Development of a Research Program for Corrosion of Galvanized Fasteners used in Cold-Formed Steel Framing

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Ian N. Robertson
ABSTRACT

This paper investigates the potential for corrosion of galvanized fasteners used in cold-formed steel framing (CFSF) by exposing test samples to a variety of environmental conditions frequently found in Hawaii. The results of this research will aid in the evaluation of galvanized CFSF fasteners in various exposure conditions. Long-term field enclosures will be used to determine the effects of exposure to various environmental conditions. Field enclosures were constructed and instrumented in preparation for the placement of the long-term connection test specimens. An accelerated corrosion chamber was installed and initial calibration cycles have commenced.
Acknowledgements

This report is based on a Masters Research Report prepared by Edward P. Neville under the direction of Ian N. Robertson. The authors wish to thank Dr. Si-Hwan Park and Dr. Lloyd Hihara for their review of and comments on the final draft of this report. The authors would also like to thank all the members of the Advisory Committee for their help with the development of this project and report.

This report is part a larger project to monitor the corrosion of galvanized fasteners used in cold-formed steel framing. Funding for this project has been provided by the Department of Housing and Urban Development (HUD), the Steel Framing Alliance, the University of Hawaii College of Engineering, and many vendors and contractors. This support is gratefully acknowledged.
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Chapter 1
Introduction

1.1 Introduction
This research program investigates the potential for corrosion of galvanized fasteners used in cold-formed steel framing (CFSF) by exposing test samples to a variety of environmental conditions frequently found in Hawaii. The results of this research will aid in the evaluation of galvanized CFSF fasteners in various exposure conditions.

This project was initiated on September 26, 2000 by an award from the Department of Housing and Urban Development (HUD) to the North American Steel Framing Alliance (NASFA). The project includes a research effort to study the effects of corrosion of galvanized fasteners on CFSF connection behavior, followed by a final report and development of a Practice Guide for use by industry. NASFA has subcontracted the research component of this study to the Civil Engineering Department at the University of Hawaii (UH). The principal investigator at UH is Dr. Ian N. Robertson, Associate Professor of Structural Engineering. The project has a three-year duration with various scheduled deliverables.

The strategy of the project is to have field enclosure installed in various environmental conditions. These field enclosure will not only serve as test specimens representing standard construction methods, they will also house connection samples in various areas of the enclosures. The connection samples located in the enclosures will represent real-world exposure conditions. In the laboratory, the same type of connection samples will be exposed to various
corrosive conditions in an accelerated corrosion chamber. The objective of the study is two-fold. First, the strength reduction of CFSF connections with respect to corrosion will be determined. Second, the laboratory accelerated testing procedure will be correlated to the real-world exposure conditions found at the various sites.

### 1.2 Project Team
A research project team was assembled with the overall management of the project will be performed by Tim Waite, principal investigator for the North American Steel Framing Alliance (NASFA). Representatives of the sponsor, Housing and Urban Development (HUD), and NASFA will perform regular project reviews. An advisory committee made up of numerous members representing suppliers, contractors and user groups is guiding this research effort.

The following table identifies the committed members in 2003:

<table>
<thead>
<tr>
<th>Member</th>
<th>Company</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Tim Waite</td>
<td>Steel Framing Alliance</td>
<td>Steel Framing Alliance</td>
</tr>
<tr>
<td>Kevin Bielat</td>
<td>Steel Framing Alliance</td>
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<tr>
<td>Jonathon Humble</td>
<td>American Iron and Steel Industries</td>
<td>Steel Suppliers</td>
</tr>
<tr>
<td>Dr. Gregory Zhang</td>
<td>Teck Cominco Metals</td>
<td>Zinc Galavinizing</td>
</tr>
<tr>
<td>Brian Ide</td>
<td>Allison Ide Engineers</td>
<td>LGSEA</td>
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<tr>
<td>Les Nagata</td>
<td>Structural Analysis Group</td>
<td>LGSEA</td>
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<tr>
<td>Ronette Lee</td>
<td>Navy Aloha Center</td>
<td>Navy Housing</td>
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<tr>
<td>Wayne Yamashita</td>
<td>Army Corps of Engineers</td>
<td>Army Housing</td>
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<td>Steve Tome</td>
<td>Marine Corps, Hawaii</td>
<td>MCBH Housing</td>
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<td>Bud Waters</td>
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<tr>
<td>Bob Wilson</td>
<td>ET&amp;F Fastener</td>
<td>Fastener Supplier</td>
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*Table 1.1 – List of current committee members*
The members of the advisory committee represent a wide range of expertise drawn from all fields related to galvanized fasteners and cold-formed steel design and construction. The original committee members are listed below along with their company affiliation and the sector of the industry that they represent.

**Advisory Committee Members**

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<tr>
<th>Name</th>
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<tr>
<td>Nick Benuska</td>
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<td>HSA - Fastener Supplier</td>
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<tr>
<td>Mike Fernandez</td>
<td>Dietrich Industries</td>
<td>HSA - CFS Supplier</td>
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<tr>
<td>Brian Ide</td>
<td>JAI Engineers</td>
<td>LGSEA - Structural Engineer</td>
</tr>
<tr>
<td>Ms. Ronette Lee</td>
<td>Navy Aloha Center</td>
<td>Navy</td>
</tr>
<tr>
<td>Les Nagata</td>
<td>Structural Analysis Group</td>
<td>LGSEA - Structural Engineer</td>
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<td>Steve Tome</td>
<td>US Marine Corps</td>
<td>Marine Corps</td>
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<td>HSA - Large Contractor</td>
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<tr>
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<td>Kevin Wolfley</td>
<td>Kevin Wolfley, Inc.</td>
<td>HSA - Small Contractor</td>
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<td>Wayne Yamashita</td>
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<td>Army</td>
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<tr>
<td>Dr. Gregory Zhang</td>
<td>Cominco, Inc.</td>
<td>Cominco Inc. - Corrosion Expert</td>
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1.3 Current Project Schedule

The original Deliverable Schedule is included below. Current status of the various items is indicated along with completion dates as appropriate.

<table>
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<td>Task Description</td>
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<td>11/25/03</td>
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1.4 Scope of this report

This report encompasses the work done by Eddie Neville, a graduate student at UH. When Eddie Neville started work on the project, the field enclosures were designed, the enclosure sites were identified, the weather instrumentation was ordered and the funding for the corrosion chamber was being sought. This report covers the installation and verification of the environmental monitoring system, installation of the corrosion chamber and description of a testing plan.
2.1 Fundamentals of Corrosion
In simple terms, metal atoms are comprised of a positive core (nucleus and inner electrons) and valence electrons. These valence electrons are capable of migrating in response to a potential gradient. This migration gives rise to electrical conduction. When two conducting metals are in physical contact with each other, valence electrons redistribute and the metal with the higher electron affinity assumes a negative charge compared to the other metal. The presence of an electrolyte in contact with the metal-metal couple gives rise to a closed circuit, or corrosion cell. Current flow in the solid is performed by the migration of valence electrons, while in the electrolyte ion flow is the charge carrier. It is the consequence of this electrical current flow that metal loss occurs.
Electrochemical reactions occur at the metal-electrolyte interface. Specifically, at the anode an oxidation reaction occurs and at the cathode a reduction reaction occurs. Oxidation reactions produce free valence electrons in the metal and ions of the metal in the electrolyte. This ion production is what leads to material loss (corrosion). The reduction reaction at the cathode is highly dependant on the composition of the electrolyte. In naturally occurring seawater electrolytes the following electrochemical reaction primarily occurs at the cathode:

\[ O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (2.1) \]

Schematically, a corrosion cell consists of an anode, a cathode, electrolyte and an external conductive connection between the anode and cathode. (Figure 2.1)
Figure 2.1 – Fundamental Corrosion Cell

The above example is for dissimilar metals in electrical contact with one another. The driving force behind the corrosion cell is the different electron affinity of each type of metal. A not so obvious example of this corrosion cell can be seen in multiphase alloys, such as steel. The Fe$_3$C platelets are in contact with the α-iron, each having a different electron affinity. These two regions with different electron affinities lead to the development of a corrosion cell in the steel. This corrosion cell is the main mechanism by which steel corrodes. The process of Galvanic coupling of steel with a sacrificial anode is a common method of protecting steel from corrosion.

Galvanizing of steel is one of the most economical and effective ways to protect steel. This galvanizing is an adherent coating of zinc or zinc-iron alloys on the surface of steel that provides long-term protection from corrosion. Galvanizing of steel is accomplished by immersing the member in molten zinc. This immersion forms a metallurgical bond between the steel and zinc coating. The standard
galvanized coating is composed of pure zinc and a very small amount of aluminum. It is also possible to apply the zinc coating as paint. Zinc-rich paints that coat the steel framing must satisfy three important conditions for the galvanic process to occur. The zinc particles must be in electrical contact with each other. The zinc particles must also be in electrical contact with the steel. Finally, a continuous electrolyte must exist between the zinc particles and steel (AISI, 1996; Zhang, 1997).

The zinc coating applied to the steel provides a physical barrier as well as a cathodic protection against corrosion. In most environments, zinc corrodes less than steel. The rate of corrosion of zinc in atmospheric conditions is less than one tenth of that for steel (Zhang, 2000b). In fact, atmospheric conditions particularly detrimental to steel corrosion are those in which zinc coatings have been shown to be most effective (Zhang, 2000b). These conditions include marine and industrial atmospheric exposure. As explained by Zhang (2000a), "galvanized (i.e. zinc coated) steel is a typical example of metallic coating that provides a barrier layer to protect the steel and also sacrificially protects the locations where discontinuities occur in the coating." He adds that "... galvanic corrosion resulted in a reduction of the corrosion of steel by 3 times in rural, 40 times in industrial, and 300 times in seacoast industrial atmospheres." This galvanic effect is caused because zinc acts as the sacrificial anode protecting steel, the cathode. This sacrificial corrosion of the zinc coating occurs because zinc is higher on the galvanic series, it is more electronegative than steel.
This galvanic protection is effective over a short distance from a discontinuous edge of the zinc coating (Figure 2.2). This Galvanic Protection Distance (PD) varies depending on the environmental conditions. A PD of up to 5 mm was observed under full immersion in de-ionized water. In atmospheric conditions the PD is considerably smaller, and depends on the presence of an electrolyte to facilitate anodic sacrificial corrosion thus protecting neighboring cathodic material (Zhang, 2000c). In cold-formed steel framing there are often discontinuities in the zinc coating. This is particularly evident at cut ends, drilled holes and connections.

It is important that the protection distance is adequate to prevent rapid corrosion of exposed steel surfaces.

![Diagram showing regions A to E representing different conditions of zinc coating and steel corrosion](image)

<table>
<thead>
<tr>
<th>REGION</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Zinc coating is intact, complete barrier protection from zing</td>
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<tr>
<td>B</td>
<td>Transition to no zinc barrier</td>
</tr>
<tr>
<td>C</td>
<td>No zinc barrier, corrosion protection provided by galvanic action.</td>
</tr>
<tr>
<td>D</td>
<td>Transition to bare steel corrosion zone</td>
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<tr>
<td>E</td>
<td>No protection by zinc, bare steel corrosion rate</td>
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_Figure 2.2 - Galvanic Protection Distance_

Although a galvanized coating provides excellent protection and acts as a cathodic barrier, the zinc coating corrodes slowly over time. The galvanic corrosion rate of zinc and extent of galvanic protection of steel is dependant on
specimen dimensions and environmental factors. The type of wetness and concentration of atmospheric pollutants affect the rate of corrosion of zinc. This corrosion directly affects the durability of the galvanized steel, because it leaves the steel underneath vulnerable to corrosion attack (AISI, 1996; Zhang, 1997). According to Zhang (2000d), "the high corrosion resistance of zinc is largely due to the formation of a stable, tenacious and compact corrosion product layer during the corrosion processes in atmospheric environments. The protective corrosion product layer is formed under the effect of cyclic weathering over a period of time." He points out that for accurate simulation of field conditions during accelerated laboratory testing, it is important that wetting and drying cycles be included to allow the corrosion product layer to form. "The corrosion rates will be high under the conditions where tenacious and compact corrosion (products) cannot form" (Zhang, 2000d) such as during a continuous salt spray test. Prediction of the life of a zinc coated steel member depends on various properties of the atmospheric environment. According to Zhang and Hwang (2000), "the corrosion rate of zinc in atmospheric environments may vary from as low as about 0.1 µm/year in indoor environments to as high as more than 10 µm/year in some industrial or marine environments .... This means that a G60 galvanized steel, about 13 µm coating each side, would have a corrosion life of more than 100 years in the least corrosive environment but only for about one year in an extremely corrosive environment." Notably, this is the age at which MCBH exposed G60 sections showed red rust (Figure 2.3)
2.2 Field Enclosures

Five field enclosures have been constructed, at various sites on Oahu, to imitate real-world conditions. Industry standard construction methods were used to construct enclosures that incorporate a wide range of commonly used construction techniques and materials. The FEMA Technical Bulletin 8-96 on Corrosion Protection for Metal Connectors in Coastal Areas (FEMA 1996) was used to guide the development of the field enclosures. This FEMA funded study investigated the performance of galvanized sheet metal connector plates used in timber construction when subjected to different field exposure conditions. Five classes of were identified, mainly:

- Partially sheltered exterior exposures (e.g. crawl space and eaves)
- Boldly exposed exterior exposures (e.g. exterior walls and roof)
- Vented enclosed exposures (e.g. attic space)
- Unvented enclosed exposures (e.g. sealed wall and floor cavities)
- Interior living space exposures (e.g. inside air-conditioned occupied space)

2.2.1 Configuration of Field Enclosures

The enclosures are designed to meet local building codes while using a variety of construction materials to demonstrate a representative environment. The original design drawings and connection details are shown Figure 2.3 and Figure 2.4. The walls, floor and roof trusses for all five enclosures were prefabricated during a training seminar with local construction workers. The first two enclosures installed were at KMCB in Kaneohe (Figure 2.5). The first two enclosures were
constructed on-site with the prefabricated components. The next three enclosures were all constructed off-site, and then transported to their respective sites. Some common features all the enclosures are:

- Vented attic space
- Exposed floor joists in the crawl space
- Enclosed floor joist in the crawl space
- Hardie Board siding material
- Vinyl siding material
- Drywall enclosed wall cavities
- Insulated wall cavities
- Un-insulated wall cavities
- All steel used is G60 galvanized

The following companies and individuals have contributed materials, expertise and time towards construction of the UH corrosion field chambers.

<table>
<thead>
<tr>
<th>Company</th>
<th>Donation</th>
<th>Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hunt Building Corporation</td>
<td>Coordination, labor &amp; steel framing material for construction of all five enclosures</td>
<td>J.B. Waters, Tim Stengel, Ralph Valentino</td>
</tr>
<tr>
<td>Niche Site Concrete Inc.</td>
<td>Labor to construct footings at all 5 enclosures at MCBH, Iroquois Point and Wheeler AAF</td>
<td>Geoff Michaelson, Bill Wiland</td>
</tr>
<tr>
<td>Ameron International Inc.</td>
<td>Concrete for footings at all 5 enclosures at MCBH, Iroquois Point and Wheeler AAF</td>
<td>Bill Alina, George West, Frances Ahloy</td>
</tr>
<tr>
<td>G. W. Killebrew</td>
<td>Insulation and sheetrock for all 5 enclosures at MCBH, Iroquois Point and Wheeler AAF</td>
<td>Kekoa Faurot</td>
</tr>
<tr>
<td>Honsador Lumber - Oahu</td>
<td>Siding and doors for 2 enclosures at MCBH</td>
<td>Wayne Lincoln</td>
</tr>
<tr>
<td>John Wagner Associates, Inc. - Grabber Construction Products</td>
<td>Screw fasteners for all enclosures and for all test coupons</td>
<td>Terry Boswell</td>
</tr>
<tr>
<td>Company</td>
<td>Task Description</td>
<td>Contact Person(s)</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>E T &amp; F Fasteners</td>
<td>Pin fasteners for siding</td>
<td>Bob Wilson</td>
</tr>
<tr>
<td>RSI Roofing &amp; Bldg Supply</td>
<td>Tech shield &amp; shingles for 2 enclosures at MCBH</td>
<td>Richie Mudd</td>
</tr>
<tr>
<td>Simpson Strong Tie</td>
<td>Load-path connectors for all enclosures</td>
<td>Steve Duddles</td>
</tr>
<tr>
<td>Pacific Steel Construction</td>
<td>Labor for construction of all 5 enclosures at MCBH, Iroquois Point and Wheeler AAF</td>
<td>Ken Ball</td>
</tr>
<tr>
<td>American Tradition Homes</td>
<td>Labor for construction of 2 enclosures at MCBH and installation of vinyl siding at 3 enclosures at Iroquois Point and Wheeler AAF</td>
<td>John Pearson, Matt Winward &amp; Dan Kinney</td>
</tr>
<tr>
<td>Sunrise Construction, Inc.</td>
<td>Labor for construction of 2 enclosures at MCBH</td>
<td>Marcus Gillespie</td>
</tr>
<tr>
<td>Dietrich Industries Inc.</td>
<td>Steel to make test coupons</td>
<td>Akira Usami</td>
</tr>
<tr>
<td>Skyline Roofing, Inc.</td>
<td>Roof installation for 3 enclosures at Iroquois Point and Wheeler AAF</td>
<td>Charlie Spiegel</td>
</tr>
</tbody>
</table>

Table 2.1 – List of contributors to the field enclosures
Figure 2.3 – Field Enclosure Drawings
2.2.2 Field Enclosure locations
Technical Bulletin 8-96 (FEMA 1996) also identifies three environmental exposure conditions based on distance from the coastline, namely coastal (within 100 meters of the coastline), intermediate (between 100 and 1000 meters of the coastline), and inland (beyond 1000 meters from the coastline). The locations of the five field enclosures and the environmental exposure condition are listed below (Table 2.1). Military installations were selected for added security against potential vandalism of the field enclosures.
<table>
<thead>
<tr>
<th>Station Location</th>
<th>Environmental Exposure Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Kaneohe Marine Corps Base, Ocean-side</td>
<td>Coastal (within 100 meters of coastline)</td>
</tr>
<tr>
<td>2 Kaneohe Marine Corps Base, Inland</td>
<td>Intermediate (100 –1000 meters of coastline)</td>
</tr>
<tr>
<td>3 Iroquois Point, Ocean-side</td>
<td>Coastal (within 100 meters of coastline)</td>
</tr>
<tr>
<td>4 Iroquois Point, Harbor-side</td>
<td>Intermediate (100 –1000 meters of coastline)</td>
</tr>
<tr>
<td>5 Wheeler Army Airfield</td>
<td>Inland (beyond 1000 meters from coastline)</td>
</tr>
</tbody>
</table>

Table 2.2 – Field enclosure location and associated exposure condition

Figure 2.3 – Field enclosure locations on Oahu
Figure 2.4 – Kaneohe Bay Locations, arrows indicate direction pictures were taken.
Figure 2.5 – KMCB Station 1, looking to the coastline

Figure 2.6 – KMCB Station 1, looking towards the mountains
Figure 2.7 – KMCB Station 2 looking towards the mountains
Figure 2.8 – Iroquois Point enclosure locations
Figure 2.9 – Iroquois Point Station 3

Figure 2.10 – Iroquois Point Inland Site, Station 4.
Figure 2.11– Wheeler Army Airfield enclosure location
2.3 Corrosion specimens
The field enclosures have been constructed using common construction methods with varying fascia materials and connection types. In the long-term the enclosures serve as test specimens themselves. In conjunction with observing the corrosion of various connection types within the enclosures, connection specimens and bare metal specimens (coupons) will be placed in various regions of the enclosures. The connection specimens serve to allow periodic tension tests to be conducted to investigate the impact of corrosion on connection strength loss relative to each area. The coupons, on the other hand, will represent the baseline corrosion of bare steel and bare zinc, without any galvanic protection. The coupons will help standardize the baseline corrosion of each area within and external to the structure.

2.3.1 Fastener Test Specimens
Preliminary testing of different connection types with different fastener types was conducted in the UH lab. From the preliminary testing, it was determined that the best results are demonstrated by a two-screw lap splice connection using #10 self-drilling screws. Different screw head, shaft size and material fasteners were used in the preliminary testing samples. It was noticed that the flat pan headed fastener with LOX™ recess had a tendency to separate from the shaft the fastener during the tension test. The hexagonal headed fastener did not demonstrate this head-shaft failure in the initial tests. One of the goals of this study is to demonstrate and predict the failure of connections made in light gauge steel. The mechanism of failure desired is the shearing of the fastener due to
material loss from corrosion. The head-shaft failure, demonstrated by the LOX™ recessed fastener, occurs before any shaft shear failure.

**Figure 2.12 – Different screw heads considered during testing**
To verify the repeatability of the failure mechanism a second test was conducted. The second test consisted of tension tests of two-screw lap splice specimens with both the LOX™ recessed and hexagonal headed fasteners (Figure 2.12, Figure 2.13).

**Figure 2.13 – Connection sample undergoing tension test to failure**
The head-shaft separation was readily apparent in seven out of ten tension tests performed on the LOX™ recessed fastener. The data scatter of the maximum load for the LOX™ recessed head was much higher than that for the hex head screw (Table 2.2). Figure 2.14 shows the results from both the hex head and the LOX™ recessed head tension tests.

<table>
<thead>
<tr>
<th></th>
<th>Mean Ultimate Strength (lbf)</th>
<th>Standard deviation of the Ultimate Strength (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hex Head</td>
<td>2926.4</td>
<td>94.7</td>
</tr>
<tr>
<td>LOX™ Head</td>
<td>2669.8</td>
<td>205</td>
</tr>
</tbody>
</table>

Table 2.3 – Ultimate Strength Variation During Tension Tests

The more uniform failure mode of the hex headed fastener is the desirable behavior for repeatability. All fasteners produced results that exceed the required shear strength and are adequate for construction.

In parallel with the field tests, laboratory testing of different sample coupons will be conducted. The laboratory testing consists of placing the samples in an accelerated corrosion condition with follow on testing. The testing of the samples will be conducted in the corrosion chamber at UH.
Figure 2.14 – Tension test results for each screw type
2.3.2 Connection Specimen Locations
Numerous tensile test specimens are to be included in the field enclosures for periodic monitoring of the effects of atmospheric corrosion on screwed connections. The configuration selected for use in the field enclosures is the 1” wide 16 gage strips with 2 #10 screws as shown in Figure 2.15.

Figure 2.15 - Test Connection Samples to be located in Field Enclosures
Numerous test specimens are to be included in the field enclosures for testing at various stages during the project. Each test series will consist of three nominally identical test specimens. Some specimens will be installed during construction, while others will be left outside the enclosure for 3 and 6 months to simulate conditions for prefabricated framing that is left exposed prior to construction, or conditions at a delayed construction site. Specimens will be extracted from the enclosure after 6 months, one year and two years of exposure for testing at the
UH Material Testing Laboratory under the same conditions as the initial control specimens. Additional specimens are included in the event that permission is granted to leave the enclosures in place for longer than the planned two years. Table 2.2 shows the number and location of test specimens to be included in each field enclosure. A total of 285 test specimens will be required for each field enclosure, for an overall total of 1,425 test specimens.

<table>
<thead>
<tr>
<th>Location in Enclosure</th>
<th>Time installed</th>
<th>No. of series*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside occupied space</td>
<td>At construction</td>
<td>5**</td>
</tr>
<tr>
<td>Inside occupied space</td>
<td>After 3 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>Inside occupied space</td>
<td>After 6 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>Inside sealed wall cavity</td>
<td>At construction</td>
<td>5</td>
</tr>
<tr>
<td>Inside sealed wall cavity</td>
<td>After 3 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>Inside sealed wall cavity</td>
<td>After 6 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>Inside unsealed wall cavity</td>
<td>At construction</td>
<td>5</td>
</tr>
<tr>
<td>Inside unsealed wall cavity</td>
<td>After 3 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>Inside unsealed wall cavity</td>
<td>After 6 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>Inside vented attic</td>
<td>At construction</td>
<td>5</td>
</tr>
<tr>
<td>Inside vented attic</td>
<td>After 3 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>Inside vented attic</td>
<td>After 6 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>In crawl space (with sheathing)</td>
<td>At construction</td>
<td>5</td>
</tr>
<tr>
<td>In crawl space (with sheathing)</td>
<td>After 3 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>In crawl space (with sheathing)</td>
<td>After 6 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>In crawl space (w/o sheathing)</td>
<td>At construction</td>
<td>5</td>
</tr>
<tr>
<td>In crawl space (w/o sheathing)</td>
<td>After 3 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>In crawl space (w/o sheathing)</td>
<td>After 6 months ext. exposure</td>
<td>5</td>
</tr>
<tr>
<td>Permanent exterior exposure</td>
<td>At construction</td>
<td>5</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>95</td>
</tr>
</tbody>
</table>

* Each test series consists of three test specimens.
** One series tested at each of 6 months, 1 year and 2 years exposure, with two test series saved for potential longer term testing.

**Table 2.4 – Table of Connection Samples to be used for testing**
2.4 Corrosion Chamber

The corrosion chamber purchased for this project is the QFOG Cyclic Corrosion Tester 1100, manufactured by Q-Panel Lab Products of Cleveland, Ohio. The corrosion chamber exposes the testing coupons to a series of different environments in a repetitive cycle. The complete description of the corrosion chamber is discussed in Chapter 4.
3.1 Weather Monitoring

In order to correlate corrosion rate to in-service conditions, the field enclosure environment must be monitored. The following is a list of monitored parameters at each field enclosure site:

- External Temperature
- External Humidity
- Internal Temperature (4 locations housing test connection samples)
- Internal Humidity (4 locations housing test connection samples)
- Wind Speed
- Wind Direction
- Rainfall
- Solar radiation levels
- Atmospheric chloride levels

The majority of the monitored parameters are recorded by an automated data collection system. Our weather monitoring system was installed at each field enclosure (Figure 3.1). Each system consists of the following components purchased from Campbell Scientific Inc., Logan, Utah:

- CR10X Measurement and Control Module (Data logger)
- CS500 Temperature and Relative Humidity Probe (5 probes)
- LI200S Pyranometer (Solar Radiation sensor)
- TE525 Tipping Bucket Rain Gage
- 03001 Wind Sentry (Wind speed and direction)
- Solar Panel
- PS12LA Power Supply
3.2 CR10X Measurement and Control Module
The CR10X is a fully programmable datalogger and controller with non-volatile memory and a battery-backed clock. The assembly and wiring of each weather station was done at the UH lab. After assembly, each station was programmed and powered on to verify proper operation prior to field installation. The wiring diagram for the monitoring stations is listed in Appendix A. The CR10X is accessed via a laptop computer using the PC208 Datalogger Support Software supplied by Campbell Scientific. The software is used to access the datalogger, load the program and retrieve the stored data. The datalogger program is created in the EDLOG program (supplied with the PC208 software). The program created for Weather Station 1 is listed in Appendix B. The datalogger itself has various types of internal memory installed to complete its tasks. The CR10X has 2 Megabytes of Flash Electrically Erasable Programmable Read Only Memory (EEPROM) and 128 kilobytes of Static Random Access Memory (SRAM). The SRAM is used to compile and execute the program instructions.
and serves as an intermediate data storage location. The EEPROM is used to store the active program and as a final storage area for data.

Figure 3.1 – CR10X Datalogger and Control Unit

The datalogger is programmed to sample all probes once every second. This sampled data is averaged every 15 minutes and recorded in final storage where it is later retrieved for analysis. The program currently installed in the CR10X allows for storage of approximately 10 months of data. The program that is loaded in each CR10X and the procedure for downloading the data from the datalogger is located in Appendix B.
3.3 CS500 Temperature and Relative Humidity Probe

Figure 3.2 – Temperature and Relative Humidity sensor prior to wiring

The CS500 probe contains a Platinum Resistance Temperature (PVT) detector and a Vaisala INTERCAP® capacitive relative humidity sensor. The CS500 probe used to measure the external parameters is installed inside a 6-plate radiation shield (part number 41301). The shield mitigates the effect of solar radiation on the temperature readings. The other probes will be placed in various locations throughout the field enclosure.
Figure 3.3 – External probe installed in 6-plate radiation shield

As shown in figure 3.4, the accuracy of the temperature probe depends on the temperature it is sampling. For the temperature region we are investigating, 15-32°C (60-90°F), the accuracy is approximately ±0.5°C (±1.8°F). The accuracy of the Relative Humidity measurement is ±3% for RH between 10-90% and ±6% for RH between 90-100% at 20°C.
3.4 LI200S Pyranometer

The LI200S measures incoming solar radiation with a silicon photovoltaic detector mounted in a cosine-corrected head. The detector outputs current, and a shunt resistor in the sensor cable converts the signal from current to voltage. The LI200S is calibrated against an Eppley Precision Spectral Pyranometer to accurately measure sun plus sky radiation. The datalogger is programmed to store the average flux density, with units in Watts per square meter. Each LI200S comes with a calibration value that is required to calculate the correct multiplier used in the programming instruction. The LI200S has a maximum absolute error in natural daylight of ±5%, but is typically ±3%.

Figure 3.2 – Temperature error graph
Figure 3.4 – Schematic of solar radiation sensor with shunt resistor

Figure 3.5 – LI200S mounted on leveling plate

3.5 TE525WS Tipping Bucket Rain Gage
The tipping rain bucket is an adaptation of the standard Weather Bureau tipping bucket rain gage. An 8-inch diameter funnel is used to direct rainwater to the bucket mechanism. As the bucket fills with rainwater, gravity causes the bucket to rotate downward. The bucket is attached to a switch that closes as the bucket
tips to one side. The bucket will then rotate in the opposite direction as it fills with more rainwater. This back and forth tipping of the bucket closes and opens the switch. The number of switch cycles is what is measure by the datalogger.

The number of switch closures is converted to a rainfall rate in inches per hour prior to being stored in the datalogger memory. The accuracy of the rain gage is indicated in Table 3.1.

<table>
<thead>
<tr>
<th>Rainfall Rate</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 1 in./hr</td>
<td>±1%</td>
</tr>
<tr>
<td>1 to 2 in./hr</td>
<td>+0, -2.5%</td>
</tr>
<tr>
<td>2 to 3 in./hr</td>
<td>+0, -3.5%</td>
</tr>
</tbody>
</table>

Table 3.1 – TE525WS Tipping Bucket Rain Gage accuracy

Figure 3.6 – Tipping Bucket Rain Gage showing internal bucket
3.6 Wind Sentry
A R.M. Young model 03001-5 wind sentry is used to measure wind speed and direction. Wind speed is monitored using a R.M. Young model 03101-5 anemometer. The anemometer consists of a three-cup wheel attached to a transducer. The cup wheel rotation creates an AC sine wave voltage signal with frequency directly proportional to wind speed. This AC signal is induced in a stationary coil by a two-pole ring magnet mounted on the cup wheel shaft. One complete sine wave cycle is produced for each cup wheel rotation. The datalogger is programmed to record wind speed in miles per hour (mph). An R.M. Young model 03301-5 wind vane is used to record wind direction. Wind vane position is transmitted by a 10K ohm precision conductive plastic potentiometer, which requires a regulated excitation voltage. With a constant voltage applied to the potentiometer, the output signal is an analog voltage directly proportional to azimuth angle.
3.7 Atmospheric Chloride Monitoring

The amount of chlorides entrained in the air is required to determine how corrosive an environment will be. To determine and monitor chloride levels in the atmosphere around the field enclosures, an atmospheric chloride candle will be installed at each site. The chloride candle measurements are conducted in accordance with the International Organization for Standardization 9225 (ISO 9225:1992(E)) standard. The principle behind the chloride candle relies on a rain-protected wet textile surface, with a known area, being exposed for a specified duration. The amount of chloride deposition is determined by chemical
analysis. From the results of this analysis the chloride deposition rate is calculated, expressed in milligrams per square meter per day [mg/(m²•d)].

The chloride candles consist of a test tube, rubber stopper, candle wick (surgical gauze) and a 500 mL polyethylene flask (Figure 3.8). The test tube is used to support the wick of the candle for exposure. The test tube is inserted through a hole in the rubber stopper. The gauze is placed over the test tube, exposing a known area of gauze. The other end of the gauze is routed through grooves in the stopper and allowed to fall to the bottom of the flask where a glycerol and distilled water solution [20% (V/V)] is used to maintain the wick wet. The atmospheric candle is placed under a 500 mm x 500 mm square roof attached to the side of each field enclosure (Figure 3.9). The roof serves to minimize the effect of dilution from rainfall. After the candle has been exposed to the environment, the candle wick is washed into the flask. The fluid in the flask is then analyzed for its chloride content. The ISO 9225 calls for mercuric titration to be conducted on the sample to determine the chloride content. The UH laboratory is not ideal for conducting the mercuric titration due to the inexperience of the lab worker in doing titration and the hazardous waste considerations with the mercury used in the titration. A local chemical analysis firm will be contracted to conduct the chloride analysis for this project. If a third party analysis is too cost prohibitive, the sample could be analyzed for the conductivity level. This conductivity level could be correlated to the chloride content, with a few assumptions made.
Figure 3.9 – Atmospheric Chloride Candle and Shelter Schematic.
At the time of this report, the atmospheric candles have not been placed at the field sites. The initial exposure period will be approximately three weeks. After the initial chloride level determination, the exposure duration will be adjusted to provide sufficient chloride levels for accurate analysis, but not long enough to be affected by prolonged exposure. The wick will accelerate the evaporation of the candle solution. The glycerol solution is used to mitigate the evaporative effect. The initial three-week exposure should require only the original amount of glycerol solution in the flask. If the evaporation of the solution is excessive, the solution can be adjusted to a glycerol and water concentration of 40% (V/V). If the growth of fungi becomes excessive, octanoic acid (C₈H₁₆O₂) can be added (20 drops per 1000 mL of solution).
Chapter 4
Corrosion Chamber

4.1 Description of Chamber

The corrosion chamber purchased for this project is the QFOG Cyclic Corrosion Tester 1100 (Figure 4.1), manufactured by Q-Panel Lab Products of Cleveland, Ohio. The QFOG 1100 has a chamber volume of approximately 1100 liters, which is capable of handling up to two hundred 4”x12” samples. The corrosion chamber was purchased with funds from two main contributors. The UH College of Engineering contributed $10,000 to the purchase of the chamber. The Steel Framing Alliance collected and contributed $7,000 in donations from companies listed in Table 4.1.

<table>
<thead>
<tr>
<th>Company</th>
<th>Address</th>
<th>Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMCO</td>
<td>263 Covina Lane</td>
<td>Tom Porter</td>
</tr>
<tr>
<td></td>
<td>City of Industry, CA 91746</td>
<td></td>
</tr>
<tr>
<td>Western Metal Lath</td>
<td>6510 General Drive</td>
<td>John Maciel</td>
</tr>
<tr>
<td></td>
<td>Riverside, CA 92509</td>
<td></td>
</tr>
<tr>
<td>Steeler, Inc.</td>
<td>10023 MLK Jr. Way So.</td>
<td>Michael Vailencour</td>
</tr>
<tr>
<td></td>
<td>Seattle, WA 98178</td>
<td></td>
</tr>
<tr>
<td>E T &amp; F Fasteners</td>
<td>29019 Solon Rd.</td>
<td>Dave Nolan</td>
</tr>
<tr>
<td></td>
<td>Solon, OH 44139</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 – List of contributors for the Corrosion Chamber
The corrosion chamber was installed on the west side of Holmes Hall at UH. The chamber is located along the exterior of the building; this reduces the impact of the corrosive chamber exhaust on the surroundings (Figure 4.2). The corrosion chamber is not a self-contained unit; various utilities are required to be connected to the chamber once the chamber is in place. The chamber requires a source of air, with a pressure range of 40-120 psi and a maximum flow rate of 3.5 standard cubic feet per minute (SCFM), which is free of oil, dirt and moisture.
Figure 4.2 – Corrosion chamber adjacent to Structures Lab
A stand-alone oil-less air compressor and tank (Campbell and Hausfeld model WL6100) was purchased and installed next to the chamber (Figure 4.3). A water
and debris filter was installed on the inlet to the chamber to remove any moisture and dirt from the incoming air (Figure 4.3).

Figure 4.3 – Oil-less air compressor and air filter

The chamber also requires a source of purified water, which fills the bubble tower that maintains the humidity level in the chamber. A General Electric, model GXRV10ABL, reverse osmosis water purification system was installed adjacent to the chamber (Figure 4.4). The UH facilities department was called to install a permanent water line to supply the water purifier with tap water.
Figure 4.4 – Reverse Osmosis water purifier behind the QFOG chamber

The chamber and the reverse osmosis system are required to discharge to a drain. The chamber has a drain for the main chamber, solution tank and bubble tower while the reverse osmosis system has a drain from the contaminate side of the membrane filter. The location of the chamber is not close to a drain access that would allow gravity drainage to the sewer system. A tank with a submersible sump pump was assembled and installed adjacent to the chamber (Figure 4.5). The sump pump has a pressure actuated level switch that starts the pump when the tank level is between 7-10 inches and pumps the tank down to a level of approximately 1-2 inches. The last connection need for the chamber is the electrical power. The chamber requires a 220-volt power source to operate. The larger voltage is needed to operate the chamber heaters as well as provide power to the controls and solution pump.
Figure 4.5 – Drain sump with sump pump and associated plumbing

The corrosion chamber exposes the samples to a series of different environments in a repetitive cycle. The following exposure functions are used to develop the exposure environments:

**Fog Function**: During the Fog Function, the chamber generates a conventional salt spray. Typically compressed air is humidified in the bubbler tower as it is passed to the spray nozzles. The corrosive solution is pumped to the spray nozzle where it mixes with the compressed air. The spray nozzle atomizes the corrosive solution. Heaters are used to maintain the programmed chamber temperature during the Fog cycle.

**Dry-Off Function**: During the Dry-Off Function, a purge blower moves ambient air over heaters then into the chamber. This produces a low humidity condition inside the chamber. The chamber heaters in conjunction with the purge air heaters maintain the chamber temperature. This mode can also be operated without heaters.
**Humidity Function:** During the Humidity Function, the chamber environment is maintained at a 100% relative humidity condition by moving hot water vapor into the chamber. The vapor generator heaters maintain the chamber temperature.

**Dwell Function:** During the Dwell Function, the chamber temperature is maintained by the chamber heaters. No fog, dry-off, air purge, or humidity is generated.

**4.2 Discussion of Industry Standard Testing Procedures**

Numerous testing schemes and standards have been developed to accelerate the corrosion of materials in order to develop more resistant materials and protective coatings. The American Society for Testing and Materials (ASTM), the Society of Automotive Engineers (SAE) and several corporations standardized their corrosion tests. The oldest standardized corrosion standard practice is the ASTM B117. The ASTM B117 was originally published in 1939. The latest revision to ASTM B117 was done in 1995.

**ASTM B117**

The ASTM B117 standard describes the apparatus, procedure, and condition required to create and maintain the salt spray test environment. The ASTM B117 does not prescribe the type of specimen or the exposure period to be used. The ASTM B117 does define the salt solution parameters, air supply specifications, and the condition in the chamber.

The salt spray concentration is specified to be 5 ± 1% NaCl by mass. The salt used shall be substantially free of nickel and copper. Some salts contain
additives that may act as corrosion inhibitors, therefore careful attention should be given to the chemical content of the salt.

The compressed air supply to the nozzle is specified to be free of oil and dirt and maintained between 10 and 25 psi.

ASTM B117 still is widely used in all spheres of industry, yet it was initially developed over the period 1910-1920 and first standardized in 1939. ASTM B117 specification defines a corrosion test that applies a continuous salt spray (fog) to the specimens. According to the specification, the spray operates continuously except for the short daily interruptions necessary to inspect, rearrange, or remove test specimens, to check and replenish the solution in the reservoir, and to make necessary recordings of temperature. The cycling of wetting and drying is not defined in this older standard.

Prohesion Test
During the 1970’s considerable work was done to determine an alternative to the continuous salt spray defined by ASTM B117 test. A pioneer in the early testing development was F.D. Timmins who determined that the conventional salt spray test was qualifying coatings in the laboratory, but failures were still occurring in practice (Cremer, 1989). Timmins along with Dr. J.B. Harrison and T.C.K Tickle questioned the use of a relatively concentrated solution of 5% sodium chloride at elevated temperatures (Cremer, 1989). Harrison and Tickle noticed that the behavior of zinc phosphate primers was excellent outdoors in an industrial environment, but their performance during accelerated salt spray testing was poor (Cremer, 1989). Harrison hypothesized that a solution of common atmospheric salts would be more appropriate. Timmins decided that a
weak solution of Harrison’s mixture should be used, consisting of 0.40% wt ammonium sulphate and 0.05% wt sodium chloride. It was also concluded that ambient temperature spray would correspond closely to natural weathering.

Timmins dubbed his test Prohesion, which is an acronym for Protection is Adhesion. The prohesion test has been standardized as ASTM G85 modification 5.

**ASTM G85**
The current ASTM G85 standard was approved on February 15, 1994. The original standard was published in 1985. The G85 standard defines the following five modifications to salt spray (fog) testing:

- Acetic acid-salt spray test, continuous
- Cyclic acidified salt spray test
- Seawater acidified test, cyclic (SWAAT)
- SO₂ salt spray test, cyclic
- Dilute electrolyte cyclic fog dry test

Each modification has its own salt solution, solution pH, temperature parameters, and standard cycle events. Table 4.1 shows the defining parameters for each modification.
### Table 4.2 – Comparison of the variations in ASTM G85 standard

<table>
<thead>
<tr>
<th>Modification</th>
<th>Salt solution</th>
<th>Solution pH</th>
<th>Temperature requirements</th>
<th>Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid-salt spray test</td>
<td>5 ±1% NaCl by weight</td>
<td>3.1 – 3.3 using acetic acid</td>
<td>Bubble tower: 117±2°F</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Chamber: 95+2 or -3°F</td>
<td></td>
</tr>
<tr>
<td>Cyclic acidified salt spray test</td>
<td>5 ±1% NaCl by weight</td>
<td>2.8 – 3.0 using acetic acid</td>
<td>Bubble tower: 135±2°F</td>
<td>¾ hour spray followed by 2-hour dry air purge (use ambient air) followed by a 3¼ hour soak at high relative humidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Chamber: 120±2 or -3°F</td>
<td></td>
</tr>
<tr>
<td>Seawater acidified test, cyclic (SWAAT)</td>
<td>42 g of synthetic sea salt and 10 mL of glacial acetic acid per liter</td>
<td>2.8 – 3.0</td>
<td>Bubble tower: 117±2°F or 135 ± 2°F depending on chamber temp.</td>
<td>30 minute spray followed by 90 minute soak at &gt;98% relative humidity.</td>
</tr>
<tr>
<td>SO₂ salt spray test</td>
<td>42 g of synthetic sea salt OR 5 ±1% NaCl by weight. SO₂ gas will be injected into cabinet</td>
<td>2.5 – 3.2</td>
<td>Bubble tower: 117±2°F</td>
<td>Depends on material or product being tested. Example cycle: ½ hour salt spray followed by ½ hour SO₂ gas followed by 2 hour soak.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Chamber: 95+2 or -3°F</td>
<td></td>
</tr>
<tr>
<td>Dilute electrolyte cyclic fog dry test</td>
<td>0.05% NaCl and 0.35% ammonium sulfate, (NH₄)₂SO₄ by weight.</td>
<td>5.0 – 5.4</td>
<td>Dryoff Temperature: 95±3°F</td>
<td>1 hour of fog followed by 1 hour of dry-off at elevated temperature.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fog Temperature: 75±6°F</td>
<td></td>
</tr>
</tbody>
</table>

**CCT-1 and CCT-4**

The Japanese automotive manufacturers developed the Cyclic Corrosion Test 1 and 4 (also known as CCT-A and CCT-D (QFOG, 2000)). The CCT programs installed in the Q-Fog corrosion chamber have added transition steps.
CCT-1 exposure conditions include:

- Electrolyte solution: 5% sodium chloride
- Acidity: not specified
- Typical duration: 200 cycles (1600 hours)

The CCT-1 exposure cycle is:

1. Step 1: Salt fog at 35°C for 4 hours
2. Step 2: Dry-Off at 60°C for 2 hours
3. Step 3*: Dry-Off at 40°C for ½ hour
4. Step 4: Soak at 50°C, RH>95% for 2 hours
5. Step 5: Go to step 1

*Q-Fog programmers added Step 3 to improve transition times between steps.

The other Japanese automotive testing procedure, CCT-4, is unique in the sense that after a salt fog cycle followed by drying off cycle, a sub-cycle inserted. The sub-cycle, consisting of alternating periods of high humidity and dry-off, is performed for five repetitions. In SAE and AISI research projects CCT-4 was shown to be one of the exposures that best correlated with actual vehicle corrosion results (Repp, 2002).

CCT-4 exposure conditions include:

- Electrolyte solution: 5% sodium chloride
- Acidity: not specified
- Typical duration: 50 cycles (1200 hours)

The CCT-4 exposure cycle is:

1. Step 1: Salt fog at 35°C for 10 minutes
2. Step 2: Dry-Off at 60°C for 2 hours, 10 minutes
3. Step 3*: Dry-Off at 50°C for 15 minutes
4. Step 4: 95% RH at 60°C for 1 hour, 15 minutes
5. Step 5: Sub-cycle: steps 6 – 8 repeat 5 times
6. Step 6: Dry-Off at 60°C for 2 hours, 25 minutes
7. Step 7*: Dry-Off at 50°C for 15 minutes
8. Step 8: 95% RH at 60°C for 1 hour, 20 minutes
9. Step 9*: Dry-Off at 35°C for 10 minutes
10. Step 10: Go to Step 1
*Q-Fog programmers added Step 3, 7 and 9 to improve transition times between steps.

**SAE J2334**
The Society of Automotive Engineers (SAE) has developed a standard testing procedure for cosmetic corrosion. The SAE J2334 Cosmetic Corrosion Testing Procedure was originally issued in June of 1998. The latest revision to the SAE J2334 was published in October 2002. This cosmetic corrosion lab test procedure is based on field correlated lab test procedure parameters as determined by a Design of Experiment process conducted by the SAE Automotive Corrosion and Prevention Committee (SAE/ACAP) and the Auto/Steel Partnership (A/SP) Corrosion Task Force. Results from this test will provide excellent correlation to severe corrosive field environments with respect to cosmetic corrosion performance (Repp, 2002).

SAE J2334 standard encompasses various methods of establishing the different environments. It is generally understood that some form of chamber will be used. SAE J2334 has separate testing alternatives for manual application of the salt solution and automatic application with a cyclic corrosion chamber. The automatic method will be discussed here since UH has purchased an automated chamber. The electrolyte solution outlined in the J2334 is comprised of the following salts:

- 0.5% NaCl
- 0.1% CaCl₂
- 0.075% NaHCO₃
The test cycle outline in the J2334 consists of three basic stages:

1. Humid Stage—50 °C and 100% Humidity, 6 h in duration,
2. Salt Application Stage—15 min duration conducted at ambient conditions
3. Dry Stage—60 °C and 50% RH, 17 h and 45 min in duration

![Cosmetic Corrosion Lab Test Cycles SAE J2334 - 7 Day/Week - Automatic Operation](image)

**Figure 4.1 – Daily testing cycle for SAE J2334 standard**

Typical test durations are a minimum of 60 cycles in length. The J2334 is primarily designed to evaluate automotive coatings. Longer duration testing may be required when heavier metallic precoats are used.

**Summary of Industry testing procedures**

The ideal testing procedure is one that will produce consistent and reproducible results and also replicate the relative corrosiveness of zinc and steel in atmospheric conditions. The consistency of the testing process is required when performing the testing in a single location. It will be the consistency at a single location that for correlation of a given exposure in the laboratory to actual corrosion rates in the field. The reproducibility of the testing procedure relates to the ability of other laboratories to perform the same test and achieve the same
results. There are numerous factors that determine the consistency and the reproducibility of the testing procedure.

Industry experts tend to agree on one thing with regard to corrosion testing. That is, the widely used ASTM B117 salt spray test produces extremely poor correlation to observed corrosion in the environment. In fact, Robert E. Townsend a consultant for Bethlehem Steel submitted a paper titled “The Salt Spray Test is Bogus” to the 2000 SAE World Congress [Romanchick, 2000]. In the paper, Townsend criticizes the use of ASTM B117 in the automotive industry. The reason that the ASTM B117 test methods do not accurately reproduce corrosion performance for auto parts is that they do not accurately reproduce the conditions in which automotive parts must exist. For one thing, parts tested in a salt-spray cabinet are continuously wet, while those parts on a vehicle experience periods of wet and dry [Romanchick, 2000]. The same conclusion can be made when trying to relate construction related corrosion to exposures in the ASTM B117.

Other differences between ASTM B117 are the concentration of the salts used, the composition of the salts used and temperatures of the exposures. It is quite obvious that the ASTM B117 is not adequate. The automotive industry has done ample research to update their testing procedures for coatings. The SAE J2334 has been revised to incorporate different methods for salt solution application and for different methods of obtaining the desired relative humidity. The United States Army, as a representative for the Department of Defense, has worked closely with automotive industry leaders to continually update the J2334
standard. A report from Corrpro Companies, Inc. at the 2002 US Army Corrosion Summit concluded that the J2334 procedure produced the most repeatable and reproducible results out of any of the testing standards. This conclusion was based on 5-years of test data from 13 different laboratories. For the purposes of this research, the J2334 will not be used because the exposure condition of 50% relative humidity is not one of the environments automatically producible in the Q-Fog chamber. The next best standard from the round-robin testing analysis was the CCT-4 used by the Japanese automotive industry. The results of the automotive industry testing can be used as a starting point for the light gauge steel construction industry.

4.3 Proposed Testing Procedure
Using the CCT-4 standard as a model, the testing program at UH will consist of the cyclic corrosion test as well as incorporating a fog uniformity test. The solution that will be used will be 5% sodium chloride by weight. Sulfates will not be used in the solution since sulfates are usually considered in industrial exposures. The test duration will be 50 cycles (1200 hours) in overall duration, with intermittent testing every ten cycles to observe the corrosion progression. Intermittent testing is explained below. The cycle will consist of a wetting of the samples with the electrolyte followed by a dry-off period. A high humidity exposure will follow the dry-off period. The sub-cycle of alternating drying and humidity will continue for five repetitions. Followed by a final dry-off stage that leads into the wetting with the salt fog again.
Samples Exposed in Chamber
As discussed in section 2.2, testing samples will be placed in various locations throughout the field enclosures. Similar samples will be exposed in the corrosion chamber. The samples in the field will be the standard corrosion example we are trying to achieve in the laboratory. In addition to the connection samples, plain steel and zinc samples (coupons) will be tested in the chamber to monitor the corrosion process. Mass loss of the coupons will be recorded to monitor the
corrosiveness of the environment. Coupons will be removed and analyzed after a predetermined number of cycles throughout the test to monitor corrosion. To analyze coupons, remove 1 coupon from rack and prepare for weighing and mass loss determination. Insure enough coupons are exposed in the test so monitoring frequency can be accomplished. Additional unexposed coupons can be added throughout the test to obtain interval data in addition to cumulative data. Before weighing, clean the coupons using a mild “sand blast” (preferably glass beads) to remove all corrosion by-products from the coupon surface. Once clean, wipe the coupons with methanol and weigh to determine the coupon mass loss rate using equation 4.1.

\[
\text{Loss Rate} = \frac{\text{Initial Mass - End of Exposure Mass}}{\text{Surface Area} \times \text{Days Exposed}} \left( \frac{\text{g}}{\text{m}^2 \cdot \text{day}} \right) (4.1)
\]

Generally, the preparation and processing of the testing coupons should follow:

- Sand blast the coupon to obtain a clean finish
- Stamp the coupon number and date of preparation
- Weigh the coupon and record
- Measure the dimensions of the coupon and record
- Place the coupon in the corrosion chamber or the field enclosure as applicable
- Remove the coupon at a predetermined time
- Sand blast (preferably with glass beads) or wire brush the coupon to remove all corrosion products.
- Weigh the cleaned testing coupon and compute the mass loss rate

**Testing Documentation**

Prior to each test, the fog deposition rate should be determined following the procedure for doing the fog deposition test is listed in Appendix D. The air pressure and pump speed should be adjusted to provide a rate between 1 – 2 mL/hour of fog in each collection funnel. The test results should be maintained in
a log to ensure consistent fog dispersion for each test. Along with fog deposition, the solution concentration and periodicity of refilling should be logged. These values are above and beyond the data collected from mass loss and sample degradation. A QFOG LOG has been established in the laboratory.
5.1 Summary
This paper investigates the potential for corrosion of galvanized fasteners used in cold-formed steel framing (CFSF) by exposing test samples to a variety of environmental conditions frequently found in Hawaii. The results of this research will aid in the evaluation of galvanized CFSF fasteners in various exposure conditions. Long-term field enclosures will be used to determine the effects of exposure to various environmental conditions. Laboratory tension testing was used to select the size and configuration of the long-term test specimens. The field enclosures on the island of Oahu have been constructed and placed in their locations. Weather instrumentation has been installed at all sites, commencing the monitoring of environmental conditions at each location. The cyclic corrosion chamber has been installed at the UH structures laboratory and preliminary fog dispersion tests have been commenced. Various cyclic corrosion test procedures presented in this literature were evaluated and a preliminary test procedure selected for initial chamber tests. The testing program for the fastener study is ready to commence with follow on analysis and possible testing modification.
References and Additional Literature


Romanchik, D., May 2000 “Engineers Say Salt Spray Test is Bogus”, Article, Automotive Test Report.


www.armycorrosion.com/past_summits/summit2002/02presentations/Day_2_Afternoon/Landy_session/John_Repp.pdf
Appendix A
CR10X Wiring Diagrams

Temperature / Humidity Sensor #1
- Red: 12 V
- Clear: G
- Green: G
- Brown: SE 6
- Black: SE 1

Temperature / Humidity Sensor #2
- Red: 12 V
- Clear: G
- Green: G
- Brown: SE 7
- Black: SE 2

Temperature / Humidity Sensor #3
- Red: 12 V
- Clear: G
- Green: G
- Brown: SE 8
- Black: SE 3

Temperature / Humidity Sensor #4
- Red: 12 V
- Clear: G
- Green: G
- Brown: SE 9
- Black: SE 4

Temperature / Humidity Sensor #5
- Red: 12 V
- Clear: G
- Green: G
- Brown: SE 10
- Black: SE 6

Terminals on CR10X
Legend:

G – Ground
AG – Analog Ground
12V – 12 volt DC
CHG – Charging connection
INT – Internal connection for lead acid battery
SE (1-12) – Single excitation channel input
P (1-2) – Pulse channel input
E1 – Excitation channel
Appendix B
Weather Station Program and Data Retrieval

Program for the CR10X datalogger
The following is the text version of the program. The EDLOG program should be used to input/change any program parameters.

```
;{CR10X}
;KANEHOE OCEAN - STATION 1
*Table 1 Program
  01: 1   Execution Interval (seconds)
;Monitoring battery voltage
1:  Batt Voltage (P10)
  1: 1   Loc [ Battvolt ]
;Measure the temperature of all 5 sensors
2:  Volt (SE) (P1)
  1: 5   Reps
  2: 5   2500 mV Slow Range
  3: 1   SE Channel
  4: 2   Loc [ Temp_1 ]
  5: 0.18  Mult
  6: -40   Offset
;Measure the relative humidity of all 5 sensors
3:  Volt (SE) (P1)
  1: 5   Reps
  2: 5   2500 mV Slow Range
  3: 6   SE Channel
  4: 7   Loc [ RH_1 ]
  5: .1   Mult
  6: 0.0   Offset
; Measure Pyranometer (#40431)
4:  Volt (SE) (P1)
  1: 1   Reps
  2: 22   7.5 mV 60 Hz Rejection Range
  3: 12   SE Channel
  4: 12   Loc [ W_m2 ]
  5: 110.011  Mult
  6: 0.0   Offset
;Set negative values to zero
5:  If (X<=F) (P89)
  1: 12   X Loc [ W_m2 ]
  2: 4   <
  3: 0.0   F
  4: 30   Then Do
  6:  Z=F (P30)
  1: 0.0   F
  2: 00   Exponent of 10
  3: 12   Z Loc [ W_m2 ]
7:  End (P95)
; Wind Speed
8:  Pulse (P3)
  1: 1   Reps
```
2: 1        Pulse Channel 1
3: 21       Low Level AC, Output Hz
4: 13       Loc [ WS_MPH     ]
5: 1.677    Mult
6: .4       Offset

; Wind Direction
9:  Excite-Delay (SE) (P4)
  1: 1        Reps
  2: 5        2500 mV Slow Range
  3: 11       SE Channel
  4: 1        Excite all reps w/Exchan 1
  5: 2        Delay (units 0.01 sec)
  6: 2500     mV Excitation
  7: 14       Loc [ WD_0to360 ]
  8: .142     Mult
  9: 0.0      Offset

; Measure rainfall
10: Pulse (P3)
   1: 1        Reps
   2: 2        Pulse Channel 2
   3: 2        Switch Closure, All Counts
   4: 15       Loc [ Rain_in   ]
   5: .01      Mult
   6: 0.0      Offset

; Write to final storage
11: If time is (P92)
   1: 0000     Minutes (Seconds --) into a
   2: 15       Interval (same units as above)
   3: 10       Set Output Flag High (Flag 0)
12: Real Time (P77)
   1: 1111     Year,Day,Hour/Minute,Seconds (midnight = 0000)
; Take the average of battvolt, temp, humidity, and solar radiation
13: Average (P71)
   1: 12       Reps
   2: 1        Loc [ Battvolt ]
; Write the wind vector
14: Wind Vector (P69)
   1: 1        Reps
   2: 0        Samples per Sub-Interval
   3: 00       Sensor/Output Option
   4: 13       Wind Speed/East Loc [ WS_MPH     ]
   5: 14       Wind Direction/North Loc [ WD_0to360 ]

; Totalize the rainfall
15: Totalize (P72)
   1: 1        Reps
   2: 15       Loc [ Rain_in   ]

*Table 2 Program
  02: 0        Execution Interval (seconds)
*Table 3 Subroutines ;
End Program

67  Appendix B
Data file name format

Data files are saved with the following format.

    #_yymmdd.dat

# - is the station number (1,2,3,4,5)
yy – is the last two digits of the year the data was collected in
mm – is the two digit month the data was collected in
dd – is the two digit day the data was collected in

Data file format

The data files are CSV (comma separated value) format. They can easily be read with any spreadsheet program and/or text editing program. The data is saved using the following format

111,year,day(julien calendar),time hhmm (24hour clock),seconds,battery voltage,temp1,temp2,temp3,temp4,temp5,humidity1,humidity2,humidity3,humidity4,humidity5,solar radiation(W/m^2),wind speed(mph),wind direction,standard deviation of wind direction,rainfall(in.)

For example the sample data:

111,2002,63,0,0,12.25,67.41,67.73,67.45,67.71,67.73,57.2,60.36,57.71,58.91,58.98,0,10.39,89.7,10.42,0

Represents:

<table>
<thead>
<tr>
<th>Date and Time</th>
<th>3/4/2002 00:00:00 (midnight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Voltage</td>
<td>12.25</td>
</tr>
<tr>
<td>Temp1</td>
<td>67.41</td>
</tr>
<tr>
<td>Temp2</td>
<td>67.73</td>
</tr>
<tr>
<td>Temp3</td>
<td>67.45</td>
</tr>
<tr>
<td>Temp4</td>
<td>67.71</td>
</tr>
<tr>
<td>External Temp</td>
<td>67.73</td>
</tr>
<tr>
<td>Humidity1</td>
<td>57.20</td>
</tr>
<tr>
<td>Humidity2</td>
<td>60.36</td>
</tr>
<tr>
<td>Humidity3</td>
<td>57.71</td>
</tr>
<tr>
<td>Humidity4</td>
<td>58.91</td>
</tr>
<tr>
<td>External Humidity</td>
<td>58.98</td>
</tr>
<tr>
<td>Solar Radiation (W/m^2)</td>
<td>0 (expected since this was midnight)</td>
</tr>
<tr>
<td>Wind Speed (mph)</td>
<td>10.39</td>
</tr>
<tr>
<td>Wind direction</td>
<td>89.7</td>
</tr>
<tr>
<td>Standard deviation of wind direction</td>
<td>10.42</td>
</tr>
<tr>
<td>Rainfall (in.)</td>
<td>0</td>
</tr>
</tbody>
</table>
Note: The temp5 and humidity5 values are the temperature and humidity of the external probe.

Data Retrieval Procedure

Boot up the laptop computer

Plug the serial cable into the computer and the datalogger

Double-click on the “PC208W” icon on the desktop

Select the station you are retrieving the data from

Press “CONNECT”

Verify the clock on the computer and the clock on the datalogger are synchronized.

........
Appendix C
Fog Deposition Procedure

When to Perform
Prior to every test

Description
This test will verify the solution pump flow rate and spray air pressure values to achieve the appropriate spray rate. The electrolyte solution will be continuously sprayed and collected over a 16-hour period.

Prerequisites
Four collection vessels will be used. Place the collection funnels in predetermined positions. Preferably, place one collection funnel approximately 15 cm from the nozzle. Place another collection funnel the furthest possible distance from the jet (one of the corners). The other two funnel placements should be placed in random positions.

Procedure
1. Ensure collection flasks are in place.
2. Fill the reservoir with the 5% by weight NaCl solution.
3. Turn on the water supply to the Q-Fog.
   a. Open the spigot in the structures lab
   b. Open the ball valve on the rear of the chamber
4. Turn on the air supply to the Q-Fog
   a. Plug the air compressor into the AC socket
   b. Install the hose from the compressor to the Q-Fog.
   c. Adjust the pressure supply on the air compressor to 100 psi.
   d. Open the supply valve on the rear of the chamber.
5. Turn the Q-Fog chamber on
   a. Shut the 220 V breakers in the structures lab
   b. Shut the circuit breakers on the rear of the chamber
      Note: You should hear the chamber commence the diagnostic check
6. Set the Test Duration
   a. Hit “Program” key. Use the up/down arrow to select “PROGRAM 1”. Press “Enter”.
   b. Use the up/down and left/right arrows to select “16 Hours” for the test duration. Press “Enter”.
   c. Use the up/down arrows to choose “STOP”. This tells the Q-Fog to stop the test when completed. Press “Enter”.
   d. Press “Enter”. This accepts all the test duration parameters.
7. Select the B-117 test cycle
a. Press “Program” key. Use the up/down arrows to select “PROGRAM 2”. Press “Enter”.
b. Use the up/down arrow to select “ASTM B117”. Press “Enter” to select test.
c. Use the up/down arrows to select “STEP 1”. Press “Enter”.
d. Press “Enter”. This accepts all the test cycle setting.

8. Press “RUN” key to begin collection test. The bubble tower will begin to fill at this time.
9. Press the “STOP” key at any time to stop the test. Press the “RUN” key again and the test will resume.

Results
The desired results of the 16-hour fog deposition test for the corresponding cyclic testing program are listed below.

Prohesion Test

<table>
<thead>
<tr>
<th>Electrolyte Solution</th>
<th>0.05% sodium chloride and 0.35% ammonium sulfate.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution Acidity</td>
<td>pH between 5.0 and 5.4</td>
</tr>
<tr>
<td>Deposition Rate in 100 mm diameter funnel</td>
<td>1 to 2 milliliters/hour</td>
</tr>
<tr>
<td>Recommended Spray Pressure*</td>
<td>8 psi</td>
</tr>
<tr>
<td>Recommended Flow Rate*</td>
<td>0.6 liters/hour</td>
</tr>
</tbody>
</table>

* Adjust spray pressure and pump speed to achieve desired deposition rate.

CCT-1 (Cycle C)

<table>
<thead>
<tr>
<th>Electrolyte Solution</th>
<th>5% sodium chloride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution Acidity</td>
<td>Not specified</td>
</tr>
<tr>
<td>Deposition Rate in 100 mm diameter funnel</td>
<td>1 to 2 milliliters/hour</td>
</tr>
<tr>
<td>Recommended Spray Pressure*</td>
<td>8 psi</td>
</tr>
<tr>
<td>Recommended Flow Rate*</td>
<td>0.6 liters/hour</td>
</tr>
</tbody>
</table>

* Adjust spray pressure and pump speed to achieve desired deposition rate.

CCT-4 (Cycle D)

<table>
<thead>
<tr>
<th>Electrolyte Solution</th>
<th>5% sodium chloride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution Acidity</td>
<td>Not specified</td>
</tr>
<tr>
<td>Deposition Rate in 100 mm diameter funnel</td>
<td>4 to 8 milliliters/hour</td>
</tr>
<tr>
<td>Recommended Spray Pressure*</td>
<td>12 psi</td>
</tr>
<tr>
<td>Recommended Flow Rate*</td>
<td>2.0 liters/hour</td>
</tr>
</tbody>
</table>

* Adjust spray pressure and pump speed to achieve desired deposition rate.
Make the following adjustments for the given test results.

<table>
<thead>
<tr>
<th>SYMPTOM</th>
<th>ADJUSTMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>High collection volume in BOTH vessels</td>
<td>Reduce pump speed</td>
</tr>
<tr>
<td>Low collection volume in BOTH vessels</td>
<td>Increase pump speed</td>
</tr>
<tr>
<td>High collection in closest vessel</td>
<td>Increase spray air pressure to disperse spray away from nozzle.</td>
</tr>
<tr>
<td>High collection in farthest vessel</td>
<td>Reduce spray air pressure to allow spray to fall nearer to nozzle.</td>
</tr>
</tbody>
</table>
Appendix D
Testing Procedure CCT-4

Description
This test is the CCT-4 testing program in the Q-Fog chamber. One cycle of the test is 24 hours in length.

Prerequisites
Ensure all test specimens are placed in the chamber in accordance with the Q-fog operations manual.

Procedure
1. Fill the reservoir with the 5% by weight NaCl solution.
2. Turn on the water supply to the Q-Fog.
   a. Open the spigot in the structures lab
   b. Open the ball valve on the rear of the chamber
3. Turn on the air supply to the Q-Fog
   a. Plug the air compressor into the AC socket
   b. Install the hose from the compressor to the Q-Fog.
   c. Adjust the pressure supply on the air compressor to 100 psi.
   d. Open the supply valve on the rear of the chamber.
4. Turn the Q-Fog chamber on
   a. Shut the 220 V breakers in the structures lab
   b. Shut the circuit breakers on the rear of the chamber
Note: You should hear the chamber commence the diagnostic check
5. Set the test duration (initially set to 1200 hours; 50 cycles)
   a. Hit “Program” key. Use the up/down arrow to select “PROGRAM 1”. Press “Enter”.
   b. Use the up/down and left/right arrows to select “1200 Hours” for the test duration. Press “Enter”.
   c. Use the up/down arrows to choose “STOP”. This tells the Q-Fog to stop the test when completed. Press “Enter”.
   d. Press “Enter”. This accepts all the test duration parameters.
2. Select the CCT-4 test cycle
   a. Press “Program” key. Use the up/down arrows to select “PROGRAM 2”. Press “Enter”.
   b. Use the up/down arrow to select “CCT-4”. Press “Enter” to select test.
   c. Use the up/down arrow to select “STEP 1”. Press “Enter”.
   d. Press “Enter”. This accepts all the test cycle setting.
3. Press “RUN” key to begin collection test. The bubble tower will begin to fill at this time.
a. Press the "STOP" key at any time to stop the test. Press the "RUN" key again and the test will resume.