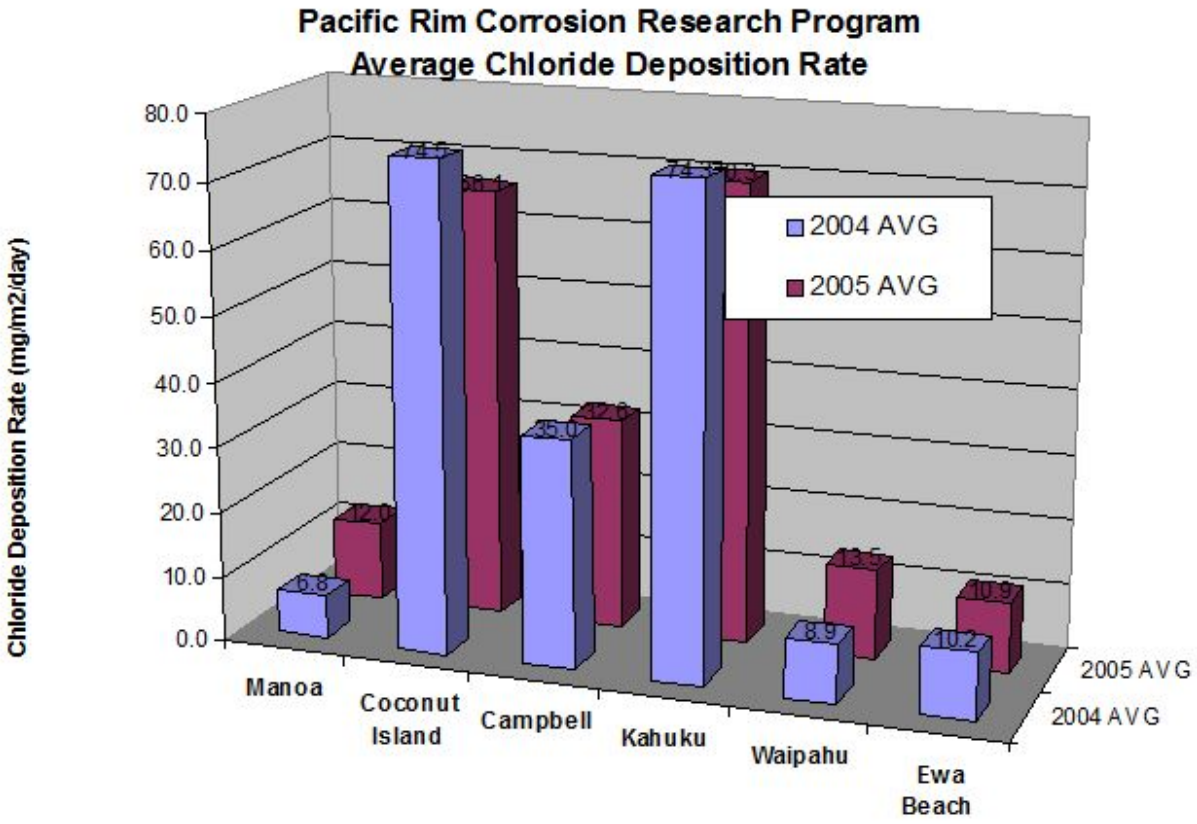

Figure 12 – PRCRP Average Chloride Deposition Rate

4.4.2 DATA CALIBRATION

The average annual chloride deposition rates of the PRCRP research sites at Coconut Island and Kahuku were used as pivotal points in the generation of the chloride deposition rate map of the island of Oahu. The data collected for this study describes only how much chloride was collected from the surface from each bus stop. The average annual chloride deposition rates from the PRCRP sites in 2004 and 2005 were used to determine the approximate duration of exposure of each of the nearby bus stop samples collected in this research.

To relate each of the bus stop samples collected, it was assumed that each of the bus stops had the same period of exposure (although this may not be true). Based on these 'estimated' periods of exposure, the chloride concentration values from each of the bus stops were normalized to represent an average annual chloride deposition rate. The deposition rates were then plotted geographically using ArcGIS resulting in an average annual chloride deposition rate map.

Contour lines were generated using the geographical analysis program ArcGIS. This program will analyze the geo-statistical data and estimate the most appropriate position of the contour lines.

4.4.2.1 ArcGIS CONTOUR METHOD: KERNEL SMOOTHING

"Kernel Density calculates the density of features in a neighborhood around those features. It can be calculated for both point and line features.

Possible uses include finding density of houses, crime reports or density of roads or utility lines influencing a town or wildlife habitat. The population field could be used to weigh some features more heavily than others, depending on their meaning, or to allow one point to represent several observations. For example, one address might represent a condominium with six units, or some crimes might be weighed more severely than others in determining overall crime levels. For line features a divided highway probably has more impact than a narrow dirt road and a high-tension line has more impact than a standard electric pole." (ArcGIS Desktop 9.3 Help)

5 RESULTS

5.1 STATION LOCATION AND BEAM DIMENSIONS

Table 1 provides the location of every bus stop from which a chloride sample was collected, including information pertaining to the sample collection site. Table 1 lists the bus stop latitude and longitude location, the calculated inside and outside beam sampling area, and the bottle number in which the sample was stored.

Table 1 – General Test Station Information

SAMPLE #	SITE #	LOCATION (deg, min, sec)						DISTANCE FROM NEAREST SHORELINE (km)	SAMPLE AREA (in^2)	BOTTLE #
		LATITUDE			LONGITUDE					
1	1	21	19	49	157	50	39	3.50	12.45	3B
2	2	21	20	13	157	50	17	4.88	13.41	1B
3	3	21	22	29	157	46	51	4.11	14.46	3A
4	4	21	22	51	157	45	23	3.15	12.52	2B
5	5	21	23	36	157	44	41	1.34	13.36	2A
6	6	21	23	44	157	43	30	0.15	15.43	1A
7	167	21	23	10	157	45	5	2.37	9.28	4A
8	177	21	22	52	157	44	28	2.32	13.88	5A
9	176	21	22	39	157	43	43	2.07	12.00	6B
10	174	21	22	18	157	44	5	2.92	9.81	8A
11	178	21	21	45	157	44	10	4.19	11.47	7B
12	160	21	19	53	157	41	49	0.37	15.80	7A
13	186	21	20	25	157	42	15	0.47	15.89	8B
14	185	21	20	48	157	42	49	0.91	14.24	5B
15	180	21	20	54	157	43	25	1.86	15.45	8A
16	179	21	21	18	157	43	47	2.24	14.70	9A
17	164	21	17	31	157	40	1	0.29	10.68	9B
18	163	21	17	10	157	40	27	0.12	16.76	4B
19	9	21	16	31	157	47	36	0.72	15.61	10A
20	7	21	16	35	157	42	16	0.45	13.08	10B
21	40	21	17	41	157	41	12	0.36	15.48	12B
22	166	21	17	37	157	40	22	0.83	15.04	11A
23	13	21	17	15	157	42	9	0.07	15.95	11B
24	15	21	17	38	157	42	38	1.42	14.80	13A
25	16	21	18	17	157	42	35	2.39	18.99	13B
26	11	21	16	56	157	42	46	0.06	14.64	15A
27	21	21	16	42	157	45	7	0.13	15.98	14A
28	22	21	16	34	157	46	3	0.27	13.66	15B
29	25	21	16	51	157	46	45	1.19	13.88	12A
30	31	21	16	20	157	47	9	0.95	19.14	14B
31	121	21	16	37	157	47	46	1.99	14.24	S3
32	120	21	16	11	157	47	37	1.13	15.45	S4
33	100	21	16	34	157	48	23	1.77	20.46	S1
34	37	21	16	8	157	48	49	0.95	15.27	S2

Table 1 – General Test Station Information (Continued)

SAMPLE #	SITE #	LOCATION (deg, min, sec)						DISTANCE FROM NEAREST SHORELINE (km)	SAMPLE AREA (in^2)	BOTTLE #
		LATITUDE			LONGITUDE					
35	114	21	17	50	157	47	13	3.15	14.03	15E
36	129	21	17	57	157	47	50	3.88	14.95	11K
37	124	21	18	23	157	47	21	5.05	11.16	2R
38	111	21	17	13	157	48	26	2.25	9.32	14J
39	137	21	19	36	157	48	8	6.27	11.04	8J
40	131	21	18	46	157	48	22	4.55	10.00	1R
41	156	21	17	57	157	49	17	2.64	8.54	3J
42	84	21	17	13	157	49	23	1.28	10.17	15H
43	58	21	16	46	157	50	0	0.15	13.13	6E
44	188	21	17	52	157	50	49	0.97	9.67	6H
45	187	21	18	17	157	50	9	2.22	10.96	2H
46	189	21	18	59	157	50	17	3.25	9.32	10H
47	199	21	19	4	157	51	16	1.41	10.25	5R
48	194	21	19	33	157	51	45	2.02	9.86	3H
49	242	21	20	17	157	52	18	2.35	10.18	16J
50	205	21	19	36	157	53	5	1.00	9.41	4K
51	264	21	20	10	157	53	9	0.91	8.66	3K
52	196	21	19	17	157	52	22	0.64	9.31	4H
53	315	21	21	34	157	54	1	3.54	10.21	16R
54	335	21	20	39	157	53	52	1.50	9.55	4E
55	499	21	20	43	157	54	41	2.25	8.40	11J
56	482	21	21	0	157	55	15	2.25	8.86	2K
57	416	21	20	58	157	56	6	0.87	10.04	7R
58	430	21	21	50	157	56	15	0.33	14.95	14H
59	548	21	22	34	157	55	43	0.57	10.64	15R
60	568	21	22	56	157	56	23	0.47	10.58	10E
61	590	21	23	16	157	57	20	0.30	10.67	14E
62	652	21	23	50	157	56	41	1.74	9.85	2E
63	759	21	23	39	157	58	16	0.87	14.92	5E
64	790	21	23	45	157	58	52	1.06	14.50	9E
65	720	21	24	22	157	57	53	2.02	9.50	10J
66	690	21	24	57	157	57	40	3.08	10.95	9R
67	692	21	25	46	157	56	44	6.43	10.25	16E
68	704	21	25	31	157	57	29	5.31	12.55	12R
69	817	21	24	7	157	59	43	1.56	10.72	9K

Table 1 – General Test Station Information (Continued)

SAMPLE #	SITE #	LOCATION (deg, min, sec)						DISTANCE FROM NEAREST SHORELINE (km)	SAMPLE AREA (in^2)	BOTTLE #
		LATITUDE			LONGITUDE					
70	643	21	26	41	158	0	48	6.69	15.86	12E
71	809	21	24	40	158	0	1	2.73	9.99	7K
72	799	21	25	12	158	0	21	3.89	11.21	10K
73	845	21	26	0	157	49	26	0.67	12.14	11E
74	889	21	22	54	158	0	57	0.45	11.62	16H
75	937	21	19	19	158	0	58	1.53	12.08	13R
76	979	21	18	33	158	0	59	0.18	10.53	11H
77	964	21	18	54	157	59	33	0.17	10.68	6J
78	232	21	20	15	158	1	55	3.40	10.56	10R
79	921	21	21	17	158	1	42	0.81	10.45	2J
80	916	21	22	13	158	1	32	0.53	10.72	11R
81	257	21	26	8	157	49	54	3.45	10.28	9H
82	290	21	19	55	158	4	55	3.73	10.44	7E
83	314	21	20	38	158	4	49	5.09	11.06	13E
84	358	21	21	48	158	5	5	7.30	10.75	1K
85	436	21	24	12	158	9	3	1.36	11.11	12K
86	479	21	25	46	158	10	48	0.11	15.92	8H
87	554	21	27	27	158	10	4	2.56	11.23	8E
88	578	21	27	12	158	11	44	0.35	11.16	12H
89	608	21	28	56	158	12	10	1.91	10.84	12J
90	606	21	28	35	158	13	10	0.02	10.56	1E
91	459	21	24	16	158	10	36	0.09	9.93	15J
92	415	21	23	30	158	9	23	0.02	11.54	5K
93	378	21	22	21	158	8	16	0.16	10.44	4J
94	366	21	20	29	158	6	21	1.96	15.86	8R
95	734	21	28	6	158	0	2	8.87	10.03	14R
96	717	21	28	47	158	1	32	7.75	14.74	7H
97	830	21	29	19	158	2	28	12.31	10.28	8K
98	771	21	30	17	158	0	11	12.91	9.78	S5
99	784	21	30	7	158	1	5	12.89	10.11	3R
100	843	21	31	39	158	2	21	10.24	9.99	14K
101	848	21	33	49	158	6	43	2.46	15.86	16K
102	878	21	34	35	158	7	18	0.76	10.49	13J
103	856	21	34	54	158	6	17	1.14	15.80	13H
104	901	21	36	49	158	5	24	0.11	10.89	6R

Table 1 – General Test Station Information (Continued)

SAMPLE #	SITE #	LOCATION (deg, min, sec)						DISTANCE FROM NEAREST SHORELINE (km)	SAMPLE AREA (in^2)	BOTTLE #
		LATITUDE			LONGITUDE					
105	920	21	38	56	158	3	44	0.10	11.13	4R
106	935	21	39	52	158	2	58	0.08	11.01	5J
107	962	21	41	43	158	0	51	0.17	10.31	5H
108	333	21	29	4	157	50	51	0.06	11.15	6K
109	311	21	31	2	157	50	12	0.06	12.15	1H
110	999	21	39	9	157	55	43	0.09	11.80	9J
111	989	21	40	24	157	56	30	0.51	10.72	15K
112	221	21	37	22	157	55	5	0.13	11.40	7J
113	244	21	36	13	157	53	59	0.01	10.76	3E
114	268	21	34	18	157	52	34	0.11	10.73	1J
115	285	21	33	25	157	51	20	0.05	11.04	13K
116	12	21	26	30	157	49	56	1.80	10.52	17A
117	342	21	28	1	157	50	37	0.13	15.07	18E
118	357	21	27	15	157	49	34	0.02	11.29	17J
119	371	21	26	33	157	48	41	0.13	10.82	18A
120	42	21	25	40	157	48	27	0.32	11.36	17H
121	24	21	24	56	157	48	3	1.57	11.21	17R
122	411	21	23	33	157	47	41	2.72	11.15	18K
123	463	21	25	25	157	45	48	0.73	10.55	17B
124	527	21	24	58	157	45	3	0.73	11.41	18R
125	451	21	24	40	157	46	27	0.21	10.46	17K
126	435	21	24	21	157	47	16	0.78	11.88	18B

5.2 CONCENTRATION DATA

5.2.1 CORRECTION DUE TO HANDLING

The samples were collected without using sterile gloves and therefore the error needs to be quantified. Sample # 127-130 was samples handled with bare hands in the same manner as in the field (without any actual sampling). The average chloride

content found in Table 2 accounts for the chloride contained in the cotton pads as well as any possible transfer from handling.

Table 2 – Control Chloride Sample Data

SAMPLE #	BOTTLE #	RAW CHLORIDE CONCENTRATION (ppm)
127	18H	2.2267
128	11J	2.5962
129	17E	1.6870
130	19R	1.3329
AVERAGE		1.9607

The average chloride concentration of these control samples was 1.9607 ppm. This value is regarded as an error and is subtracted from the bus stop sample chloride concentrations. Any values that result with a value less than zero will be considered to have no chloride present and adjusted to a zero value. The values less than zero are indicated in Table 3 highlighted in red.

Table 3 contains the raw chloride concentration from the Dionex DX-120 in ppm. Column four is the chloride concentration corrected by the (1.9607 ppm) control sample chloride concentrations.

- RAW CONCENTRATION [ppm] - BASE CONCENTRATION 1.9607 [ppm] = CONCENTRATION [ppm]
- CONCENTRATION [ppm] / 1,000 = CONCENTRATION [mg/mL]
- CONCENTRATION [mg/mL] * VOLUME LIQUID [mL] = MASS [mg]

Table 3 – Chloride Sampling Results

SAMPLE #	BOTTLE #	RAW CHLORIDE CONCENTRATION (ppm)	CORRECTED CHLORIDE CONCENTRATION (ppm)	CORRECTED CHLORIDE CONCENTRATION (mg/mL)	CORRECTED CHLORIDE CONTENT (mg)
1	3B	7.4494	5.4887	0.0055	0.2195
2	1B	8.3091	6.3484	0.0063	0.2539
3	3A	5.6778	3.7171	0.0037	0.1487
4	2B	56.7565	54.7958	0.0548	2.1918
5	2A	11.8171	9.8564	0.0099	0.3943
6	1A	40.1737	38.2130	0.0382	1.5285
7	4A	25.9575	23.9968	0.0240	0.9599
8	5A	4.3324	2.3716	0.0024	0.0949
9	6B	9.9718	8.0111	0.0080	0.3204
10	8A	5.6459	3.6852	0.0037	0.1474
11	7B	8.2729	6.3122	0.0063	0.2525
12	7A	5.2901	3.3294	0.0033	0.1332
13	8B	15.3649	13.4042	0.0134	0.5362
14	5B	6.5892	4.6285	0.0046	0.1851
15	8A	20.2547	18.2940	0.0183	0.7318
16	9A	9.5397	7.5790	0.0076	0.3032
17	9B	5.7182	3.7575	0.0038	0.1503
18	4B	25.1151	23.1544	0.0232	0.9262
19	10A	91.0734	89.1127	0.0891	3.5645
20	10B	58.3393	56.3785	0.0564	2.2551
21	12B	10.8675	8.9068	0.0089	0.3563
22	11A	7.8626	5.9019	0.0059	0.2361
23	11B	76.4438	74.4831	0.0745	2.9793
24	13A	4.8081	2.8474	0.0028	0.1139
25	13B	6.4254	4.4647	0.0045	0.1786
26	15A	10.4368	8.4761	0.0085	0.3390
27	14A	6.5740	4.6133	0.0046	0.1845
28	15B	9.6194	7.6587	0.0077	0.3063
29	12A	4.0753	2.1146	0.0021	0.0846
30	14B	4.8666	2.9059	0.0029	0.1162
31	S3	5.0517	3.0910	0.0031	0.1236
32	S4	8.9236	6.9628	0.0070	0.2785
33	S1	7.4494	5.4887	0.0055	0.2195
34	S2	10.6840	8.7233	0.0087	0.3489

Table 3 – Chloride Sampling Results (Continued)

SAMPLE #	BOTTLE #	RAW CHLORIDE CONCENTRATION (ppm)	CORRECTED CHLORIDE CONCENTRATION (ppm)	CORRECTED CHLORIDE CONCENTRATION (mg/mL)	CORRECTED CHLORIDE CONTENT (mg)
35	15E	4.1348	2.1741	0.0022	0.0870
36	11K	11.1535	9.1928	0.0092	0.3677
37	2R	3.4484	1.4877	0.0015	0.0595
38	14J	23.7304	21.7697	0.0218	0.8708
39	8J	8.6709	6.7102	0.0067	0.2684
40	1R	4.4438	2.4831	0.0025	0.0993
41	3J	6.0043	4.0435	0.0040	0.1617
42	15H	10.4821	8.5214	0.0085	0.3409
43	6E	21.8701	19.9094	0.0199	0.7964
44	6H	76.2611	74.3003	0.0743	2.9720
45	2H	6.5485	4.5878	0.0046	0.1835
46	10H	3.4902	1.5295	0.0015	0.0612
47	5R	6.2401	4.2794	0.0043	0.1712
48	3H	15.5388	13.5781	0.0136	0.5431
49	16J	3.3964	1.4357	0.0014	0.0574
50	4K	3.6799	1.7192	0.0017	0.0688
51	3K	4.2063	2.2456	0.0022	0.0898
52	4H	10.4125	8.4518	0.0085	0.3381
53	16R	16.7095	14.7488	0.0147	0.5900
54	4E	4.8859	2.9252	0.0029	0.1170
55	11J	3.8802	1.9195	0.0019	0.0768
56	2K	4.7364	2.7757	0.0028	0.1110
57	7R	3.0603	1.0996	0.0011	0.0440
58	14H	21.6935	19.7328	0.0197	0.7893
59	15R	6.5483	4.5876	0.0046	0.1835
60	10E	7.2708	5.3101	0.0053	0.2124
61	14E	5.5284	3.5677	0.0036	0.1427
62	2E	3.1761	1.2154	0.0012	0.0486
63	5E	14.5607	12.6000	0.0126	0.5040
64	9E	39.2309	37.2702	0.0373	1.4908
65	10J	5.7103	3.7496	0.0037	0.1500
66	9R	11.1289	9.1682	0.0092	0.3667
67	16E	2.8419	0.8812	0.0009	0.0352
68	12R	6.3256	4.3648	0.0044	0.1746
69	9K	1.9952	0.0345	0.0000	0.0014

Table 3 – Chloride Sampling Results (Continued)

SAMPLE #	BOTTLE #	RAW CHLORIDE CONCENTRATION (ppm)	CORRECTED CHLORIDE CONCENTRATION (ppm)	CORRECTED CHLORIDE CONCENTRATION (mg/mL)	CORRECTED CHLORIDE CONTENT (mg)
70	12E	6.1940	4.2333	0.0042	0.1693
71	7K	3.3071	1.3463	0.0013	0.0539
72	10K	2.4867	0.5260	0.0005	0.0210
73	11E	12.0786	10.1179	0.0101	0.4047
74	16H	14.5913	12.6306	0.0126	0.5052
75	13R	7.0338	5.0731	0.0051	0.2029
76	11H	2.6693	0.7086	0.0007	0.0283
77	6J	8.1452	6.1844	0.0062	0.2474
78	10R	9.1112	7.1505	0.0072	0.2860
79	2J	2.1460	0.1853	0.0002	0.0074
80	11R	3.8723	1.9116	0.0019	0.0765
81	9H	2.2371	0.2764	0.0003	0.0111
82	7E	5.4264	3.4657	0.0035	0.1386
83	13E	4.9002	2.9395	0.0029	0.1176
84	1K	9.4978	7.5371	0.0075	0.3015
85	12K	23.4079	21.4472	0.0214	0.8579
86	8H	10.5784	8.6176	0.0086	0.3447
87	8E	7.7641	5.8034	0.0058	0.2321
88	12H	7.2695	5.3088	0.0053	0.2124
89	12J	15.4647	13.5040	0.0135	0.5402
90	1E	37.2175	35.2568	0.0353	1.4103
91	15J	42.0829	40.1222	0.0401	1.6049
92	5K	39.0825	37.1218	0.0371	1.4849
93	4J	4.0512	2.0905	0.0021	0.0836
94	8R	30.8213	28.8606	0.0289	1.1544
95	14R	3.0159	1.0552	0.0011	0.0422
96	7H	10.6625	8.7018	0.0087	0.3481
97	8K	3.4252	1.4644	0.0015	0.0586
98	S5	1.9514	-0.0093	0.0000	-0.0004
99	3R	1.6079	-0.3528	-0.0004	-0.0141
100	14K	2.2766	0.3159	0.0003	0.0126
101	16K	3.4673	1.5066	0.0015	0.0603
102	13J	11.5069	9.5462	0.0095	0.3818
103	13H	5.0283	3.0676	0.0031	0.1227
104	6R	6.0187	4.0579	0.0041	0.1623

Table 3 – Chloride Sampling Results (Continued)

SAMPLE #	BOTTLE #	RAW CHLORIDE CONCENTRATION (ppm)	CORRECTED CHLORIDE CONCENTRATION (ppm)	CORRECTED CHLORIDE CONCENTRATION (mg/mL)	CORRECTED CHLORIDE CONTENT (mg)
105	4R	7.1872	5.2265	0.0052	0.2091
106	5J	3.8268	1.8661	0.0019	0.0746
107	5H	15.8039	13.8432	0.0138	0.5537
108	6K	5.1954	3.2347	0.0032	0.1294
109	1H	17.6505	15.6897	0.0157	0.6276
110	9J	39.4035	37.4428	0.0374	1.4977
111	15K	2.9612	1.0005	0.0010	0.0400
112	7J	5.8214	3.8607	0.0039	0.1544
113	3E	48.3127	46.3520	0.0464	1.8541
114	1J	2.1745	0.2138	0.0002	0.0086
115	13K	3.7939	1.8331	0.0018	0.0733
116	17A	4.0064	2.0457	0.0020	0.0818
117	18E	10.8024	8.8417	0.0088	0.3537
118	17J	11.7801	9.8194	0.0098	0.3928
119	18A	4.0924	2.1317	0.0021	0.0853
120	17H	4.6149	2.6542	0.0027	0.1062
121	17R	6.0610	4.1003	0.0041	0.1640
122	18K	12.3392	10.3785	0.0104	0.4151
123	17B	2.7651	0.8044	0.0008	0.0322
124	18R	17.2711	15.3104	0.0153	0.6124
125	17K	4.0623	2.1016	0.0021	0.0841
126	18B	6.7711	4.8104	0.0048	0.1924

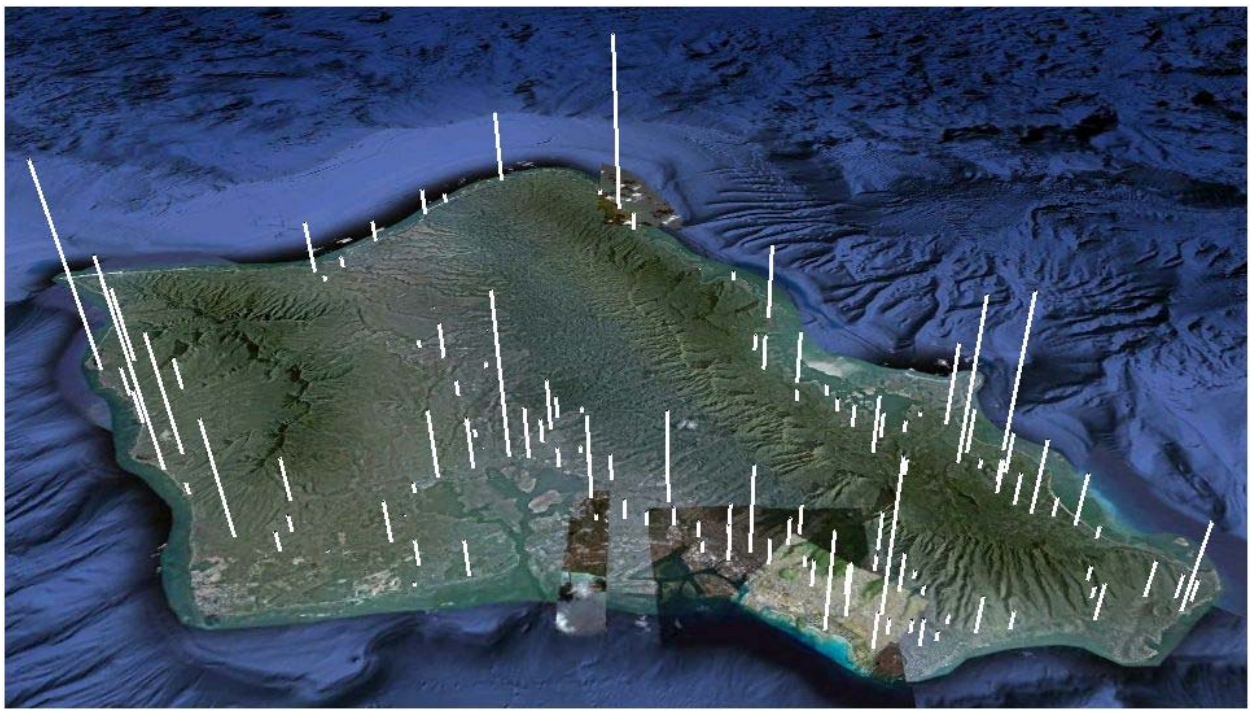

Figure 13 – Pin Cushion Map of Bus Stop Chloride Concentration

6 ANALYSIS

6.1 EXTREME VALUES

The chloride levels ranged from 9 mg/m^2 to 489 mg/m^2 and were not evenly distributed. The mean and standard deviation was 53, and 77.3 mg/m^2 respectively. Seven (7) data points exceeded two times the standard deviation from the mean (207.8 mg/m^2) and were removed from the data set. Outlier site numbers were 4, 7, 9, 13, 188, 244, and 459. These outlier data points are represented in Figure 14, and the bus stop locations are shown in Figure 15.

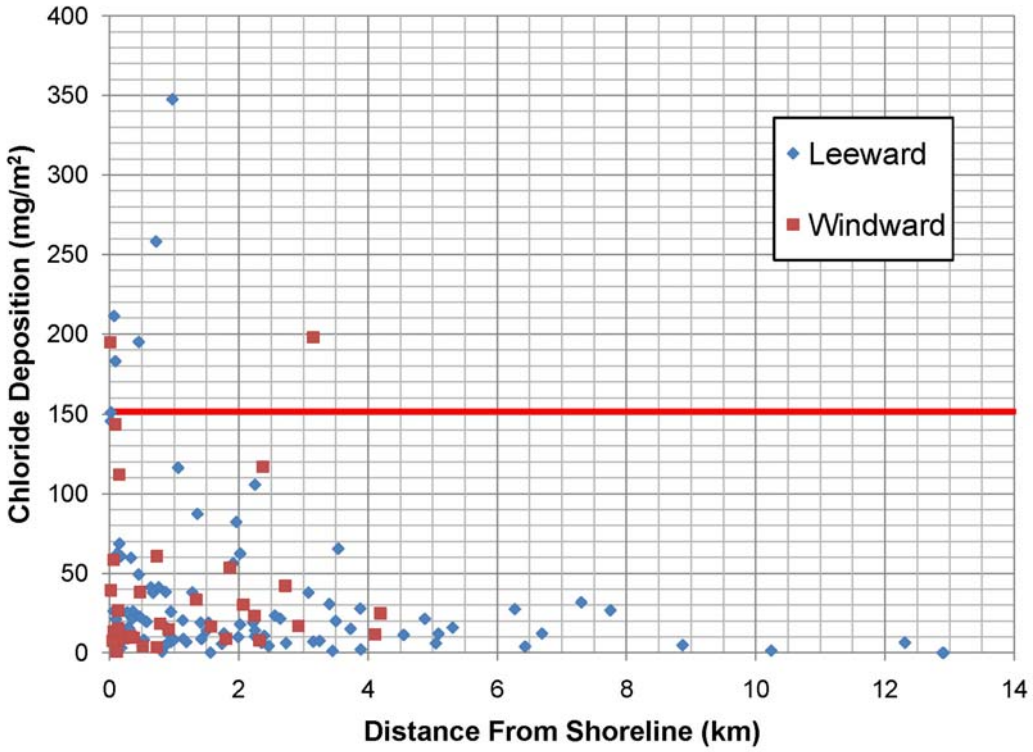

Figure 14 – Graphical Outlier Representation

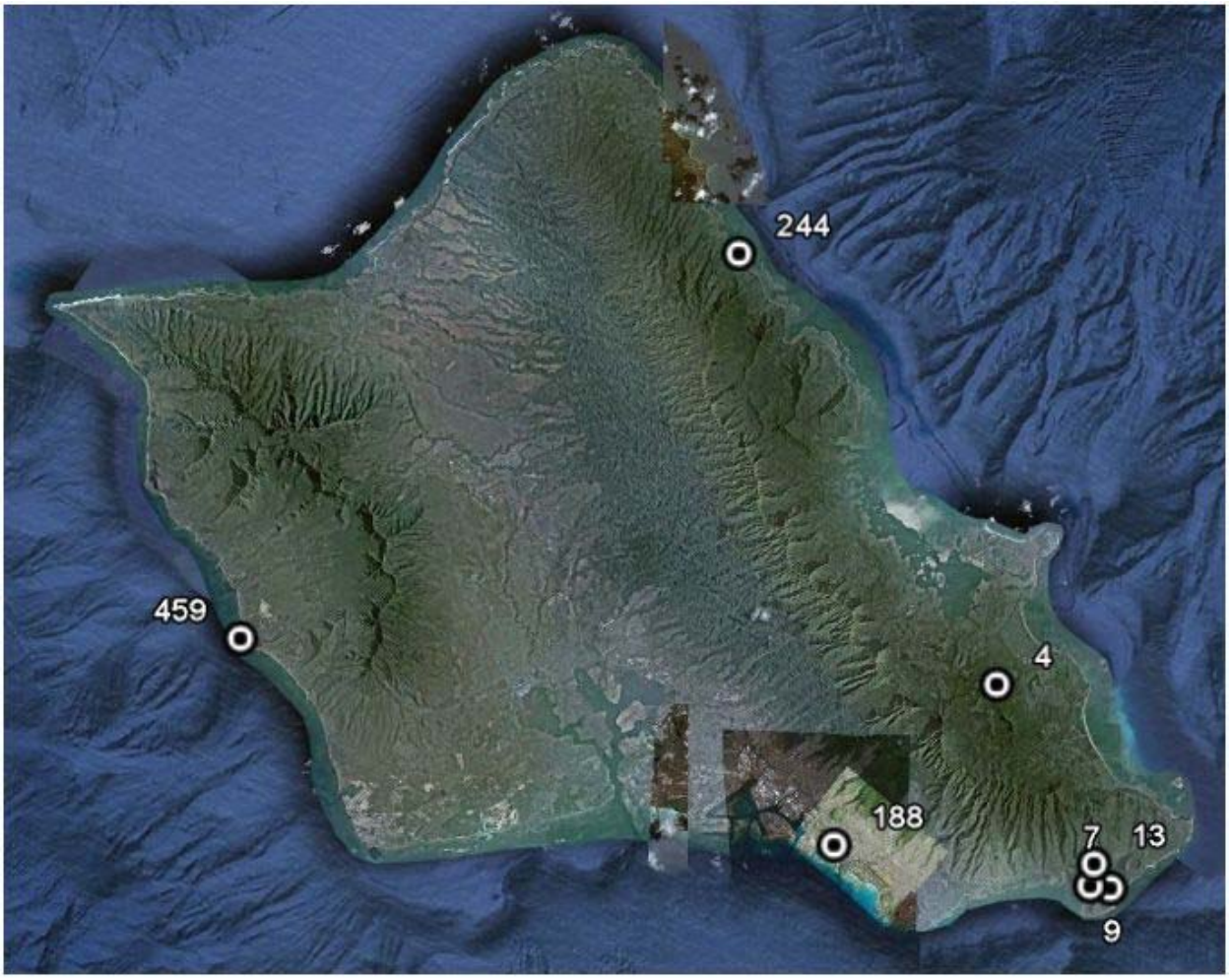

Figure 15 – Extreme Value Bus Stop Locations

These test stations were all within 2.5 kilometers from the shoreline and disturbed all around the island of Oahu. There was no clear explanation as to why these bus stops had so much higher chloride deposition than similar neighboring bus stops.

As stated in previous parallel studies the chloride deposition rates are heavily influenced by wind speed and direction, proximity to shoreline, vegetation, topographical features and likely ocean wave heights. These highly influential factors suggest severe changes in chloride deposition rates may occur over short distances.

6.1.1 DATA CALIBRATION

In order to calibrate the chloride deposition data collected in this study with daily deposition rates measured in the PRCRP study, collection sites within 2 miles of the six PRCRP stations, exampled in Figure 16, were identified and listed in Table 4. Each chloride concentration deposition reading from these 18 sites was divided by the corresponding PRCRP chloride deposition rate to determine the bus stop's appropriate time of exposure for calibration purposes. These 18 calibration values were then averaged to determine a single calibration factor of 1.37 days. This average value was then applied to all other collection sites around Oahu to convert chloride concentration to chloride deposition rates. The results are provided in Table 5.

Figure 16 – Site Selection for Calibration

Table 4 – Data Calibration

SAMPLE #	SITE #	CORRECTED CHLORIDE DEPOSITION (mg/m^2)	CALIBRATION FACTOR (days)
COCONUT ISLAND (75.9 mg/m2/day)			
120	42	14.49	0.19
119	371	12.22	0.16
123	463	4.73	0.06
121	24	22.69	0.30
125	451	12.46	0.16
126	435	25.11	0.33
KAHUKU (78.0 mg/m2/day)			
111	989	5.78	0.07
EWA BEACH INLAND (10.7 mg/m2/day)			
84	358	54.78	4.06
79	921	12.73	0.10
80	916	22.41	1.03
WAIPAHU (11.6 mg/m2/day)			
74	889	67.39	5.81
80	916	11.06	0.95
73	845	51.66	4.45
CAMPBELL INDUSTRIAL PARK (32.2 mg/m2/day)			
82	290	20.58	0.64
81	257	1.67	0.05
83	314	16.48	0.51
MANOA VALLEY (9.2 mg/m2/day)			
39	137	37.67	4.09
40	131	15.40	1.67
AVERAGE		20.83	1.37

Table 5 – Chloride Deposition Rate

SAMPLE #	BOTTLE #	SITE #	TOTAL SAMPLE AREA (m^2)	CORRECTED CHLORIDE CONTENT (mg)	CORRECTED CHLORIDE DEPOSITION (mg/m^2)	ADJUSTED CHLORIDE DEPOSITION RATE (mg/m^2/day)
1	3B	1	0.0080	0.2195	27.3380	19.95
2	1B	2	0.0087	0.2539	29.3468	21.41
3	3A	3	0.0093	0.1487	15.9324	11.63
4	2B	4	0.0081	2.1918	271.2581	197.93
5	2A	5	0.0086	0.3943	45.7429	33.38
6	1A	6	0.0100	1.5285	153.5004	112.01
7	4A	167	0.0060	0.9599	160.3825	117.03
8	5A	177	0.0090	0.0949	10.5961	7.73
9	6B	176	0.0077	0.3204	41.4011	30.21
10	8A	174	0.0063	0.1474	23.2849	16.99
11	7B	178	0.0074	0.2525	34.1149	24.89
12	7A	160	0.0102	0.1332	13.0609	9.53
13	8B	186	0.0103	0.5362	52.2925	38.16
14	5B	185	0.0092	0.1851	20.1462	14.70
15	8A	180	0.0100	0.7318	73.4168	53.57
16	9A	179	0.0095	0.3032	31.9590	23.32
17	9B	164	0.0069	0.1503	21.8068	15.91
18	4B	163	0.0108	0.9262	85.6462	62.49
19	10A	9	0.0101	3.5645	353.8542	258.20
20	10B	7	0.0084	2.2551	267.2766	195.03
21	12B	40	0.0100	0.3563	35.6806	26.04
22	11A	166	0.0097	0.2361	24.3372	17.76
23	11B	13	0.0103	2.9793	289.6037	211.32
24	13A	15	0.0096	0.1139	11.9249	8.70
25	13B	16	0.0123	0.1786	14.5750	10.64
26	15A	11	0.0094	0.3390	35.9053	26.20
27	14A	21	0.0103	0.1845	17.9001	13.06
28	15B	22	0.0088	0.3063	34.7548	25.36
29	12A	25	0.0090	0.0846	9.4462	6.89
30	14B	31	0.0123	0.1162	9.4127	6.87
31	S3	121	0.0092	0.1236	13.4543	9.82
32	S4	120	0.0100	0.2785	27.9359	20.38
33	S1	100	0.0132	0.2195	16.6312	12.14
34	S2	37	0.0099	0.3489	35.4107	25.84

Table 5 – Chloride Deposition Rate (Continued)

SAMPLE #	BOTTLE #	SITE #	TOTAL SAMPLE AREA (m^2)	CORRECTED CHLORIDE CONTENT (mg)	CORRECTED CHLORIDE DEPOSITION (mg/m^2)	ADJUSTED CHLORIDE DEPOSITION RATE (mg/m^2/day)
35	15E	114	0.0091	0.0870	9.6047	7.01
36	11K	129	0.0096	0.3677	38.1161	27.81
37	2R	124	0.0072	0.0595	8.2626	6.03
38	14J	111	0.0060	0.8708	144.8154	105.67
39	8J	137	0.0071	0.2684	37.6717	27.49
40	1R	131	0.0065	0.0993	15.3950	11.23
41	3J	156	0.0055	0.1617	29.3660	21.43
42	15H	84	0.0066	0.3409	51.9400	37.90
43	6E	58	0.0085	0.7964	94.0484	68.63
44	6H	188	0.0062	2.9720	476.2914	347.54
45	2H	187	0.0071	0.1835	25.9504	18.94
46	10H	189	0.0060	0.0612	10.1700	7.42
47	5R	199	0.0066	0.1712	25.8950	18.90
48	3H	194	0.0064	0.5431	85.4187	62.33
49	16J	242	0.0066	0.0574	8.7409	6.38
50	4K	205	0.0061	0.0688	11.3226	8.26
51	3K	264	0.0056	0.0898	16.0839	11.74
52	4H	196	0.0060	0.3381	56.2697	41.06
53	16R	315	0.0066	0.5900	89.5878	65.37
54	4E	335	0.0062	0.1170	19.0006	13.86
55	11J	499	0.0054	0.0768	14.1599	10.33
56	2K	482	0.0057	0.1110	19.4188	14.17
57	7R	416	0.0065	0.0440	6.7908	4.96
58	14H	430	0.0096	0.7893	81.8182	59.70
59	15R	548	0.0069	0.1835	26.7208	19.50
60	10E	568	0.0068	0.2124	31.1118	22.70
61	14E	590	0.0069	0.1427	20.7215	15.12
62	2E	652	0.0064	0.0486	7.6467	5.58
63	5E	759	0.0096	0.5040	52.3427	38.19
64	9E	790	0.0094	1.4908	159.3625	116.28
65	10J	720	0.0061	0.1500	24.4713	17.86
66	9R	690	0.0071	0.3667	51.8968	37.87
67	16E	692	0.0066	0.0352	5.3301	3.89
68	12R	704	0.0081	0.1746	21.5621	15.73
69	9K	817	0.0069	0.0014	0.1994	0.15

Table 5 – Chloride Deposition Rate (Continued)

SAMPLE #	BOTTLE #	SITE #	TOTAL SAMPLE AREA (m^2)	CORRECTED CHLORIDE CONTENT (mg)	CORRECTED CHLORIDE DEPOSITION (mg/m^2)	ADJUSTED CHLORIDE DEPOSITION RATE (mg/m^2/day)
70	12E	643	0.0102	0.1693	16.5496	12.08
71	7K	809	0.0064	0.0539	8.3523	6.09
72	10K	799	0.0072	0.0210	2.9102	2.12
73	11E	845	0.0078	0.4047	51.6577	37.69
74	16H	889	0.0075	0.5052	67.3862	49.17
75	13R	937	0.0078	0.2029	26.0456	19.01
76	11H	979	0.0068	0.0283	4.1722	3.04
77	6J	964	0.0069	0.2474	35.8918	26.19
78	10R	232	0.0068	0.2860	41.9880	30.64
79	2J	921	0.0067	0.0074	1.0995	0.80
80	11R	916	0.0069	0.0765	11.0610	8.07
81	9H	257	0.0066	0.0111	1.6678	1.22
82	7E	290	0.0067	0.1386	20.5790	15.02
83	13E	314	0.0071	0.1176	16.4812	12.03
84	1K	358	0.0069	0.3015	43.4718	31.72
85	12K	436	0.0072	0.8579	119.6470	87.30
86	8H	479	0.0103	0.3447	33.5697	24.50
87	8E	554	0.0072	0.2321	32.0376	23.38
88	12H	578	0.0072	0.2124	29.5031	21.53
89	12J	608	0.0070	0.5402	77.2364	56.36
90	1E	606	0.0068	1.4103	207.0279	151.06
91	15J	459	0.0064	1.6049	250.6181	182.87
92	5K	415	0.0074	1.4849	199.4031	145.50
93	4J	378	0.0067	0.0836	12.4137	9.06
94	8R	366	0.0102	1.1544	112.8268	82.33
95	14R	734	0.0065	0.0422	6.5243	4.76
96	7H	717	0.0095	0.3481	36.5966	26.70
97	8K	830	0.0066	0.0586	8.8337	6.45
98	S5	771	0.0063	0	0	0.00
99	3R	784	0.0065	0	0	0.00
100	14K	843	0.0064	0.0126	1.9608	1.43
101	16K	848	0.0102	0.0603	5.8900	4.30
102	13J	878	0.0068	0.3818	56.4101	41.16
103	13H	856	0.0102	0.1227	12.0355	8.78
104	6R	901	0.0070	0.1623	23.1106	16.86

Table 5 – Chloride Deposition Rate (Continued)

SAMPLE #	BOTTLE #	SITE #	TOTAL SAMPLE AREA (m^2)	CORRECTED CHLORIDE CONTENT (mg)	CORRECTED CHLORIDE DEPOSITION (mg/m^2)	ADJUSTED CHLORIDE DEPOSITION RATE (mg/m^2/day)
105	4R	920	0.0072	0.2091	29.1188	21.25
106	5J	935	0.0071	0.0746	10.5117	7.67
107	5H	962	0.0067	0.5537	83.2269	60.73
108	6K	333	0.0072	0.1294	17.9899	13.13
109	1H	311	0.0078	0.6276	80.0862	58.44
110	9J	999	0.0076	1.4977	196.8143	143.61
111	15K	989	0.0069	0.0400	5.7837	4.22
112	7J	221	0.0074	0.1544	20.9949	15.32
113	3E	244	0.0069	1.8541	267.0420	194.86
114	1J	268	0.0069	0.0086	1.2350	0.90
115	13K	285	0.0071	0.0733	10.2948	7.51
116	17A	12	0.0068	0.0818	12.0572	8.80
117	18E	342	0.0097	0.3537	36.3728	26.54
118	17J	357	0.0073	0.3928	53.9288	39.35
119	18A	371	0.0070	0.0853	12.2195	8.92
120	17H	42	0.0073	0.1062	14.4918	10.57
121	17R	24	0.0072	0.1640	22.6861	16.55
122	18K	411	0.0072	0.4151	57.7210	42.12
123	17B	463	0.0068	0.0322	4.7274	3.45
124	18R	527	0.0074	0.6124	83.2289	60.73
125	17K	451	0.0067	0.0841	12.4582	9.09
126	18B	435	0.0077	0.1924	25.1082	18.32

Figure 17 shows the calibrated bus stop chloride deposition rate values from Table 5 (white) and the six PRCRP site chloride deposition rates used in the calibration of collected field data (blue).

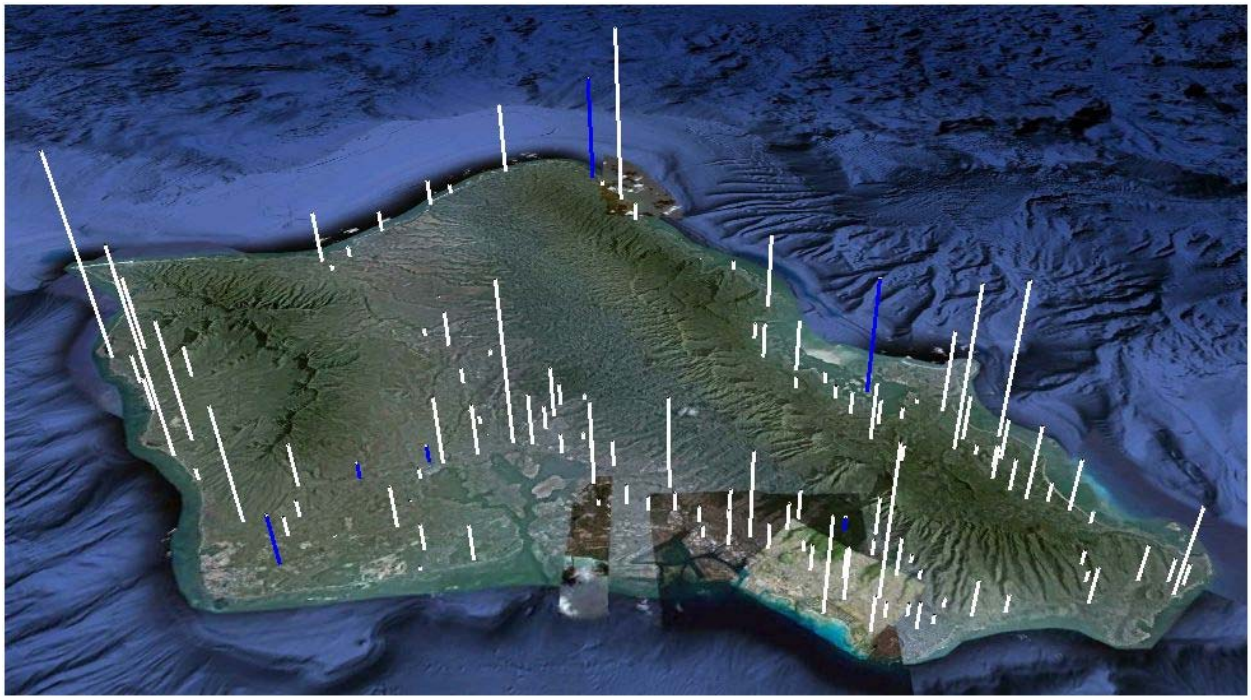

Figure 17 – Calibrated Bus Stop and PRCRP Chloride Deposition Rates

The PRCRP chloride deposition rates suggest that the chloride deposition on the bus stops is equivalent to an ISO 9225 wet wick candle exposed to the same atmospheric conditions for an average of 1.37 days. The low concentration levels found on the bus stop beams may be attributed to the:

- Painted beam surface doesn't collect atmospheric chloride in the same manner as the wet wick of the standardized candles in the International Organization for Standardization 9225 (ISO 9225:1992 (E))
- Lack of a complete 360 degree of exposure surface
- Bus stop roof overhang is conflicting with the beams exposure

Documented photos show no strong correlation between the concentration levels and the 'dirtier' or 'cleaner' bus stop beams.

6.2 DESIGN AND EXTREME VALUE EQUATIONS

Figure 18 shows the chloride deposition rate plotted against the distance from the shoreline for all 126 collection sites. The chloride deposition rate has an inverse relationship to the distance from shoreline. Two linear functions are proposed in Figure 12 which can be used to estimate the chloride deposition rate (mg/m^2/day) as a function of distance from the shoreline (km). These equations may be used to estimate the extreme value or the design value chloride deposition rate. The equations are:

- Extreme: $r = -13d + 150 \geq 20$ (encompasses 99% of data field)
- Design: $r = -13d + 75 \geq 20$ (encompasses 83% of data field)

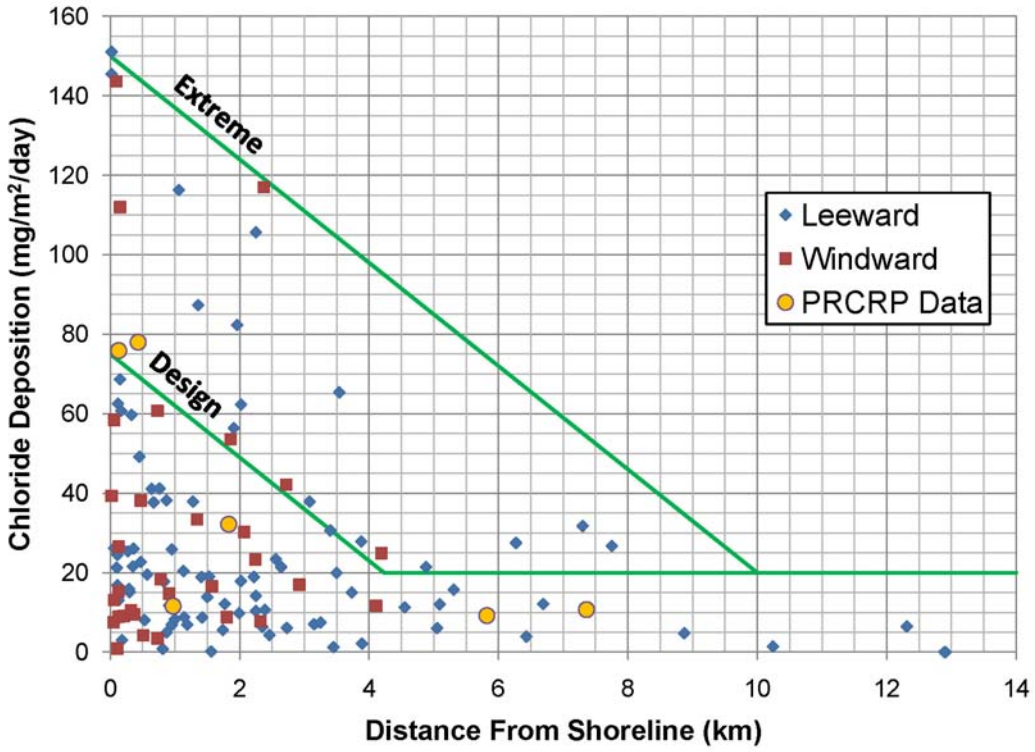

Figure 18 – Concentration Vs Distance to Shoreline

6.3 CHLORIDE DEPOSITION RATE MAP OF OAHU

Figure 19 shows a contour map of the chloride deposition rate generated by the Kernel Smoothing Interpolation function in ArcGIS. The six chloride deposition rates of the PRCRP project were included in the input data for ArcGIS.

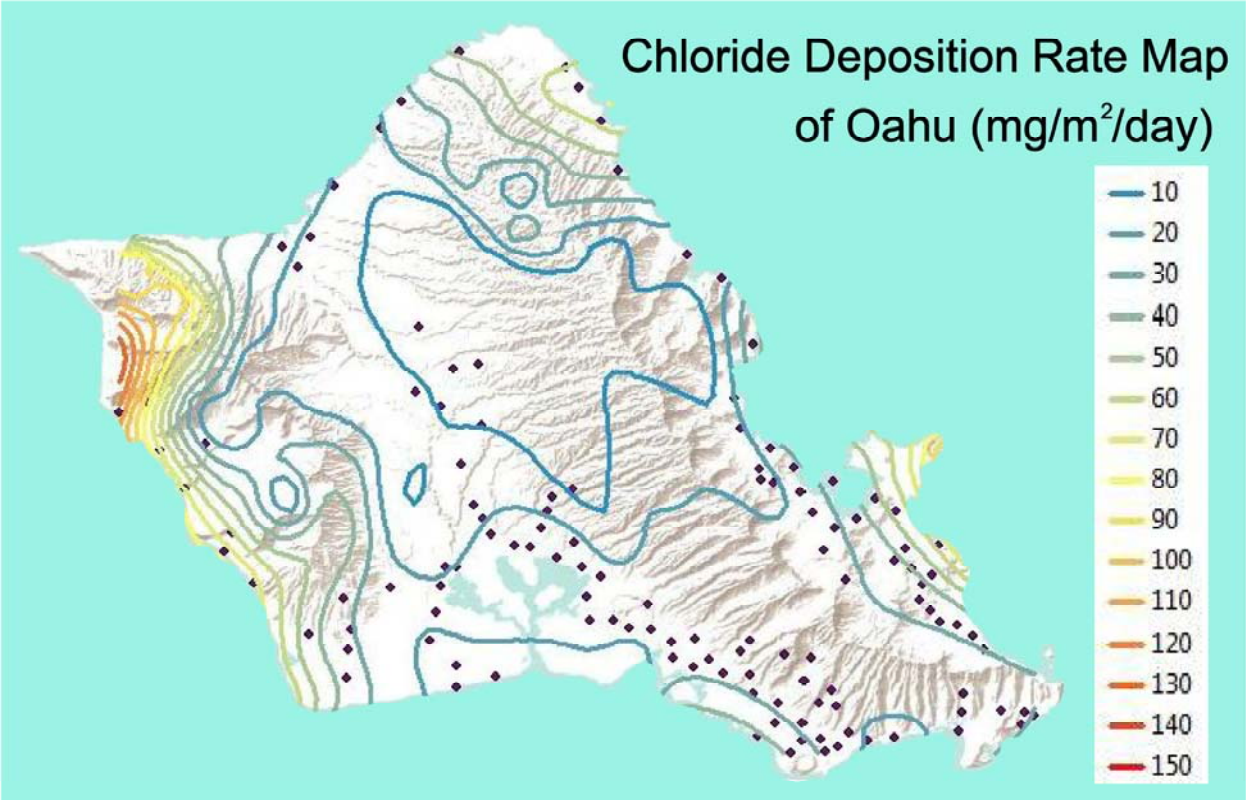

Figure 19 – Chloride Deposition Rate Map of Oahu

The chloride deposition rate map shows higher deposition rates along the windward and leeward shorelines, with reduced deposition rates on the South and North shores, while the lowest deposition rates are in Central Oahu. The chloride concentration levels appear consistent with expectations based on the presence of offshore reefs, which reduce coastal wave action, and prevailing winds, from both Trade (NE) and Kona (S-SW) directions.

7 Conclusions and Recommendations

A study was performed to quantify the chloride deposition rate on the exterior of built infrastructure. Data were collected between October 2010 and March 2011, at various locations on the island of Oahu. The data collection system used in this study involved a single chloride content measurement from roof beams of city bus shelters. One hundred and twenty six (126) sheltered bus stops were carefully selected around the island for testing. Site locations were carefully selected ranging from the coast to inland in approximately one (1) mile radii. The sample collected from each site was analyzed to determine the chloride concentration in mg/m^2. Prior research studies were used to normalize these results to obtain chloride deposition rates in $mg/m^2/day$.

Differences in chloride deposition rates exist within short distances and therefore it is important to implement a large amount of test stations for averaging. Additional data from other studies of chloride deposition rates can be added to this ArcGIS database and updated maps may be generated in the future.

- As expected, the chloride deposition rate decreases with increasing distance from the coast.
- Formulas are proposed for extreme or design value deposition rates based on distance from the shoreline.
- A chloride deposition rate contour map was developed using ArcGIS Kernel averaging.

- Offshore reefs appear to reduce the chloride deposition rate by reducing the intensity of wave breaking at the shoreline.

- Prevailing Trade winds (NE) and frequent Kona winds (S-SW) appear to increase chloride deposition rates on both windward and leeward coastlines of Oahu, respectively.

8 References

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