LUC-2-1682 Long Term Maintenance of the Anthony Wayne Suspension Bridge Main Cables

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16. Abstract

The Anthony Wayne Bridge, Ohio's only suspension bridge, is undergoing an extensive rehabilitation. Prior to taking action to preserve the cables, ODOT must decide what measures to take to evaluate the condition of the cables, how best to rehabilitate the cables to slow their aging and how to monitor the degradation in the cables' strength as they age.

The three goals of this study are:
1. Determine the current condition of the main cables.
2. Determine a rehabilitation technology to most efficiently and economically slow their aging.
3. Select a long term monitoring strategy that accurately tracks the changes the condition of the cables over time.

This research should help ODOT make decisions for preserving the cables.

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

Abstract

The Anthony Wayne Bridge is a suspension bridge located in Toledo, Ohio currently undergoing an extensive rehabilitation project. Internal inspection revealed corrosion of the steel wires within the bridge's main cable. The bridge operators have elected to pursue the installation of a dehumidification system. Such a system injects dry air into the cable to lower the relative humidity and stop the corrosion process.

The research performed in this project investigates the use of the Analatom AN110 corrosion sensor and its potential for application on the Anthony Wayne Bridge. Dehumidification systems require monitoring systems to ensure their effectiveness and proper operation. The AN110 corrosion sensor uses linear polarization resistance (LPR) technology to measure corrosion rates in real time. Such measurements could potentially provide data valuable in ensuring the effectiveness and progress of the drying-out process. Included is an extensive review of the bridge's rehabilitation process, a literature review of dehumidification and the application of LPR technology, and laboratory testing of the corrosion sensor. Laboratory testing involved the exposure of the sensor to cyclic relative humidity to observe the relationship between corrosion rate and relative humidity.

Laboratory sensor test results showed a clear and consistent relationship between the recorded corrosion rate and the relative humidity. The sensor experiments confirmed the existing understanding of the effect of relative humidity on the corrosion of steel. The use of the AN110 corrosion sensor in the monitoring of the future dehumidification system on the Anthony Wayne Bridge has potential to give insight into the internal conditions in the cable. Concerns that need to be resolved include the freeze-thaw behavior of the sensor and a field trial is necessary before considering implementation.

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Chapter 1: Introduction and Background

1.1 Project Background and Introduction

The Anthony Wayne Bridge (AWB) is a suspension bridge spanning the Maumee River in Toledo, Ohio. Located on Ohio State Route 2, the bridge is owned and operated by the City of Toledo. The Ohio Department of Transportation (ODOT) has inspection and major maintenance responsibility. The bridge is undergoing a rehabilitation that aims to extend the life of the bridge an additional 50 to 75 years. ODOT is managing the rehabilitation. The rehabilitation began in 2014 and was completed in 2017. The rehabilitation project is to be followed with a project to paint the structure, which is planned for completion in 2018. Future plans for the rehabilitation include a dehumidification system. This dehumidification system is designed to limit future corrosion within the main cables.

The rehabilitation of the main suspension cable incorporated the state-of-the-art use of acoustic emission (AE) sensors. The AE sensors provided valuable data on the existing state of the bridge's cables by monitoring for potential internal wire breaks. Under the scope of the present project, several laboratory studies utilizing AE and corrosion sensors to further develop an understanding of the corrosion process were conducted.

1.2 Bridge Description

Construction on the AWB (Figure 1-1) was completed in 1931 and it is currently the only suspension bridge in the ODOT inventory. The bridge is 4 lanes wide with a 60 foot wide deck. The bridge also carries pedestrian traffic in each direction. The main cable-supported span is 785 feet with two side spans that are each 233.5 feet. The total length of the bridge, including the two approaches, is 3215 feet. The two main cables are 13-5/16 inches in diameter and contain 19 strands of galvanized steel

Figure 1-1: Anthony Wayne Bridge at the Beginning of the Rehabilitation

wire compressed into a circular shape. Each strand contains 186 No. 6 galvanized steel wires that are each 0.192 inches in diameter. Thus, there are a total of 3534 wires in each main cable. The strands were coated in a lead paste and wrapped in No. 9 galvanized steel wires, which were then painted. Suspender ropes between the cable and deck are spaced at approximately 20 foot intervals.

1.3 Background on Acoustic Emission

Acoustic emission (AE) refers to the release of transient elastic waves generated by a deformation caused by a localized source event within a given material or structure. Acoustic sensors are capable of detecting these waves and generate a voltage in response to deformation of a piezoelectric crystal within the sensor due to the waves. This voltage is then recorded with a data acquisition system. The voltage can be used to reconstruct the wave at the sensor. The output voltage is measured in decibels referenced to the output at the crystal. The characteristics of the wave at the sensor can be used to determine the location and nature of an event. Using an array of sensors along the cable and analyzing the characteristics of the AE signal by looking for events that fall within specific characteristics, wire breaks can be detected along the entire cable. Under the right conditions, corrosion can be detected near the sensors (Niroula 2014).

1.4 Condition of the Superstructure and Main Cables Before Rehabilitation

A physical condition report finalized in 2008 rated the overall condition of the AWB as poor (Burgess and Niple, 2008). The controlling factor in this rating was the poor condition of the superstructure including cracks in the suspension span stringer webs and significant rust. Additionally, the approach spans, between the anchorage and the

side spans, had fracture critical trusses. This report revealed the need to begin a rehabilitation project.

It was critical to know the current state of the main cables before proceeding with an extensive and expensive rehabilitation process. Small windows had been opened in the wire wrap surrounding the cable previously, but the cable had never undergone a thorough inspection. The existing elastomeric wrap had been applied to the cables in 1997 and 1998 (Figure 1-3).

Figure 1-3: Existing Cable

Figure 1-4: Elephant's Foot at Cable Band

Figures 1-5A and B: Overview and Close-up of Drain Hole at Midspan

This elastomeric wrap was leaking. Water was retained in elephant foot bulges near the cable bands (Figure 1-4) and dripped out of a drain hole at the midspan sag points (Figures 1-5A and 1-5B). It was important to have a detailed understanding of the physical condition of the cable throughout its entire volume. Therefore, ODOT elected to install an acoustic emission monitoring system and perform an inspection on the cables in general conformance with NCHRP-534.

The acoustic monitoring (AE) system was installed on the main cables of the Anthony Wayne Bridge in July 2011. The intention of this system was to provide accurate information on ongoing wire breaks both quickly and with no destructive testing. The system was configured to detect signals indicative of possible wire breaks within the cables. The north and south cables of the bridge were each fitted with 15 acoustic sensors. There were 13 sensors spaced at approximately 100 feet on the main and back spans and one sensor on the cable between the anchorage and the tie down pier on each end of the bridge. This allowed information about the entire volume of the cable to be detected. The acoustic emission sensors were installed by Mistras Group and run on their Mistras Sensor Highway II system (Mistras Group, 2012). From July 2011 through April 2012, no signals were detected that would indicate a potential wire break. Mistras uses an algorithm based on 7 different criteria such as amplitude, duration, energy of the signal, etc., to classify a wire break. No signals met or exceeded the threshold for all 7 criteria.

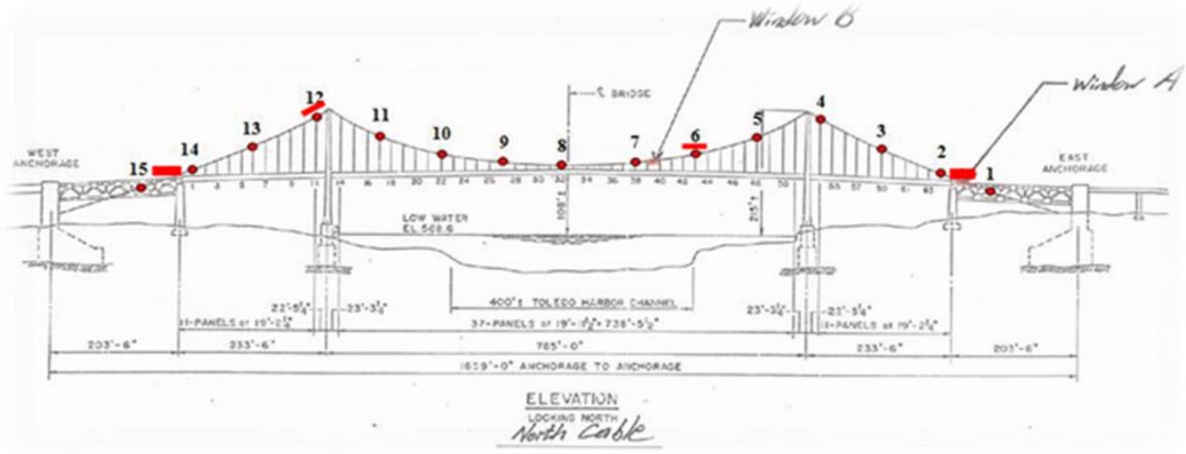

Figure 1-6: Acoustic Sensor Layout

1.5 Inspection Background

The four inspection locations were chosen based on AE data, the previous 2008 Burgess and Nipple inspection, and ODOT's desire to open the cables in areas containing previous inspection windows. From 1978 to 1993, four inspection windows ranging from 24 inches to 36 inches long were repeatedly opened. ODOT wanted to limit new areas where the cable wrap would be removed, as the temporary neoprene coating was prone to allowing water to penetrate the cable and locally accelerate the corrosion process. ODOT wished to integrate data obtained from the acoustic monitoring system into the inspection process.

In October 2011, the AWB was closed for a 24-hour period in order to use the AE sensors to attempt to determine locations with a higher rate of corrosion. Closing the bridge during this testing period eliminated traffic noise. The testing period also occurred after several days of rain. This created an environment conducive to corrosion. The acoustic monitoring system was originally configured to detect wire breaks, not corrosion. Sensors are generally placed much closer together than the installed 100 foot spacing when dealing with corrosion as the acoustic emissions from corrosion are much smaller than wire breaks. For this reason, corrosion could only be detected locally at each sensor on the AWB. In spite of additional noise from wind and rain, Mistras was able to determine potential areas of interest for the inspection locations based on the acoustic emissions during this 24-hour testing period.

Two inspection locations on each cable were selected after discussion between ODOT and Modjeski and Masters involving the AE data and other aforementioned criteria. Each cable was assigned a primary opening location and an optional opening location. The optional opening location was to be used if inspection at the primary location indicated the cable warranted further examination. Figure 1-7 shows the north and south cable opening locations.

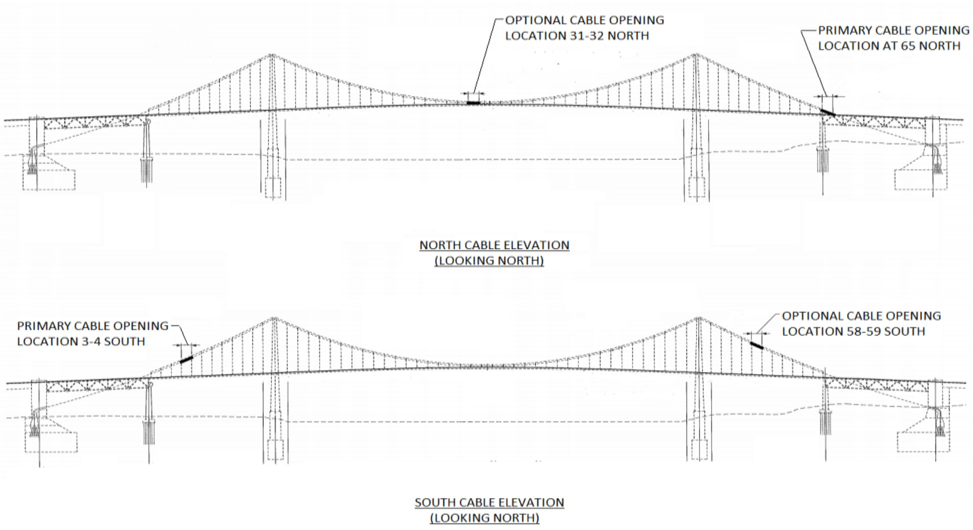

Figure 1-7: North and South Cable Opening Locations [Modjeski and Masters, 2013A]

The internal inspection of the AWB's cables was performed in November 2012 by Modjeski and Masters. The cables were opened at all four of the primary and optional locations. This involved removing the neoprene cable wrap and external wrapping wire between adjacent panel points and hammering plastic wedges into the cable to separate the wires. The length of each opening was roughly 20 feet. At a minimum, the cables were wedged open at the top, bottom and north and south sides. If conditions warranted, additional sections were wedged. The corrosion stages of the observed wires were recorded at three locations along the opened length. Based on the inspection, Modjeski and Masters reported that overall the cables were in fair to poor condition (Modjeski and Masters, 2013A).

Corrosion was measured on the NCHRP 534 scale of 4 stages, with stage 4 being the worst. The stages measure signs of zinc oxidation and the extent of rust on the surface area of a wire (Figure 1-8). Overall, just one of the 400 wires observed was stage 1, 19% were stage 2, 52% were stage 3 and 29% were stage 4. Thus, over 80% of the total wires were reported as Stage 3 or Stage 4. Tensile strength tests were also performed on wire samples removed from the cable.

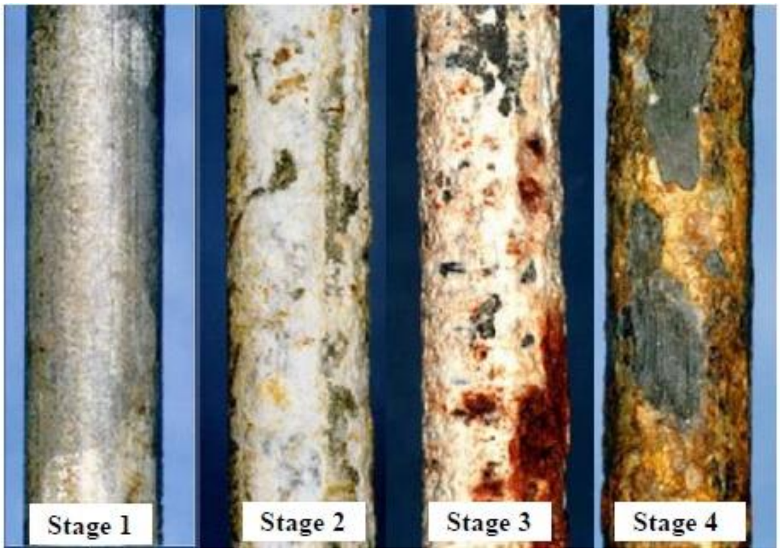

Figure 1-8: Corrosion Stages of Cable Wires (NCHRP 534)

The strength and factor of safety results from the inspection are summarized in Table 1. Two separate methods recommended in NCHRP-534 were used to model the strength of the wire, the Simplified Strength model and the Brittle Wire model. The Simplified Strength model assumes cracked and broken wires contribute nothing to the overall strength of the cable. The Brittle Wire model assumes all wires contribute equally to the strength of the cable and a wire fails immediately upon reaching ultimate stress. Both are more conservative approaches than a ductile model. However, the ultimate strain was not reported for the wire samples tested preventing the use of the NCHRP-534 Limited Ductility Model. Over 10% of the wires were found cracked at three of the inspection locations therefore, the Simplified Strength Model is overly conservative. The factor of safety was estimated to be 2.31 with the current normal weight deck in place. Table 1-1 gives the safety factors with a new light weight deck in place.

Table 1-1 is adapted from the Modjeski and Masters cable strength report (Modjeski and Masters 2013A)

Table 1-1: Strength and Factor of Safety Summary for Brittle Wire Model

Location	Cable Tension (kips)	Strength (kips)		Factor of Safety	
		As-Built	As-Insp	As-Built	As-Insp
Primary Opening, East PP 65, North	5,984	17,900	14,400	2.99	2.41
Optional Opening, PP 31 – PP 32, North	5,714	17,900	16,600	3.13	2.91
Primary Opening, PP 3 – PP 4, South	6,241	17,900	15,200	2.87	2.44
Optional Opening, PP 58 – PP 59, South	6,422	17,900	16,000	2.79	2.49
Controlling		17,900	14,400	2.79	2.41

The inspectors recommended several actions be taken by ODOT, the first of which was the installation of a lightweight deck to reduce the dead load on the bridge. It was estimated that this would increase the factor of safety to 2.41. Beyond this, the inspectors recommended more inspections, potentially over the entire length of the cables. In addition, it was advised that the acoustic monitoring should continue and actions be taken to prevent more water from reaching the internal cable wires.

The cable inspection deviated from the recommendations of NCHRP-534 in a number of ways: the number of panels opened and wire samples taken were both less than recommended and a cable band was not removed. This means that the percent error in the calculations is greater than if the intended sample size was used. Therefore, Modjeski and Masters cautioned the results of the AWB inspection should be viewed with some skepticism and recommended additional inspections. ODOT had concerns with the destructive nature of the testing. In addition, the 2012 cable tests showed results which were similar to 1995 NCHRP testing. Cable locations that were opened in 1995, however, were not sealed properly, which strengthened the argument to avoid destructive testing until a solution was developed. AE monitoring and the finding of no wire breaks supported this path.

1.6 Rehabilitation

Beginning in 2014, an extensive rehabilitation process began with the aim to extend the life of the Anthony Wayne Bridge an additional 50 to 75 years. In March, the AWB was closed for construction. This project included the installation of a lightweight deck based on the recommendation from the inspection report. Joint improvements, corrosion removal on the superstructure, and replacement of the two approaches were also included. The original approaches were large, single-span steel trusses dissimilar from the design and aesthetic of the main cable span. These trusses were deemed fracture critical and their replacement was considered necessary for meeting the long-term rehabilitation plans.

Throughout construction the acoustic monitoring system remained active and showed no signs of new wire breaks. Maintenance was done on the AE system in August 2015. In October 2015, the bridge was reopened to traffic. The bridge with the completed superstructure rehabilitation is shown in Figure 1-9. Note the new piers on the approach spans. Immediate plans for the AWB include a two year painting project on the superstructure beginning in summer 2016.

Figure 1-9: AWB after the conclusion of the approach and superstructure rehabilitation.

1.7 Cable Rehabilitation Plans

The cable inspection showed the zinc coating on the steel wires had been substantially consumed though little to no section loss was observed. Both the acoustic monitoring and physical inspection showed the highest corrosion at the locations that had been previously opened rather than the sag points of the cable where water was likely to collect. This occurred because the patches in the elastomeric wrap leaked more than other areas of the wrap. This reaffirmed ODOT's reluctance to allow more destructive testing to be done on the cables as the consultant recommended. Therefore, it was felt that there was little to be gained from more extensive opening and inspection of the cables based on the data already obtained from the 2012 inspection and the acoustic monitoring system.

With the protective zinc gone and the existing elastomeric wrap leaking, there is a need for cable rehabilitation to slow down and prevent future corrosion. Studies have shown that humidity and temperature promote corrosion (Deeble Sloane 2013A and 2013B, Betti 2014). Examining data from the various sensors inside a test cable, they found that increased levels of relative humidity results in increased levels of corrosion activity and the experimental dependence of corrosion rate on temperature was strongly linear. In a cable preservation report, Modjeski and Masters estimated the factor of safety on the cables would fall from 2.41 in 2012 to 2.15 in 2025 (Modjeski and Masters 2013B). 2.15 is the level at which ODOT considers action is required. Among other recommendations, Modjeski and Masters recommended both cable rewrap and the consideration of a cable dehumidification system.

ODOT is currently in the preliminary stages with AECOM to begin the year-long process of installation of a dehumidification system in 2018. Dehumidification is an active system which has proved effective in creating a dry, isolated cable interior in a number of environments (Deeble Sloane 2013B). Dehumidification is expected to arrest the corrosion and prevent further degradation in the safety factor of the cables.

Dehumidification works by injecting dry air through the cables of the bridge. The cables are encased in a sealing system, usually a proprietary elastomeric wrap that surrounds all structural components. The dry air is provided from a dehumidification plant on site and pumped into the cable at injection points. The air travels through the cable and exits at exhaust points, typically at the highest point of the cable (Bloomstine and Sorensen, 2006). It has been shown that corrosion cannot occur below 40% relative humidity. And, the rate of corrosion is drastically decreased below 60% relative humidity (Bloomstine, 2011). As of 2011 there were

21 bridges worldwide with dehumidification systems in place. The majority of these are in Japan and Europe. The first application in the United States was the William Preston Lane Jr. Memorial Bridge spanning Chesapeake Bay in Maryland. This bridge has cables roughly equivalent in size to the AWB (Niroula, 2014).

Dehumidification requires a new airtight elastomeric wrap. Therefore, the existing wrap would be removed entirely and replaced as part of the dehumidification installation. Dehumidification includes a sensor package that measures input and ejected air temperature, flow and humidity at the injection and exhaust points.

After the dehumidification system is in place, continued acoustic monitoring is recommended to ensure the cable is not degrading to the point where wire beaks occur. It would be desirable to have an earlier indication of the effectiveness of the dehumidification system. Therefore, ODOT funded the present laboratory study at the University of Toledo to investigate the possible usage of a corrosion sensor that could be inserted into the cable when the dehumidification system is installed.. This sensor is the same material as the steel wires within the cable and measures corrosion as a function of its own degradation. The sensor is easily placed beneath a sealing system. The direct measure of corrosion could potentially supply a real-time look at corrosion rates at the AWB. Laboratory experiments presented here aimed to replicate corrosive conditions inside a cable to determine the usefulness of this sensor on the AWB.

1.8 Laboratory Studies On the AWB

In addition to the ongoing, laboratory study on internal corrosion sensing, there have been three previous laboratory studies at the University of Toledo from 2012 to 2014 that dealt with the use of acoustic sensors in measuring corrosion on the AWB. Beyond supplying extensive literature reviews on the current state of AE monitoring, experiments were performed in the laboratory in order to gain an understanding of the full ability of AE sensors to detect corrosion. An initial study in 2012 was able to use the controlled corrosion of aluminum to confirm that acoustic monitoring could accurately detect and identify corrosion along three stages of development (Seyedianchoobi, 2012). This test involved the use of high frequency sensors, different from the lower frequency sensors used on the bridge. The hope was that in the future, data could be analyzed in such a way that a specific signature for various corrosion events could be identified via AE sensors and applied in monitoring the AWB.

A second study created corrosion cells in a laboratory setting, this time measuring the corrosion of the same steel wires on the AWB (Layton, 2013). The lab study showed that both high and low frequency sensors could very readily detect corrosion in the steel wires, with relatively little loss of signal as the corrosion cell was moved further away from a sensor. This study also mounted corrosion cells in the field, with the aim of actively detecting corrosion with the AWB's current AE monitoring system. This aspect of the study proved less successful due to high winds creating a large amount of noise.

A third study involved determining the specific AE signature of various events (Niroula, 2014). This included signals due to friction within the cable due to the natural movement of the structure, rain and wind, and wire breaks. The study replicated these events in the lab and recorded and analyzed their acoustic emissions. These results were compared with data collected by the system on the AWB. There were several events that satisfied 6 of the necessary 7 criteria needed to be considered for a potential wire break. In comparing the data of such events to the results of the laboratory testing, it was determined that all of these events were due to high levels of wind or rain.

1.9 Summary and Future Plans

The Anthony Wayne Bridge offers a noteworthy example within the United States of a suspension bridge cable rehabilitation utilizing such state-of-the-art methods as acoustic monitoring throughout the entire process. Beginning with a conventional bridge inspection, the need for the rehabilitation arose. The use of AE monitoring directly influenced the physical inspection, influencing both where the cable would be opened and the decision to limit future destructive tests. Results from the physical inspection showed increased corrosion at locations on the cable that were previously opened. ODOT felt that the additional inspections recommended as a result of the physical inspection did not give insight that justified the additional damage to the cable they would cause.

The cable inspection showed that the protective zinc on the cable wires was consumed. However, little section loss was observed. The present factor of safety of the cable was found to be acceptable, but under the current conditions it would degrade to an unacceptable level within 15years. Therefore, cable remediation is planned.

Remediation includes installing a dehumidification system with the installation of a compatible new airtight wrap. In conjunction with this system, there would be continued use of acoustic monitoring with which ODOT has familiarity due to the existing system and several laboratory studies funded from 2012 to 2014. The possibility of utilizing internal sensors that directly measure corrosion in the cable wires is the subject of this project. This sensor would permit real time confirmation of effectiveness and operation of the dehumidification system.

Chapter 2: Objectives and General Description of Research

2.1 Research Objectives

The goal of this research is to gain an understanding of the Analatom AN110 corrosion sensor and determine its effectiveness in future monitoring of the Anthony Wayne Bridge's main cables. Additionally, it will lay the groundwork for future laboratory studies done with corrosion sensor at the University of Toledo. After the dehumidification system is installed, humidity will be monitored at the injection and outflow points. However, additional instrumentation such as the AN110 corrosion sensor could provide useful information at locations in between these points, especially at locations known to collect water, such as low points. Before a large investment is made on installing the corrosion sensor, it should be tested in a laboratory setting. The research carried out under this project can be broken down into five objectives:

1. Perform a literature review of the basis of the corrosion sensor technology and the past and current applications of dehumidification systems on suspension bridges. An easily accessible summary providing a basic understanding of the sensor can assist the bridge operators in deciding on its applications, as well as troubleshooting future issues. The same can be said of a review of dehumidification systems. Past and future dehumidification projects can also provide examples to guide operators through its installation and operation.
2. Assemble the corrosion sensor from the components supplied by Analatom and gain an initial understanding of its operation and the operation of the supplied software. Construct a relatively inexpensive environmental chamber in which to place the sensor and vary relative humidity and temperature.
3. Perform longer tests cycling the relative humidity in the chamber to observe the sensor's corrosion rate and its relation to the changing humidity.
4. Discuss the results of the testing, including if the linear polarization sensor behaves as expected.
5. Provide a recommendation of the application of this sensor in the rehabilitation of the AWB.

2.2 General Background of Research

The Analatom AN110 micro-linear polarization resistance (LPR) corrosion sensor directly measures corrosion in real-time. Components in the sensor are of the same material as the relevant parts of the structure being monitored. In this case, the corrosion sensors are made of steel similar to the steel in the cable wires. The sensors themselves corrode when placed into use, and this corrosion rate is measured and converted to a voltage using the LPR technology. The Analatom AN110 sensor can be used with the existing acoustic emission monitoring system on the bridge. The dehumidification system uses a variety of temperature, humidity, and acoustic sensors to measure its effectiveness. Adding a real-time corrosion sensor could allow an even greater level of reliability in the monitoring system. Future laboratory studies will determine the feasibility and usefulness of integrating it into the sensor package monitoring the cables after the dehumidification system is installed.

This corrosion sensor was used previously in tests at Columbia University and installed on the Manhattan Bridge (Deeble Sloane 2013A and Betti 2014). At Columbia a full-scale specimen of a suspension bridge cable was used to test various indirect and direct corrosion monitoring methods. This study was able to effectively use the corrosion sensor to show the correlation between relative humidity and temperature with corrosion. The LPR sensors were then successfully installed on the Manhattan Bridge in New York City. They once again produced results confirming the relationship between corrosion and relative humidity, showing that no corrosion occurred below 45% relative humidity. The present studies at the University of Toledo will use corrosion sensors incorporating the wire in the AWB to gain a familiarity with the sensor, determine its accuracy, determine the most feasible means to attach the sensor to the cable, and determine any other limitations. Based on these results, an in-field trial on the AWB would occur before investing in their integration in the monitoring system.

Chapter 3: Literature Review

3.1 Dehumidification

Dehumidification is a remedial method used to prevent future corrosion within the main cables of suspension bridges. Using technology developed in Denmark during the 1970s and 1980s, dehumidification was first applied to bridges to protect box girders [Bloomstine, 2011]. In 1998, dehumidification was applied to the main cables of a suspension bridge for the first time. The positive results obtained with this bridge, the Akashi-Kaikyo Bridge in Japan, led to the technology being used on several more bridges within the country. By 2011, there were a total of 21 bridges throughout Europe and Asia utilizing the technology. In 2011, the Chesapeake Bay Bridge became the first bridge in North America to begin the installation of a dehumidification system [Nader, 2015]. The Maryland Department of Transportation, construction began in 2012 and it was projected to last 2.5 years.

Dehumidification works by injecting dry air into the main cables of a suspension bridge to remove moisture and lower the relative humidity within the cables. The underlying principle behind this is that corrosion does not occur below 40% relative humidity and very little corrosion occurs between 40% and 60% relative humidity. This has been identified as early as a 1935 study by W. H. J. Vernon. In this study Vernon examined the atmospheric corrosion of metals when exposed to various humid conditions and corrosive additives such a sulfur. The relationship between relative humidity and corrosion is illustrated in Figure 3-1.

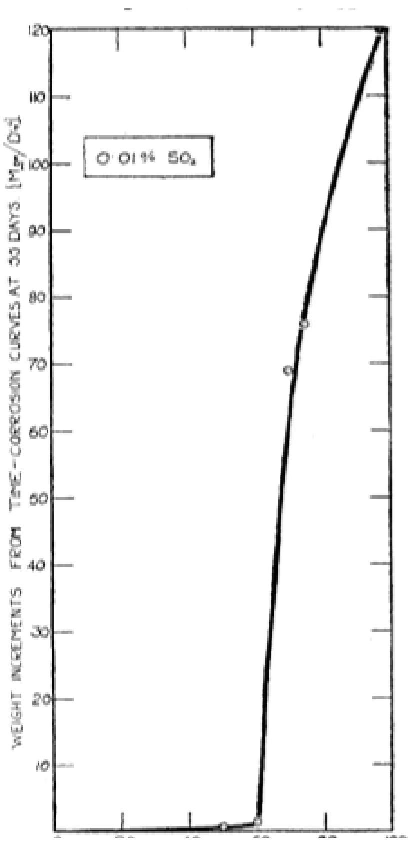

Figure 3-1: Relationship between relative humidity and atmospheric corrosion of iron (Vernon, 1935)

More recent sources confirming this relationship include studies by Suzumura (2004), Bloomstine (2011), and Betti (2013).

The protective measures around the bridge cables also serves to trap moisture inside. Suzumura (2004) sites two main causes of water entrapment in the cables: water may be collected when the wires are exposed during lengthy construction and water may enter through deficiencies in the cable band sealer and paint. A field investigation of the internal state of suspension bridge cables in Japan found that all the cables opened had water sitting at the bottom of the wrap. Further analysis showed that high temperature fluctuation at the outside of the cable allowed water to vaporize and spread to the interior, where temperature was very stable. Additionally, low exterior temperatures caused water vapor to condense on the surface of the exterior wires.

Bloomstine (2006, 2011) offers a clear explanation of the components of a dehumidification system. Any system requires a dry air system, a cable sealing system, and a monitoring and control system.

3.1.1 Dry Air System

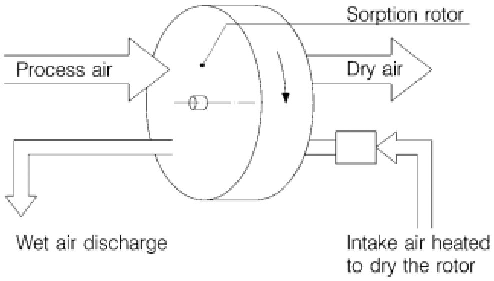

Figure 3-2: Dehumidification by sorption [Bloomstine, 2006]

A dry air system requires a means to dehumidify the air and inject the dry air into the cables. Exhaust points are also required to allow the air to leave the system. The most common method of dehumidification in systems designed for bridges is sorption. Sorption utilizes a sorbent that passively absorbs moisture in the air. This differs from the condensation method, which lowers air temperature below the dew point and causes water vapor to condense. Figure 3-2 illustrates the sorption process. Air is pulled through a slow moving rotor and passes through a sorbent material. Heated air is pushed through the other side to keep the sorbent surface dry. The dry air is then blown into injection points in the exterior cable wrapping with an additional fan. Usually, these injection points are specifically designed collars constructed on the cables. Exhaust points are also necessary to allow the air to leave the cable.

The locations of the injection and exhaust points are a large part of the design of a dehumidification system. Using classical fluid mechanics relationships, pressure drop across a length of sealed cables can be determined [Nader et al, 2015]. The cable's interior voids are a contributing factor to determining the head loss over a given length. Pressure must remain high enough that the air can reach the exhaust point, usually at a high point. For a parallel wire cable bridge such as the AWB, blowing length is around 500 to 600 feet [Beabes et al, 2015].

Figure 3-3: Example of an injection point,
with connection to dry air flow visible.
[Nader et al, 2015]

3.1.2 Cable Sealing System

An additional exterior layer is added to existing bridge cables to further protect them and allow pressurized air flow. These cable sealing systems are specialized and usually patented products of specific companies. One example is the Cableguard Wrap System, which was the preferred product in studies by Bloomstine [2006, 2013]. It is an elastomeric wrap that is applied under tension with a special machine. Strips are overlapped so that they can be sealed with a heat bond. Some advantages to this system cited by Bloomstine include comparably shorter periods of installation, limited maintenance, and no required painting. Additionally, the wrap does not bond with the cable itself, meaning that it can easily be removed and replaced.

Figure 3-4: The Cableguard Wrap System during installation [Bloomstine, 2006]

3.1.3 Monitoring and Control System

Usually housed in the same room as the dry air system, a monitoring and control system allows the bridge operator to remotely evaluate the performance of the dehumidification system and alter its operation as necessary. Variables to be controlled include the pressure of the air injected into the cables. Generally, instrumentation monitors the air at the injection and exhaust points and are connected to a local port which send the data back to a centralized computer. Temperature, relative humidity and air pressure are recorded. This data can be used to calculate the progress of water loss and determine if additional leakage has developed in the wrapping system.

The Analatom AN110 sensor as part of a corrosion monitoring system (CMS) could provide additional data beyond that provided the standard monitoring and control system used on other bridges. The sensors would be located at intermediate points between the injection and exhaust points. This is done in two primary ways. First, by collecting data on temperature and humidity at critical locations, the sensor confirms that dehumidified air is getting to the right locations and the system is working properly. Second, the corrosion sensor provides a direct measure of section loss. The dehumidification system measurement is an indirect global measurement of conditions in the stay. The corrosion sensor is a direct local measure of corrosion. Thus, the two measurements are complementary. Additionally, the corrosion monitoring system has been successful in detecting the onset of corrosion at one location, caused by a damaged protective wrapping. This showed that this system could also work as an early warning system for the safety of the cable. (Betti 2014)

3.1.4 Maintenance and Operation Costs

A dehumidification system runs continuously after its installation. One of the major costs of this includes electrical usage. Beabes [2015] uses the electrical consumption of three bridges in the United Kingdom as an example. These bridges, currently using a dehumidification system, use the equivalent of $25,000 to $50,000 worth of electricity annually. These costs can be decreased as the cables dry out, as air with a greater relative humidity can gradually be used.

Maintenance of a dehumidification system involves continuously utilizing the monitoring system to assure functionality. Filters in the dehumidification plant must be frequently replaced, usually on a planned schedule. Many of the components of the dehumidification plant are standard HVAC parts that can found with relative ease. Nevertheless, initial maintenance contracts lasting one to two years are usually included with the construction costs. This eases the bridge operator into dealing with the new process and can cost approximately $50,000 annually [Beabes et al, 2015].

3.1.5 Case Studies

Dehumidification is being increasingly used around the world. The following case studies are relevant applications of the technology in the United Kingdom and the United States.

3.1.5.1 Humber Bridge

A 2011 study summarized the rehabilitation of the Humber Bridge through dehumidification [Cocksedge et al, 2011]. The Humber Bridge is a suspension bridge with a main span of 1410 meters and two side spans of 530 meters and 280 meters, respectively. It is located near Kingston upon Hull, England and was opened in 1981. The results of internal inspections of other bridges across the UK prompted the operators of the Humber Bridge to begin their own inspections, in spite of its age. This began in 2007 with external inspections of the cable wrap that revealed signs of water leakage. Internal inspections were completed in 2009. Signs of corrosion were found throughout the cable, though very few wire breaks were found. Based on the corrosion found and the more advanced corrosion of older bridges in the country, it was decided that future deterioration should be prevented before a large loss of strength occurred. Based on the success of the Forth Road Bridge, the operators decided a dehumidification system was the best remedial action for the main cables.

AECOM was hired to design the dehumidification system in 2009. Mainly based on past work, the blowing length between injection and exhaust ports was kept between 600 and 1,200 feet. The injection and exhaustion point layout can be seen below in Figure 3-5.

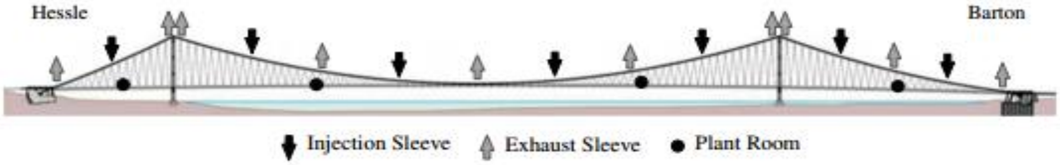

Figure 3-5: Humber Bridge dehumidification system layout [Cocksedge et al, 2011]

The dry air system used a “plenum chamber,” meaning after air was processed and dehumidified, it was stored in a pressurized chamber before being injected in the cables. Four plant rooms were constructed on the bridge in the cells of the deck’s box girders. This was more than the minimum required, but allowed for smaller equipment that made the rooms more easily accessible. The dry air system utilized the sorbent process. A system of pipes transferred the air to the injection points.

The most difficult part of construction was the installation of the cable wrap. The contractor was experienced with both the Humber Bridge and other dehumidification systems. Four gantries were used to simultaneously wrap different lengths of the main cable. By beginning at the top of the cables and working towards the bottom, the contractor eliminated the need to travel over already wrapped sections. By maximizing work on days with good weather and using experienced workers, construction on the project was completed one year ahead of schedule in December, 2010.

An acoustic monitoring system was also installed by Physical Acoustics Limited on the bridge during the construction period. Because of the conflicting construction projects, the sensors were installed via rope access. The bridge operators did not expect to hear many wire breaks in a bridge as young as Humber Bridge. However, it was viewed as a reassurance and secondary monitoring system to the dehumidification system’s monitoring instruments.

As of 2011, the dehumidification system had been running for approximately four months. The relative humidity of the dry air at the injection ports was 10%. Progress in the relative humidity at exhaust ports was already seen.

3.1.5.2 Forth Road Bridge

A 2009 report [Cocksedge et al, 2009] summarized the rehabilitation of the Forth Road bridge in Edinburgh, Scotland. The bridge was open in 1964 and has a main span of 3300 feet with two side spans of 1340 feet. The main cables contain 11,618 parallel, galvanized steel wires. Conventional protection was applied, meaning the cables were covered in a layer of lead paste, a wrap, and painted. The bridge operators began a series of inspections on the bridge in 2003 in response to many reports from the United States noting structural deficiencies in similar bridges.

Many small defects were observed when an initial exterior inspection was performed, including issues with the wrapping. This prompted an internal inspection at eight different points on the bridge, which led to unexpected results. Broken wires were found at nearly all locations, and Stage 4 corrosion was also observed. The lead paste protection had dried out and offered little protection. Tensile tests of wire samples found that they maintained an acceptable factor of safety, but predictions of continued loss of strength prompted the bridge operators to pursue remedial action. An acoustic monitoring system was also installed in 2006 to monitor future wire breaks.

Cable oiling was explored by the bridge operators, a process in which the entirety of the cable is internally coated with oil to fill voids and protect the wires. However, it was ultimately rejected as tedious, expensive, and ineffective. Dehumidification of the main cables was then explored, a new process in Europe at the time. Only two European bridges had dehumidification systems in 2006, and only one, the Hoga Kusten Bridge in Sweden, had parallel wires like the Forth Road Bridge. A visit to the Hoga Kusten Bridge exposed the Forth Road Bridge operators to the Cableguard wrapping system and standard dehumidification plants. Further visits to Japanese bridges revealed the need to carefully place injection and exhaust points to maximize effectiveness and minimize costs.

As the design moved forward, the Cableguard wrapping system was chosen based on past experience and its ability to withstand the high internal pressures of the dry air injection. There were also existing details for cable band sealers, which would have to be redeveloped if another system was chosen. A standard dehumidification system was used and the plant room was also utilized as a plenum chamber to store the dry air and create a buffer between the injection system and humid air. Course and medium filters were used as the air first entered the dry air system. Later, processed dry air passed through a fine filter on its way to dehumidification plants.

Three plants stations were installed on the bridge, one on each span. In determining the blowing lengths, it was decided to install a trial section before proceeding with the rest of the installation. This trial section was the midspan of the cable on the main span and construction was completed in 2008. The progress of the drying process can be seen in Figure 3-6. Based on these positive results, construction on the rest of the cable length was commissioned.

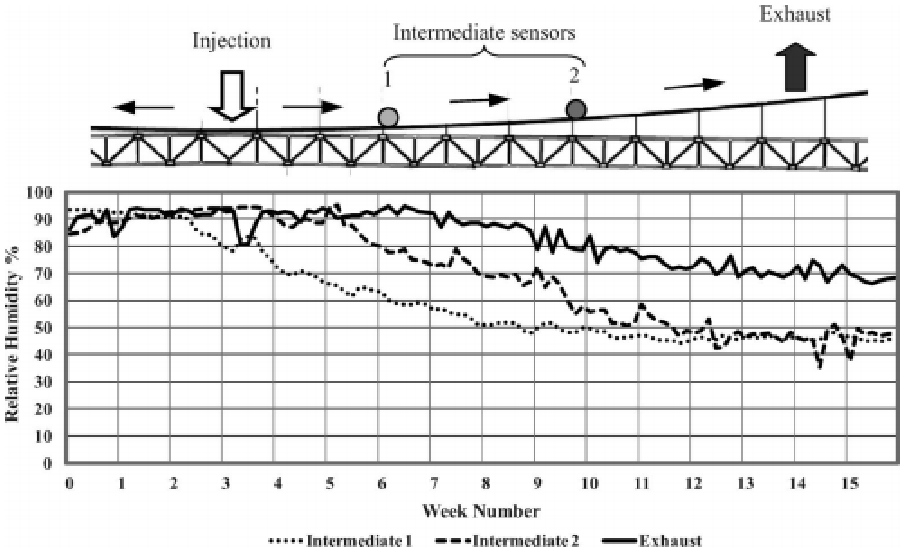

Figure 3-6: The progress of the drying process on the trial length of the dehumidification on the Forth Road Bridge. [Cocksedge et al, 2009]

3.1.5.3 William Preston Lane, Jr. Memorial Bridge

A recent paper discussed the dehumidification system recently installed on the William Preston Lane, Jr. Memorial (Bay) Bridge, the first such example in the United States (Waldvogel 2016). The installation process progressed similarly to the recent projects in the United Kingdom. Located in Maryland, the Bay Bridge crosses the Chesapeake Bay and connects the eastern shore with the city of Annapolis. It consists of an eastbound bridge open in 1952 and a westbound bridge opened in 1973. With the cable wrapping due for replacement, the opportunity was taken to begin an inspection process in 2008.

The process began with an exterior inspection on both the Eastbound and Westbound bridges. The condition of the wrapping warranted further internal inspections, leading to the recommendation of a dehumidification system. AECOM, the company that designed the dehumidification systems of both the Humber and Forth Road bridges, was hired to assist in the design process of such a system on the Bay Bridge.

The different Eastbound and Westbound bridges immediately presented a design difference. The wire strands in the Eastbound Bridge's cable were helical, while the Westbound was parallel. The airflow resistance of parallel strands is much higher, so the system layout for the bridges needed to be different. The injection and exhaust points on the Eastbound Bridge could be spaced further apart. The Eastbound Bridge had one injection point at the midpoint of its main span, and one on each of its two side spans. The Westbound Bridge required two injection points located at the quarter points of the main span and one injection point on each of its two side spans. Both bridges utilized the tower tops as ejection points, as these locations would be problematic to make airtight.

Before construction could begin on the bridge, the bridge operators required the contractor to demonstrate their ability to rewrap the cables on test rigs. This included the full operation of the dehumidification equipment and monitoring system to assure that proper pressure could be maintained within the wrap. After this, dehumidification systems were installed on the bridge. The contractors were then required to replicate their test rigs on trial sections of the bridge's cables. This was mainly due to the sensitive nature of installing the Cableguard wrapping system. The rest of the wrapping system was constructed after the trial sections were installed and operated successfully.

The dehumidification system has been running on the Westbound Bridge since February 2014 and on the Eastbound Bridge since September 2015. Within about nine months of the start of dehumidification, relative humidity in the Westbound Bridge dropped below 40% and the cables were essentially dried out. The effectiveness of this was confirmed by an existing acoustic monitoring system showing nearly no new potential wire breaks within the cables. This can be seen in Figure 3-7.

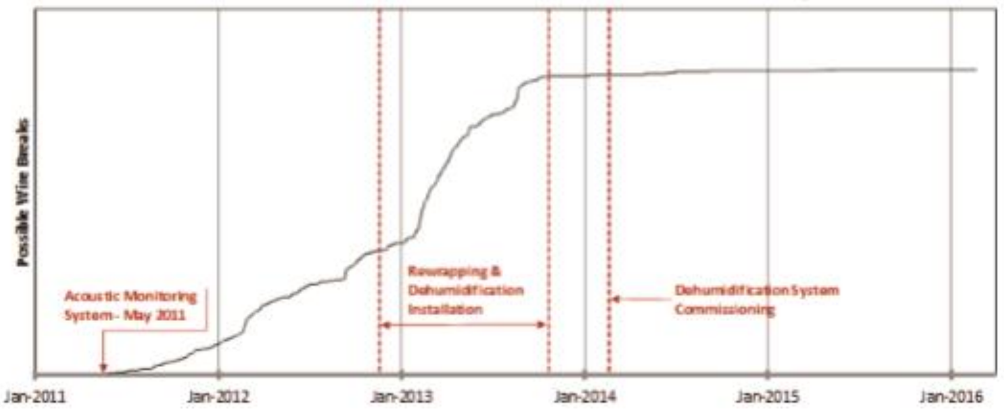

Figure 3-7: Potential wire breaks on the Westbound Bay Bridge [Waldvogel et al, 2016]

The Eastbound Bridge dried out much quicker than the Westbound. The smaller flow resistance of the helical strands allowed the relative humidity at the exhaust points to drop below 40% after just four weeks.

Overall, the dehumidification of the Bay Bridge is viewed as a success by the bridge operators. It shows the feasibility of constructing such a system within the United States and the performance results thus far are encouraging signs of its effectiveness.

3.2 Linear Polarization Resistance and the AN110 Corrosion Sensor

3.2.1 Linear Polarization Resistance Background

Linear polarization resistance (LPR) method is an electrochemical technique developed to measure the instantaneous corrosion rate of a metal. The basis of the method is the Stern-Gerny theory, which relates the current flowing through a metal with a specialized constant and the polarization resistance (Law 2004). The mass lost within a system can be calculated based on the changing resistance, and thus the changing voltage.

LPR technology has been increasingly used within the world of structural engineering. A 2004 study used LPR measurements to monitor the corrosion in concrete reinforcement bars (Law 2004). The study wished to confirm the accuracy of LPR measurements by comparing predicted weight loss to actual weight loss in the steel bars. Small reinforced concrete samples were placed in environmental cabinets with varying corrosive conditions and allowed to corrode for nearly five years. LPR measurements were taken every few weeks, while the samples were weighed at the midpoint and end of the testing period. A current was directly applied to the samples and measured as opposed to using a proprietary product for LPR measurements.

The results of this experiment indicated that LPR provided a reasonable qualitative measurement of changing corrosion rates both short-term and long-term. For example, it correctly showed higher corrosion rates in a more corrosive environment. However, it generally overestimated the mass of steel lost. The authors of the study noted this could be a reflection of their measurement methods and the effect of the corrosive environment.

3.2.2 Analatom AN110 Corrosion Sensor

The AN110 sensor is a proprietary LPR corrosion sensor manufactured by Analatom, Inc. It has been specifically designed for use in structural monitoring applications. A sensor package includes a data acquisition unit, LPR corrosion sensors, and a temperature and humidity sensor. The data acquisition (DAQ) unit with attached LPR sensors can be seen in Figure 3-8. Also included with the sensor were extension cables for the LPR sensors, a connection cable to connect the DAQ box to a computer, an antenna and wireless adapter to allow a wireless connection to a computer, and software that allowed control of the data acquisition. The software also provided a means to view recorded tests and calculate a corrosion rate from the unprocessed voltage the sensor records.

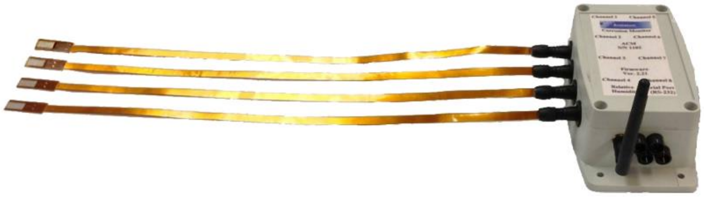

Figure 3-8: AN110 data acquisition unit with attached LPR sensors, per the manufacturer

The LPR corrosion sensor is custom manufactured based on the need. The sensor itself is constructed of the same material that is being monitored. A shim of the source material is attached to an electrode grid and then placed on a flexible Kapton backing. The shim is prepared with electro chemical etching. The DAQ box allows up to eight sensors to be connected at once.

Figure 3-9 [illegible] n sensor attached to environmental chamber

The AN110 sensor is a two-electrode sensor. The sensors are "interdigitated at 150 μm and 300 μm spacings," per the manufacturer. As the sensor corrodes, one electrode acts as a cathode in the chemical reaction and the other electrode acts as an anode (Brown, 2014). Because the sensor is the same material as the structure and in the same environment, the corrosion rate measured on the sensor reflects the corrosion rate of the source material around it. An alternative configuration to a linear polarization resistance sensor is the three-electrode design. In this design, three electrodes are made of copper and covered in a nickel immersion gold finish. One electrode serves as a counter, another as a reference, and the third makes electrical contact with the structure. The contact is accomplished through a transfer tape. By making contact with the structure, the structure itself serves as an electrode in the chemical reaction and the corrosion rate is calculated based on what the structure is locally experiencing.

A 2014 study compared the two-electrode and three-electrode LPR corrosion sensors (Brown, 2014). Total corrosion was recorded by each of the sensors for a period of 300 hours. The two-electrode system was shown to vary from the measured mass loss as the testing period went on. However, the three-electrode system remained constant in its accuracy throughout the testing period. Ultimately, the study noted that the three-electrode system was a more accurate method to test corrosion in a structure, in part because the structure is a part of the sensor's measurement. Also, the electrodes in a three-sensor configuration are not designed to corrode, and thus will have a longer lifespan than the two-electrode system. The three-electrode corrosion sensor is a new technology and Analatom, Inc. is currently developing a commercial version.

A recent study used the Analatom corrosion sensor in observing the relationship between relative humidity and corrosion in the interior of a suspension bridge cable [Sloane et al, 2013]. In this study, a full scale replica was used. The mock-up contained 73 strands of 127 steel wires each and was built in the laboratory. Humidity and corrosion sensors were placed at varying depths within the cable. Testing was performed in a cyclic corrosion testing chamber. Throughout the test, rain, heat, and air conditioning cycled on and off to create different environmental conditions.

The corrosion rate, temperature, and relative humidity at several locations within the cable were recorded and then compared. A statistical analysis was performed and showed a linear relationship between relative humidity and corrosion rate. The same was true of the relationship between temperature and corrosion rate. The trends can be seen in Figure 3-10.

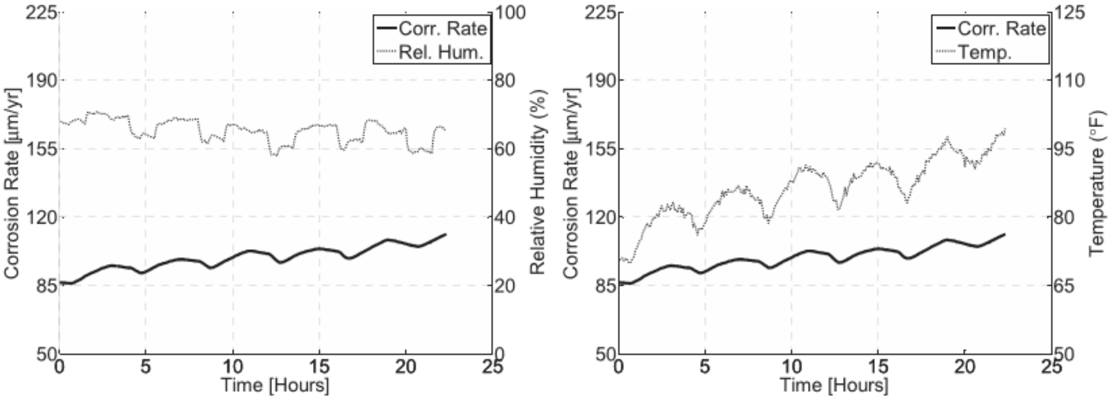

Figure 3-10: Experimental results from cyclic testing of corrosion sensor within a cable [Sloane et al, 2013]

The sensors provided much more consistent readings when closer to the center of the cable, where conditions stayed more stable. They were ultimately viewed as a valuable resource in conducting a broader study analyzing the distribution of humidity and temperature within the cross section of a cable. The authors demonstrated that the corrosion rate readings responding directly to changes in relative humidity warranted future studies and in-field tests.

Chapter 4: Laboratory Corrosion Sensor Experiments

An experimental program was developed to test the capabilities of the Analatom AN110 corrosion sensor. The sensor's response to varying environmental conditions was critical in understanding its functionality and its potential usefulness as applied to the Anthony Wayne Bridge.

4.1 Development of the Experimental Program

The experimental program can be broken down into two phases:

1. Construction of an inexpensive environmental testing chamber and the initial assembly of the AN110 sensor to gain familiarity with its operation.
2. Longer tests cycling the relative humidity to observe the sensor's corrosion rate and its relation to environmental conditions.

4.1.1 Environmental Chamber

The environmental chamber was initially designed to have the ability to control both the internal relative humidity and the internal temperature. The AWB experiences temperatures where corrosion can occur ranging from 32 degrees Fahrenheit to 120 degrees Fahrenheit. As discussed previously, corrosion can occur between 40 percent relative humidity and 100 percent relative humidity. The ambient room temperature in the laboratory was approximately 75 degrees Fahrenheit, meaning a means was required to both lower and raise the internal temperature. A 30-quart Styrofoam box was chosen as the main body of the environmental chamber. It is lightweight, has insulating properties, and can be easily worked with. Holes were cut to allow all necessary sensor cables to run back to the sensor box.

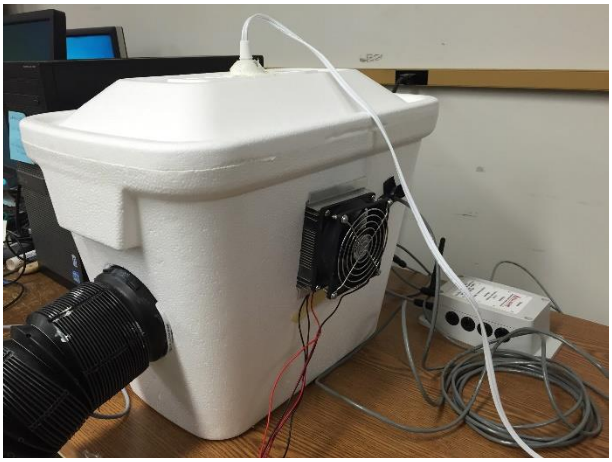

Figure 4-1: Environmental chamber with Peltier cell, connection to humidifier, and corrosion sensor box shown

For cooling the chamber, a Peltier cell was tested. A Peltier cell uses a thermoelectric reaction to create a temperature difference between two different metals when a voltage is applied. One side drops in temperature and a heatsink and fan can be used to blow the cool air into a closed space. Such devices are most commonly used to cool computer processors. A hole was cut into the box and a Peltier device installed. The device was run for an hour long period and the temperature inside the environmental chamber was recorded using the AN110's temperature and humidity sensor. The results are shown below.

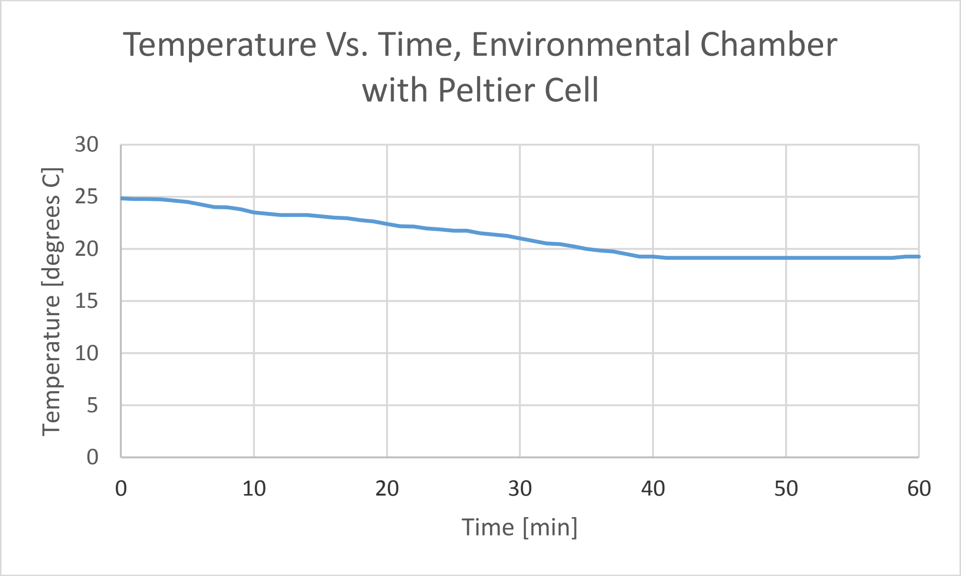

Figure 4-2: Temperature versus time in environmental chamber when using Peltier cooling cell

The Peltier cooling cell dropped the internal temperature of the chamber approximately 5 degrees Celsius from the ambient room temperature. Starting at 24.28 degrees Celsius, the temperature dropped before stabilizing at 19.13 degrees Celsius.

A simpler approach was taken with heating the chamber. A heat lamp bulb was affixed at the top of the chamber and turned on. The results of a preliminary hour long test are shown below.

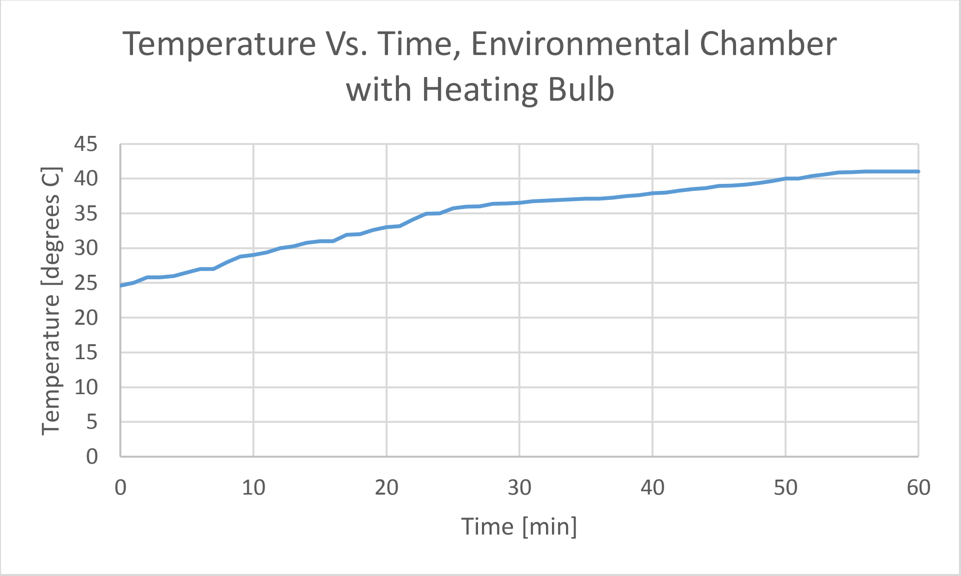

Figure 4-3: Temperature versus time in environmental chamber when using heating bulb

The heating lamp bulb raised the environmental chamber's internal temperature from 24.63 degrees Celsius to a stabilized temperature of 41.00 degrees Celsius, or approximately 106 degrees Fahrenheit.

A warm-air humidifier was used to control the relative humidity in the chamber. A four-inch circular hole was cut into the box and a plastic tube was run down to the outlet of the humidifier. When turned on, the humidifier warms the water and the mist is released through the top. The humidifier did not prove to be very sensitive when changing the relative humidity in small amounts. Turning on the device caused large, linear spikes in the relative humidity that could not easily be controlled. During attempts to calibrate the humidifier, the temperature, relative humidity, and corrosion rate were all monitored in real time using the AN110 sensor. This assured all components were in basic working order, allowed the supplied software to be used, and allowed a real-time view of how the humidifier affected relative humidity in the chamber. An example of these short real-time tests can be seen below.

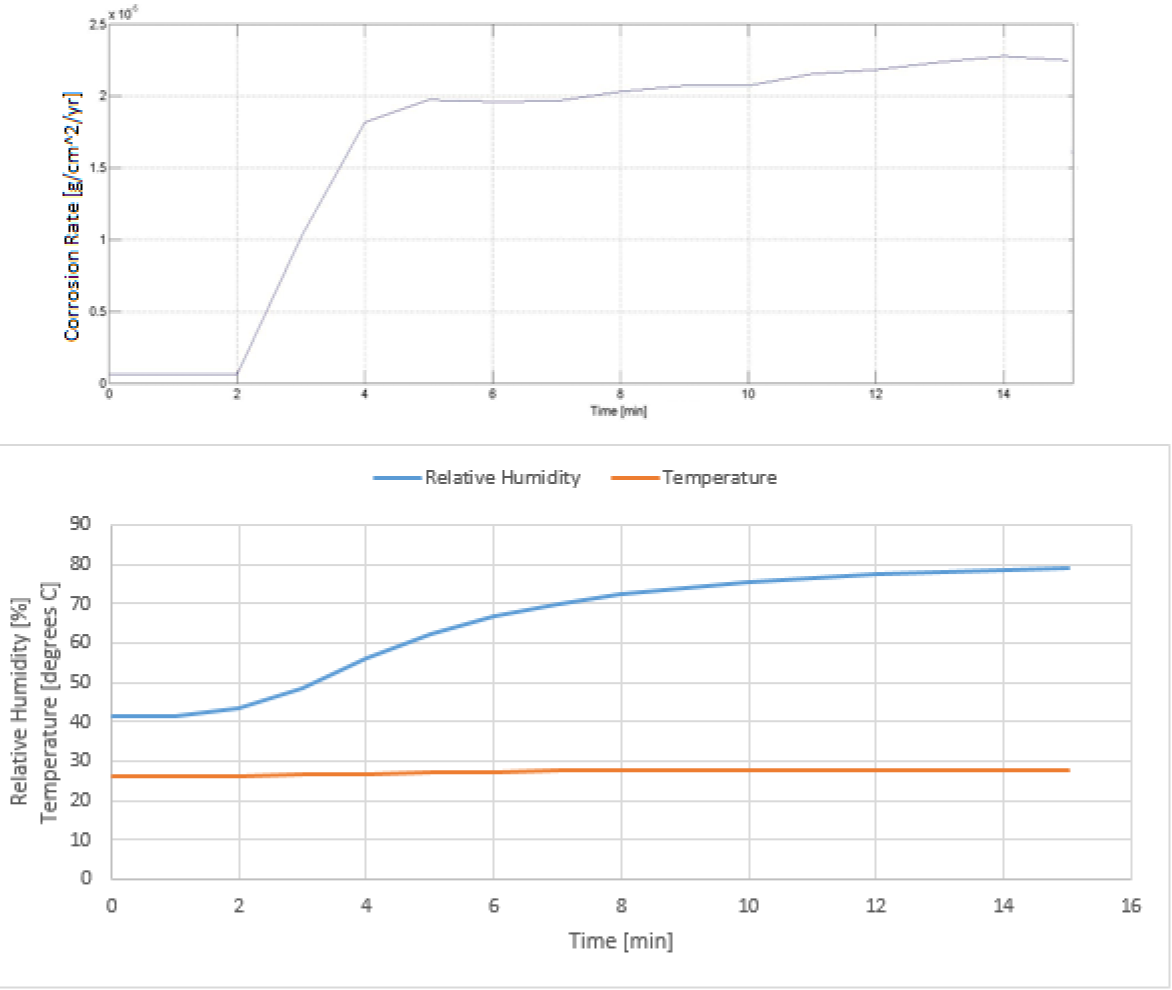

Figure 4-4: Preliminary test results observed in real-time

As seen in the example above, the preliminary testing showed a relationship between the corrosion rate and the relative humidity during short term applications of the humidifier. As the relative humidity reached approximately 60% the corrosion rate ramped. In general, the corrosion rate increased as the relative humidity increased. Temperature during these tests remained constant, reflecting the ambient room temperature.

The corrosion rate is given in terms g/cm^2/year, or mass of steel lost over the surface area of the wire. This unit can easily be converted into thickness lost per year, in cm/year, by dividing by the density of the metal. Knowing the thickness of steel lost in the steel wire can assist in future projections of strength loss. With preliminary testing showing an expected relationship between corrosion rate and relative humidity, longer testing could be planned.

4.1.2 Cyclic Testing

Based on others' work, namely Betti's 2013 study measuring corrosion in full-size cable specimens, it was clear that cycling the relative humidity within the chamber would give the best representation of how the sensor measures corrosion rates in changing conditions. Cyclic testing also provides a reasonable parallel to changing weather conditions.

A 24-hour testing period was chosen to best observe the sensor's outputs over longer periods of time. Based on earlier work in calibrating the humidifier, the most effective means of cycling the relative humidity was to bring the relative humidity to 100% and allow the levels to naturally drop down to lower percentages over the course of several hours. Moisture was allowed to escape through the small hole in the chamber used to run the sensor's cables back to the sensor box. The humidifier was attached to a timer that turned it on at 12 hour intervals. Temperature was to be held constant, subject to the ambient temperatures of the laboratory. Three 24-hour periods of cycling the relative humidity were observed. The tests were performed in consecutive days, from July 2 to July 6, with a 12 hour break between the end of one test and the beginning of another.

4.2 Experimental Results and Discussion

4.2.1 Test 1

Test 1 was begun on July 2 and the results are shown in Figure 4-5 below.

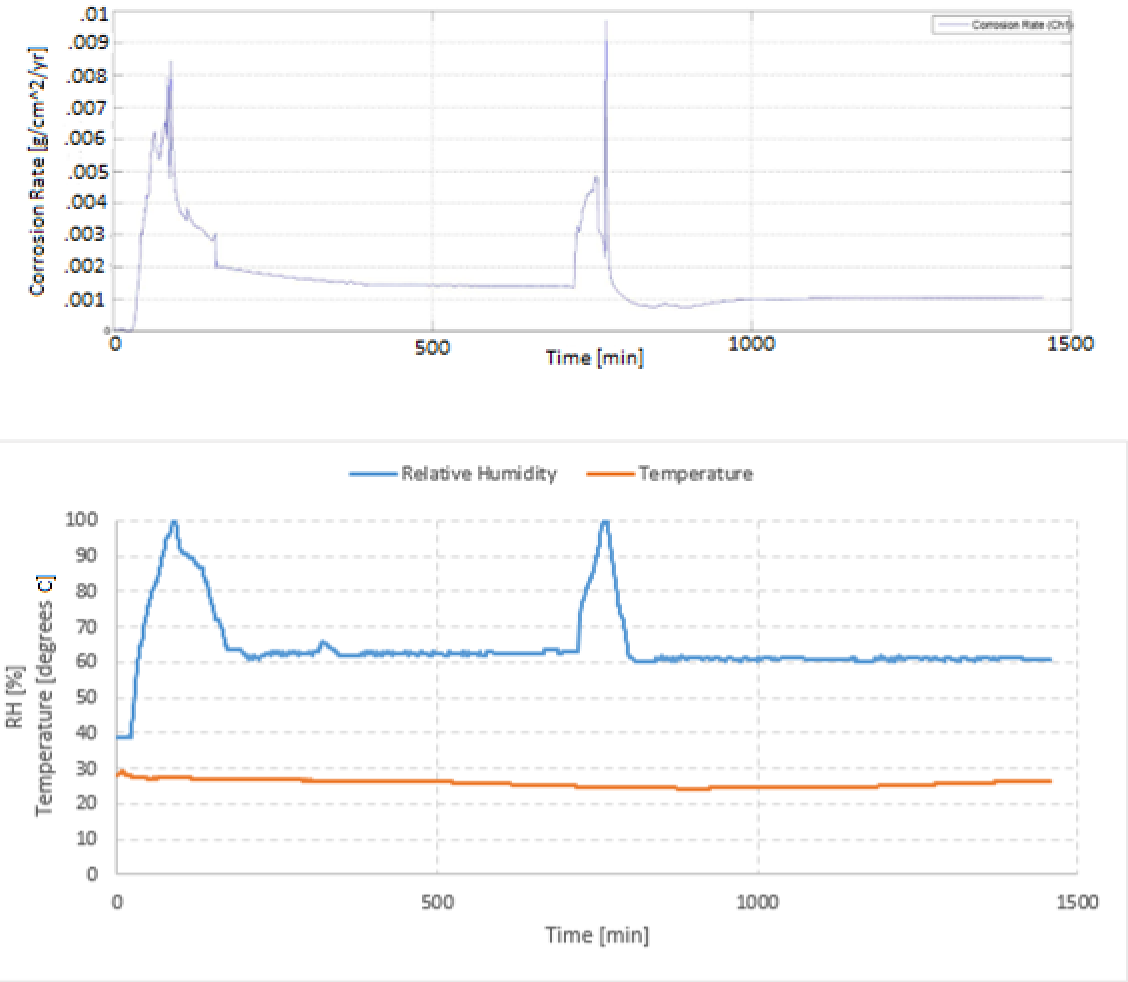

Figure 4-5: Test 1, Corrosion rate and relative humidity over 24-Hour period

Corrosion rate increased directly in relation to relative humidity. The first cycle of humid air began entering the chamber at 20 minutes into the test, when the humidity rose above 40% for the first time. The corrosion sensor output its first non-zero rate at 30 minutes, where the relative humidity was recorded at 57.5%. The first cycle of humid air can be seen in more detail in Figure 4-6 below.

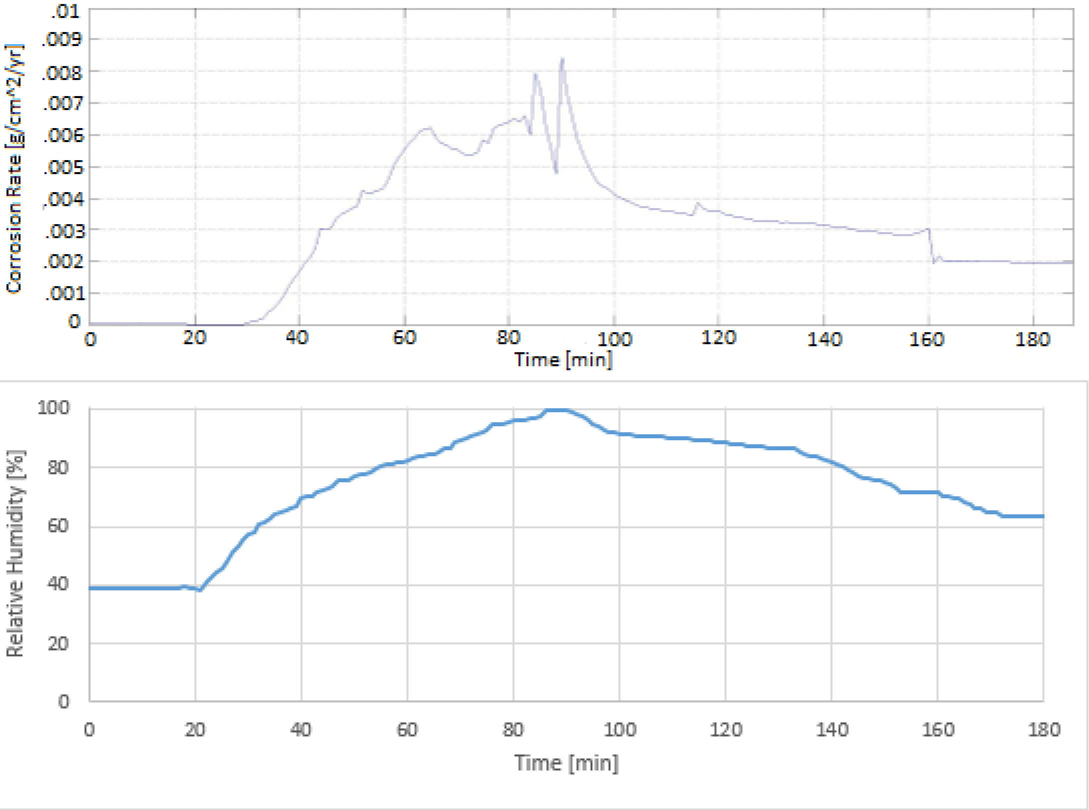

Figure 4-6: Test 1, detailed look at corrosion rate and humidity during first cycle of humid air

Between 40 minutes and 65 minutes, the corrosion rate increased at a near constant rate, as did the relative humidity. After 65 minutes, the relative humidity continued to rise, but the corrosion rate began to vary. The corrosion rate peaked at 0.008 g/cm^2/year at 90 minutes and a recorded relative humidity of 100%. After this point, relative humidity began to fall and corrosion rate dropped steeply. At 120 minutes, the corrosion rate was 0.0035 g/cm^2/year, while the relative humidity had only fallen to 88%. At 160 minutes, relative humidity stabilized between 60% and 64%, remaining in this range until the second cycle of humid air entered the chamber at 718 minutes. During this period, the corrosion rate also remained stable, remaining between 0.001 and 0.002 g/cm^2/year. Figure 4-7 below shows a detailed look at the second cycle of humid air.

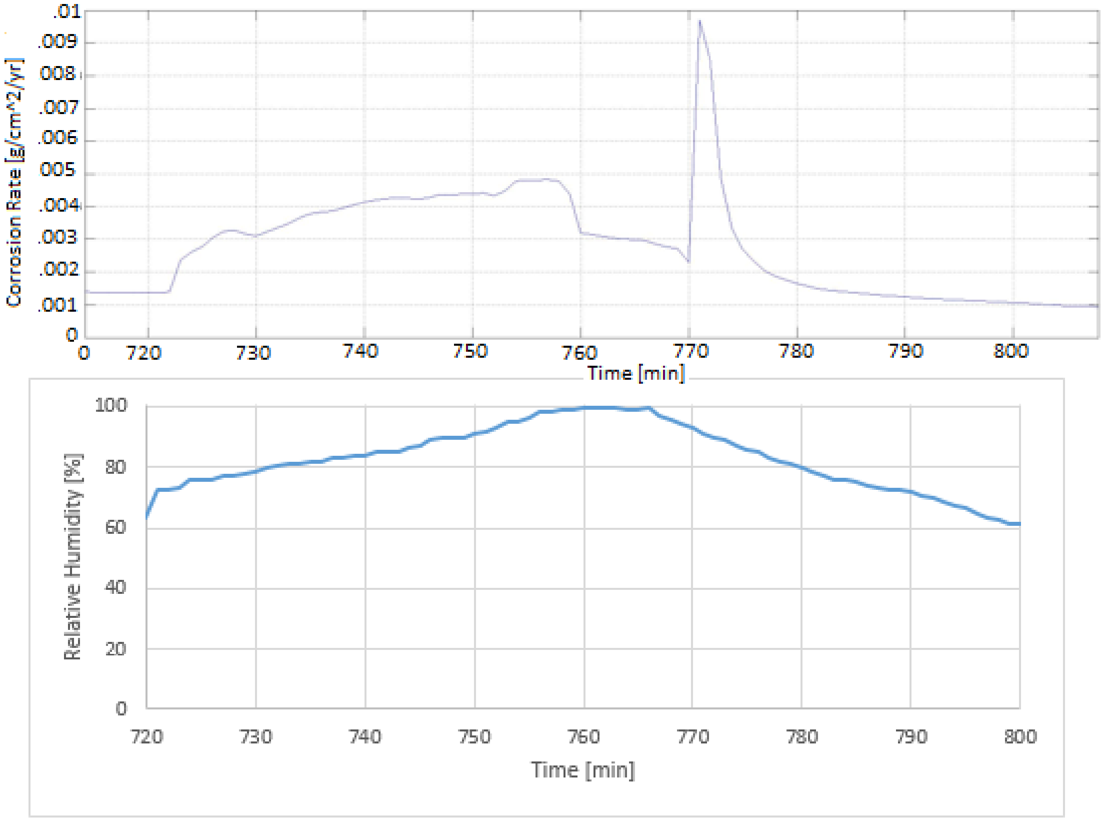

Figure 4-7: Test 1, detailed look at corrosion rate and relative humidity during the second cycle of humid air

Between 720 minutes and 760 minutes, relative humidity rose at a near constant rate, increasing from 63% to 100%. Between 720 minutes and 730 minutes, the corrosion rate doubled from 0.0015 to 0.003 g/cm^2/year as relative humidity increase from 60% to 80%. From 760 minutes to 767 minutes, relative humidity remained near 100%. The corrosion rate reached .005 g/cm^2/year at 760 minutes but began to fall as the relative humidity remained at 100%. After this point, relative humidity and corrosion rate began to fall before stabilizing at approximately 800 minutes. However, there was a spike in the corrosion rate around 770 minutes that showed no relation with the falling relative humidity. The maximum corrosion rate of the second cycle, excluding the spike, was smaller than the first cycle. Relative humidity stabilized at approximately 800 minutes until the end of the testing period, remaining between 60% to 62%. During this time, the corrosion rate also stabilized, remaining at approximately 0.001 g/cm^2/year.

4.2.2 Test 2

Test 2 was begun on July 3 and the results are shown in Figure 4-8 below.

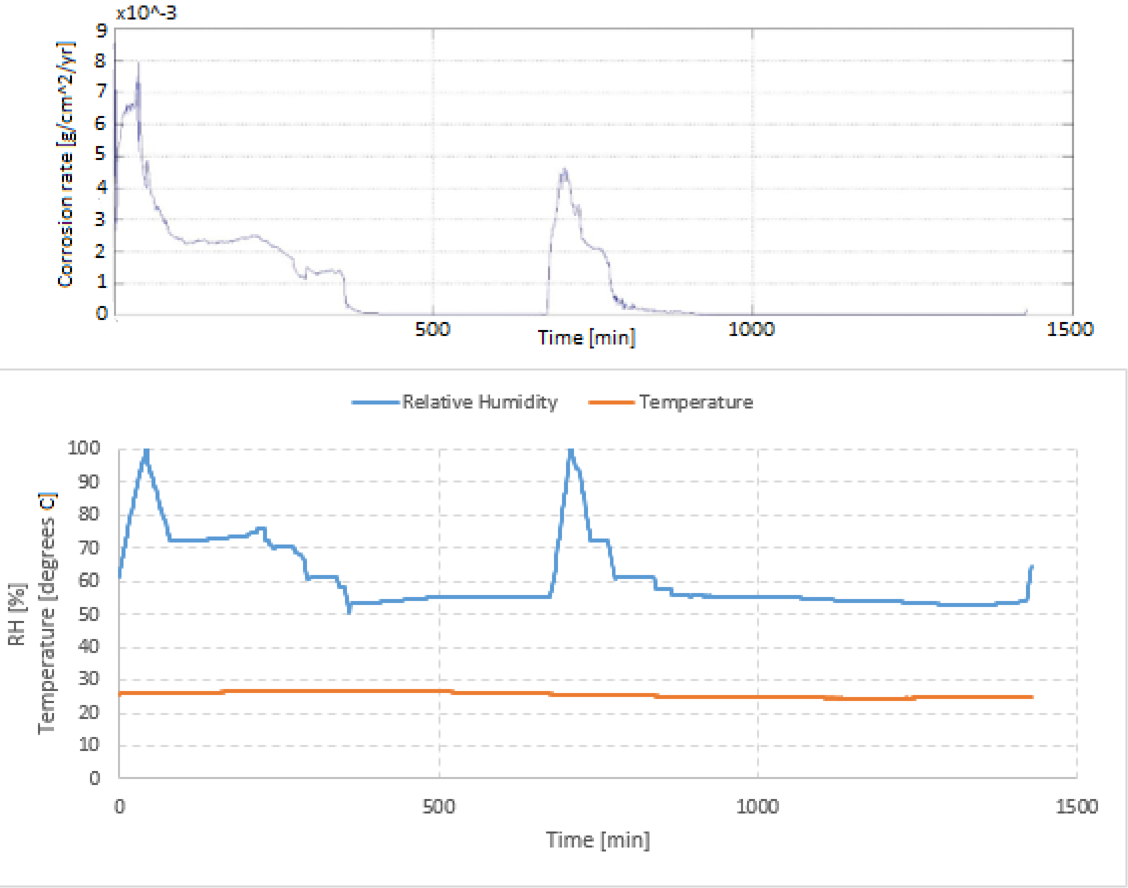

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Figure 4-8: Test 2, corrosion rate and relative humidity during 24-hour period

As can be seen in the figure above, the corrosion rate generally rises and falls directly in relation to the relative humidity. The relative humidity in the chamber stabilizes below 60% after both humid air cycles. During this period, the sensor recorded a corrosion rate of 0 g/cm^2/year. The first cycle of humid air can be seen in more detail in Figure 4-9.

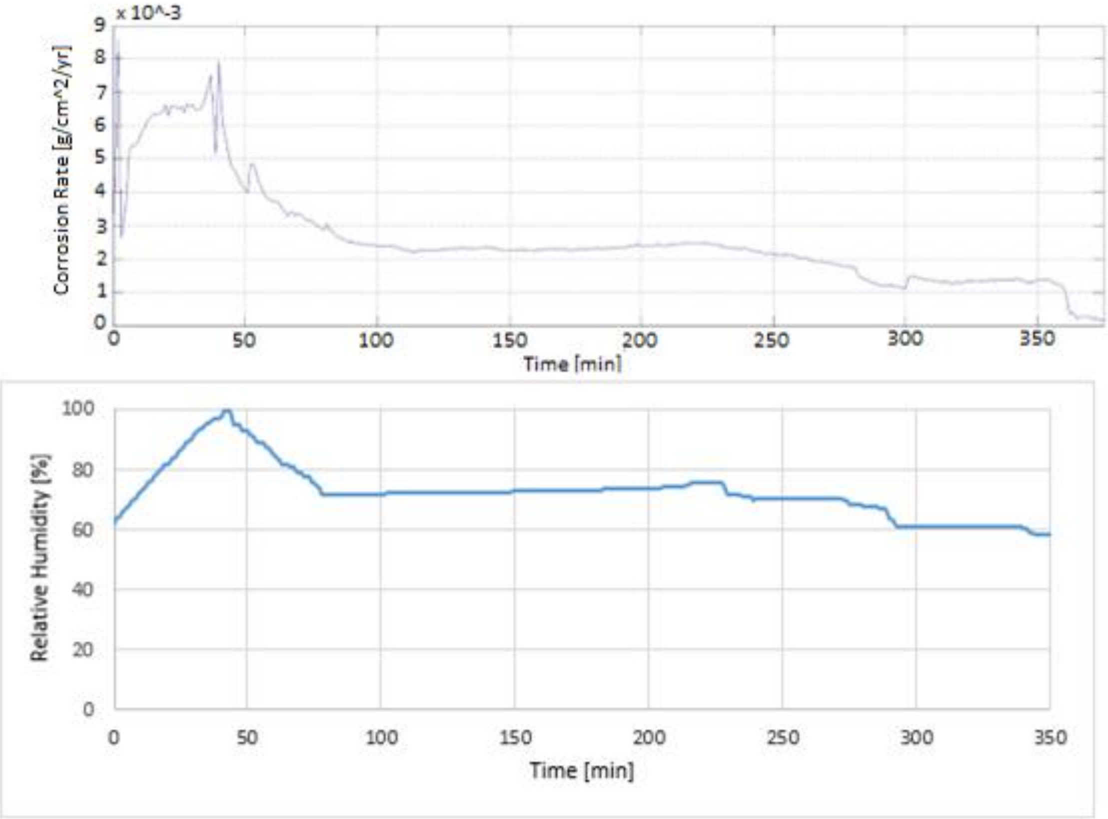

Figure 4-9: Test 2, relative humidity and corrosion rate during fist humid-air cycle

During the first cycle of humid-air, relative humidity was recorded as 61% and increased at a constant rate, peaking at 100% between 40 and 43 minutes. The maximum corrosion rate of 0.008 g/cm^2/year occurred during the period of 100% relative humidity at 41 minutes. The corrosion rate generally increased with the relative humidity, with corrosion rate changing at a much higher rate between 60% and 80% relative humidity. There was a large spike in the corrosion rate as humid air began entering the chamber. The corrosion rate fell at a higher rate as the relative humidity began to drop. Relative humidity stabilized between 72% and 75% from 81 minutes to 200 minutes. During this period of time, the corrosion rate remained at approximately 0.002 g/cm^2/year. Between 200 minutes and 360 minutes, relative humidity fell from 75% to 55%. During this period, the corrosion rate fell from 0.002 g/cm^2/year to 0 g/cm^2/year. The corrosion rate and relative humidity remained at these levels until the second cycle of humid air began entering the chamber at 674 minutes. The second cycle of humid air can be seen in more detail in Figure 4-10.

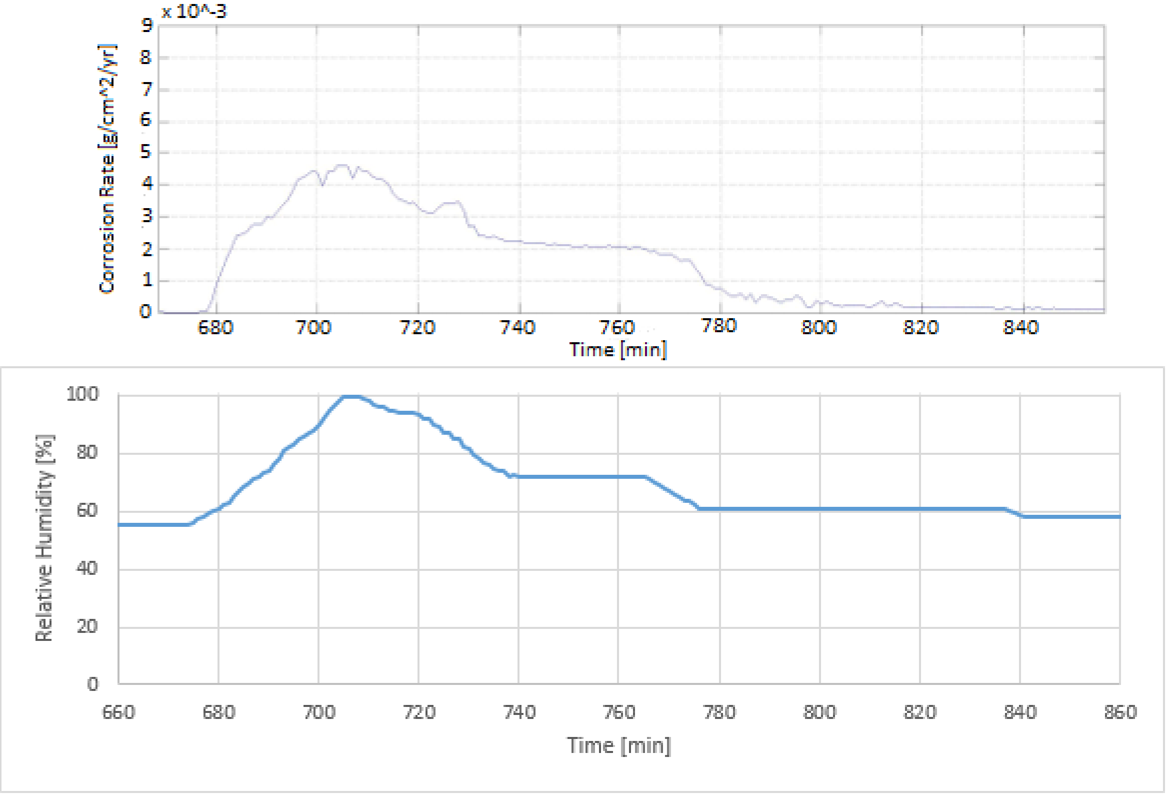

Figure 4-10: Test 2, relative humidity and corrosion rate during second cycle of humid air

Relative humidity increased from 55% to 100% from 674 minutes to 705 minutes. The corrosion rate increased from 0 g/cm^2/year to 0.0045 g/cm^2/year during this period. Once again, the corrosion rate increased at a greater rate between 60% and 80% relative humidity than it did from 80% to 100% relative humidity. The peak corrosion rate of 0.0045 g/cm^2/year occurred during the period of maximum relative humidity. However, this rate was smaller than the peak rate of 0.008 g/cm^2/year of the first cycle. The relative humidity fell at a constant rate to 72% at 740 minutes. The corrosion rate fell with the relative humidity, falling to approximately 0.002 g/cm^2/year. From 740 minutes to 765 minutes, the relative humidity remained at 72% before falling to 60% at 780 minutes. From 780 minutes until the end of the test period, relative humidity remained at or below 60%, and the corrosion rate was near 0 g/cm^2/year.

4.2.3 Test 3

Test 3 was begun on July 5 and the results are shown in Figure 4-11 below.

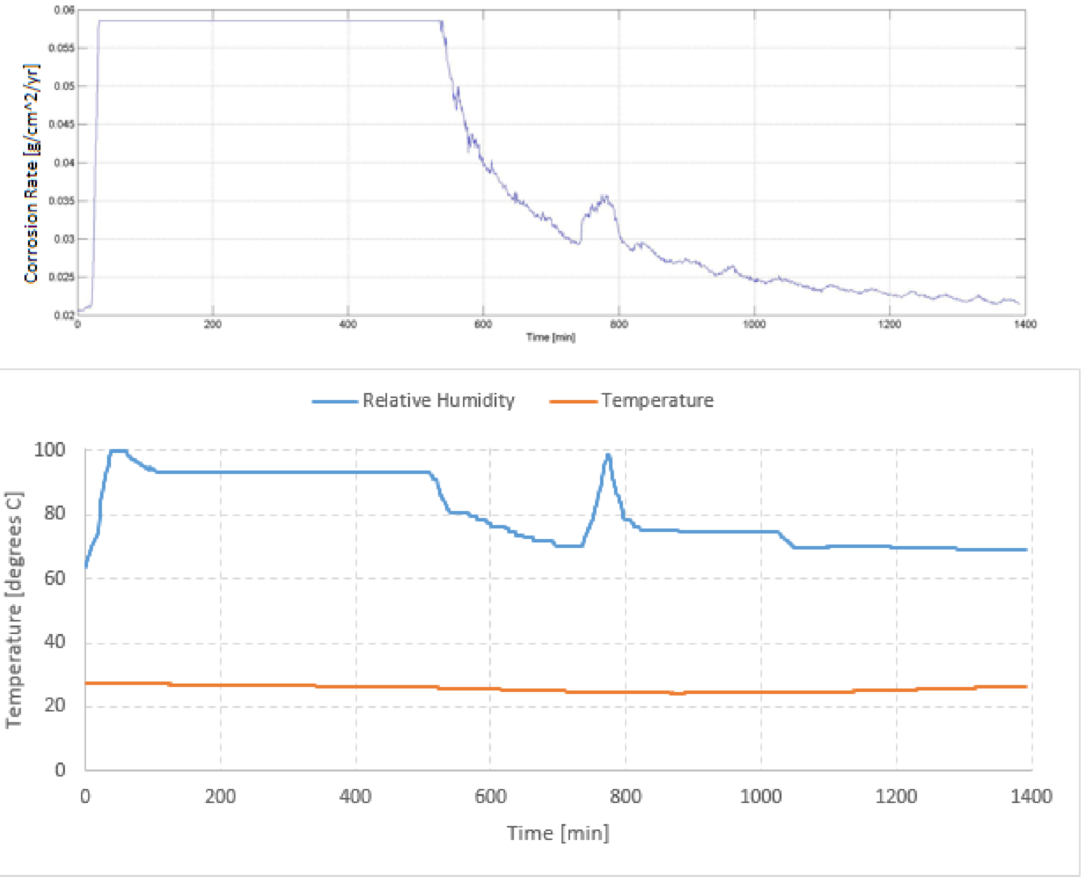

Figure 4-11: Test 3, corrosion rate and realtive humidity through third 24-hour testing period

The relative humidity throughout Test 3 stabilized at much higher levels than the two previous tests, leading to much higher corrosion rates for longer periods of time. Additionally, corrosion rates were nearly 10 times as large as the two previous tests. All three tests were performed consecutively, with 12 hour breaks between them. A combination of the humidification process and repeated testing led to humid air condensing and remaining in the chamber, a scenario also experienced by Betti in other corrosion studies (Betti, 2013). The corrosion sensor nonetheless responded to changing levels of relative humidity. The first cycle of humid air can be seen in greater detail in Figure 4-12 below.

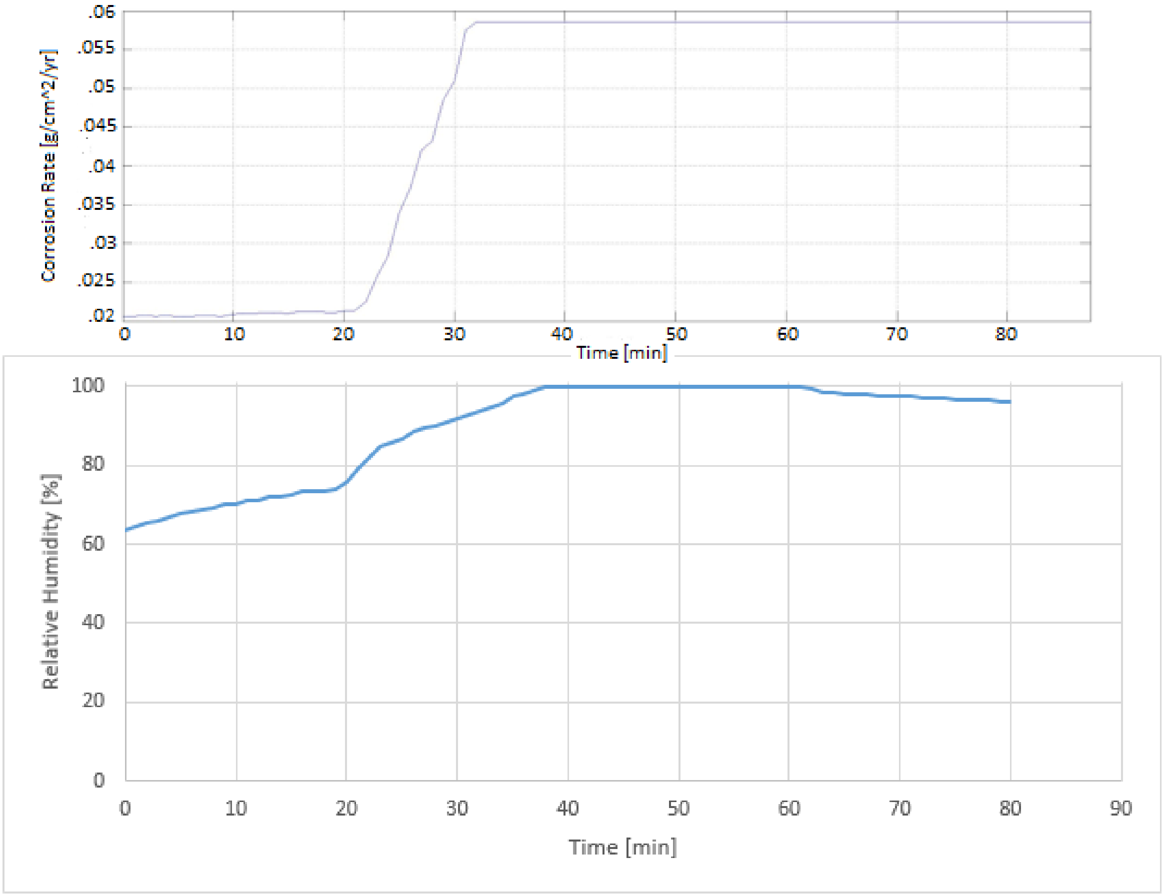

Figure 4-12: Test 3, corrosion rate and relative humidity during first cycle of humid air

Relative humidity increased from 64% at the beginning of testing to 100% at 38 minutes. During this period, the corrosion rate went from 0.02 g/cm^2/year to 0.057 g/cm^2/year. However, the corrosion rate only began increase as relative humidity reached 80% or greater. The corrosion rate remained at 0.057 g/cm^2/year from 38 minutes until 515 minutes, during which relative humidity remained stable between 90% and 100%. From 515 minutes to 733 minutes, relative humidity declined to 70%. The corrosion rate fell to 0.03 g/cm^2/year during this period. The second cycle of humid air began entering the chamber at 733 minutes. The second cycle can be seen in more detail in Figure 4-13 below.

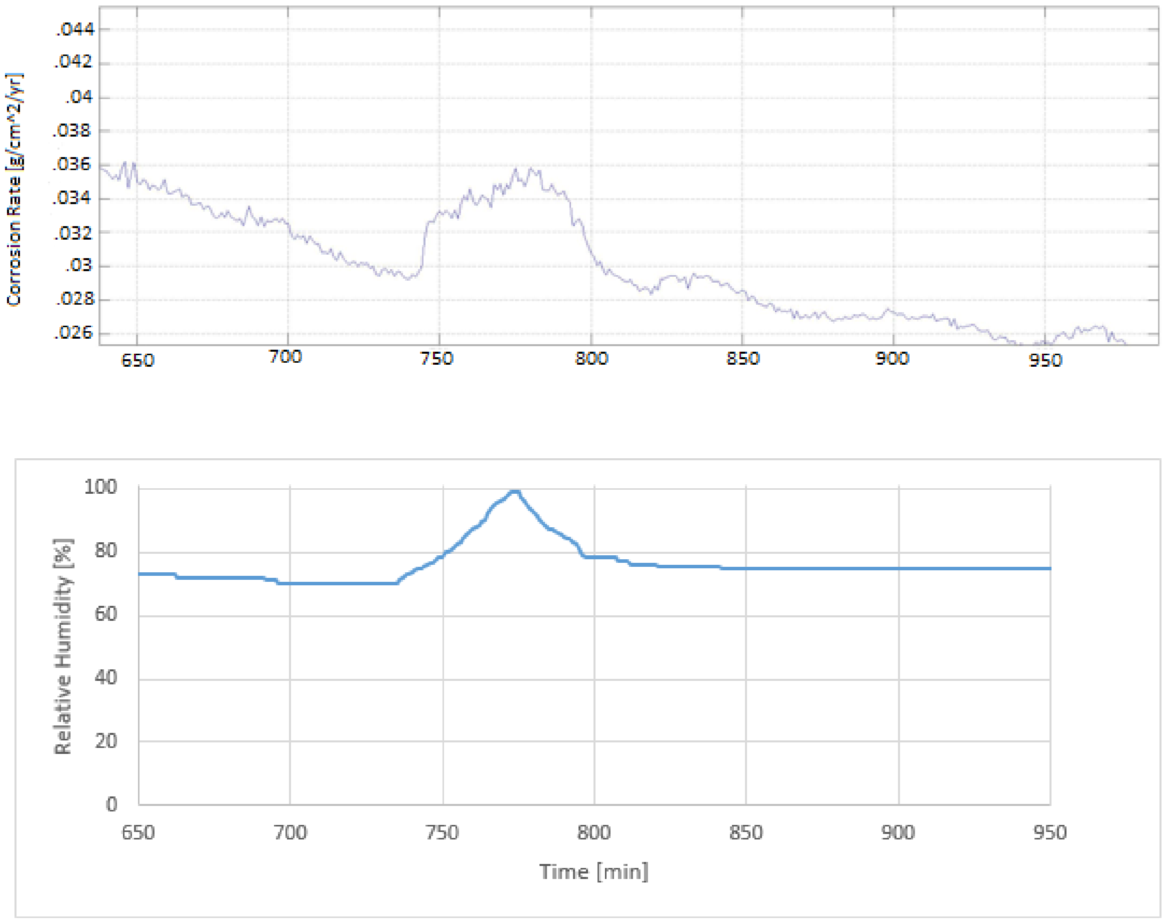

Figure 4-13: Test 3, corrosion rate and relative humidity during second cycle of humid air

Humidity rose from 72% to 99% between 733 minutes and 733 minutes. The corrosion rate increased at a greater rate between 60% and 80% relative humidity than between 80% and 99% relative humidity. At 733 minutes, the corrosion rate peaked at 0.036 g/cm^2/year and the relative humidity was 99%. The relative humidity declined at a near constant rate before stabilizing at 75% at 820 minutes. The corrosion rate declined with the relative humidity, and continued to decline at a lesser rate while the humidity remained stabilized at 75% between 820 minutes and 1024 minutes. Relative humidity fell to 70% at approximately 1050 minutes and remained stabilized until the end of the testing period. The corrosion rate continued to fall at a small rate, falling from 0.028 g/cm^2/year to 0.026 g/cm^2/year during this period.

Figure 4-14 below shows the relationship between relative humidity and corrosion during the second cycle of humid air in Test 2. Corrosion rates remain at 0 until relative humidity approaches approximately 60%. Corrosion rate increased at a higher rate from 60% to 80% relative humidity than from 80% to 100%. This relationship matches closely with the relationship shown by Vernon that is seen in Figure 3-1.

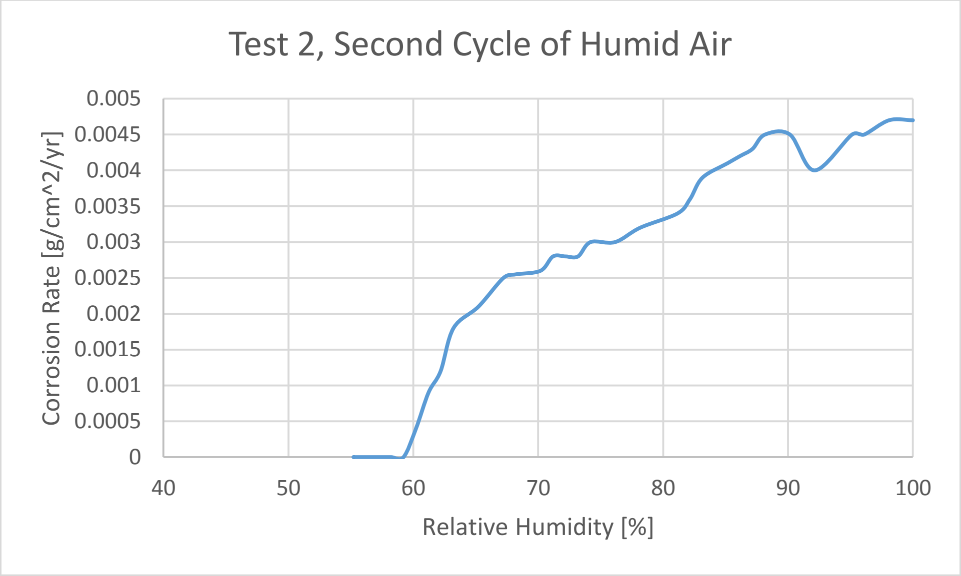

Figure 4-14: Relationship between relative humidity and corrosion during the second cycle of humid air in Test 2

Chapter 5: Conclusions and Recommendations

5.1 Summary of Anthony Wayne Bridge Main Cable Rehabilitation

In 2008, a physical condition report was issued by Burgess and Niple, Inc. detailing a variety of structural issues with the AWB. This report led to the beginning of a rehabilitation of the bridge. Among the issues were clear deficiencies in the elastomeric wrap protecting the main cables. This prompted the installation of an acoustic monitoring system by Mistras, Inc. in 2011. Though no wire breaks were detected, the system was used to detect corrosion along different lengths of the cables. This data was used in the selection process for panel openings for NCHRP 534 internal inspections performed by Modjeski and Masters.

The NCHRP 534 inspection report rated the condition of the cables as fair to poor. 80% of all wires inspected were reported to be in Stage 3 or Stage 4 corrosion. Among Modjeski and Masters' recommendations were installing a new lightweight deck, performing more internal inspections, and exploring the idea of a dehumidification system. The bridge operators were reluctant to open up more panels on the cable, as locations previously opened, showed the most significant levels of corrosion. Instead, they elected to move forward with a dehumidification system to slow the projected degradation of the steel wires. Preliminary discussion indicates that AECOM will begin construction on the system in 2018.

A dehumidification system requires active monitoring to ensure it is operating properly and is effective. Typical monitoring includes airflow and relative humidity measurements at the injection and exhaust points. The existing sensor highway on the bridge offers an opportunity to utilize additional monitoring techniques to fully evaluate the state of the bridge cable's interior. The AN110 LPR corrosion sensor monitors corrosion in real-time and could potentially provide valuable information during the drying-out process.

5.2 Experimental Results

This report documents static and cyclic testing performed on the LPR sensor. The tests consistently showed a clear relationship between increased relative humidity and increased corrosion rate. In all tests, the corrosion rate drops to zero or near-zero as relative humidity moves below 60%. The corrosion rate tended to increase at a relatively larger rate as relative humidity increased from 60% to 80%. This is in accordance with the relationship first documented by Vernon that is shown in Figure 3-1.

The peak corrosion rate of the second cycle was smaller than the peak corrosion rate of the first cycle in all testing periods. Additionally, in periods where relative humidity stabilized, it sometimes took several hours for the recorded corrosion rate to also stabilize. This is best seen after the second cycle of humid air in Test 2 and Test 3, in Figures 4-8 and 4-11, respectively. This seems indicative that long-term trends in the corrosion rate recorded by the monitor are more accurate than instantaneous readings in a changing environment. This is further illustrated by occasional spikes in the corrosion rate as humid air enters the chamber, as seen at the beginning of Test 2. Additional long-term testing to investigate this phenomenon would be beneficial.

Test 3 showed recorded corrosion rates nearly 10 times higher than Test 1 and Test 2. After the test was completed, it was clear that water had condensed and accumulated within the chamber after five consecutive days of cyclic testing. However, the qualitative relationship between the corrosion rate and changing relative humidity remained the same. The build-up of condensation is not dissimilar to the actual environment a corrosion sensor could experience within a cable. The outer layers of wire in the cross-section of a cable are subjected to large changes in temperature that can allow water to condense on them. Additionally, the outer wires are the first to be subjected to water leaking through breaks in the protective layers. The results of Test 3 show that the corrosion sensor may maintain a qualitative relationship with increasing relative humidity while experiencing harsher environments.

5.3 Recommendation of Application to Anthony Wayne Bridge

This research shows the implementation of the Analatom AN110 corrosion sensor on the AWB may be potentially advantageous for several reasons:

- The tests conducted indicate that the sensor is capable of consistently recording qualitative changes in corrosion due to a changing environment. Observing declining trends in corrosion rates would help to ensure that the dehumidification process is proceeding as expected.

- The sensor is compatible with a data acquisition for acoustic monitoring on the bridge and could be incorporated in the monitoring system with relative ease. Also, the installation of a new external wrapping system on the cable provides an excellent opportunity to install internal sensors before the cable is sealed again.
- Standard instrumentation for a dehumidification system measures the humidity and airflow at injection and exhaust points. Bridges such as the Bay Bridge continued to utilize acoustic monitoring to monitor future wires breaks. However, the internal conditions of a cable are still being investigated, notably by Betti. Intermediate sensors between injection points would help to insure that dry air is fully penetrating all points of the cable. Dirt and other obstructions can potentially block airflow in localized locations within the cross-section. Additionally, the parallel wire strands in the AWB have been shown to impede airflow much more than helical strands. Monitoring corrosion rates at intermediate points on the cable would assist in identifying critical areas and, if needed, the requirements to adjust the airflow of the dehumidification system. There was limited inspection done upon the entire length of cable and additional intermediate sensors would provide data on potentially critical areas.

Drawbacks of the sensor include

- The need to for small holes to puncture the newly installed cable sealing system so that cables can run to the proper data acquisition boxes.
- the lifespan of the sensors is relatively short, lasting approximately five to ten years.

The estimated total cost of installing the corrosion sensors on the AWB is approximately $28,000. This is broken down below in Table 5-1. This includes two data acquisition nodes for each side of the bridge, multiple corrosion sensors, and multiple relative humidity sensors. Additionally, this includes the installation fee of Mistras and additional extension cable for the sensors. The cable was estimated to cost $2 per foot.

As dehumidification becomes increasingly applied to bridges across the United States, the Anthony Wayne Bridge will be looked at as an example of its feasibility, construction, and application. The innovate use of real-time corrosion monitoring rates could prove to aid not only ODOT, but also bridge operators rehabilitating bridges across the country.

Table 5-1: Estimated cost of corrosion sensors on AWB

Item	Description	Unit Price	Quantity	Total Price
		($)		($)
1	AN110 node	6,329	2	12658
2	LPR sensors	215	16	3440
3	Relative humidity and temperature sensor	248	8	1984
4	Cable (sensor highway)	2	2000	4000
5	Software	1000	1	1000
6	Mistras installation	5000	1	5000
			Sum:	28082

The initial testing shows the functionality of the sensor. The user interface is clear and easy to work with. If additional instrumentation is desired, the Analatom AN110 corrosion sensor can provide information on the internal state of the cables without the need for further destructive testing.

5.4 Future Research

Though initial results show the corrosion sensor can qualitatively record changes in corrosion rate due to varying relative humidity, there are more areas that can be explored. The environmental chamber was designed to have the ability to manipulate temperatures. Testing of the sensor in changing temperatures would further validate existing research into the atmospheric corrosion of steel and confirm its ability to maintain accurate readings in the changing conditions on the AWB. The chamber can currently reach temperatures at the upper extreme of what the cables on the Anthony Wayne Bridge experience. Current work shows the potential of the inexpensive Peltier cooling cell, though it cannot reach the lower extreme of temperature where corrosion can still occur. Refining the environmental chamber and exposing the corrosion sensor to cyclic temperatures would further test its capabilities.

One concern lies with the performance of the sensor in freezing conditions. If condensation were to freeze on the sensor and remain frozen through winter, performance could be affected in the short-term and in the long-term. An environmental chamber that can replicate the lower extreme of temperatures on the bridge would allow for the durability of the sensor to tested. This would help ensure that ODOT's additional investment in the corrosion sensor system would last the entire projected lifespan of the AN110 sensor.

Existing tests show that the corrosion rate recorded often fluctuated greatly as humid air entered the chamber. The corrosion rate also took several hours to fully stabilize as relative humidity dropped and stabilized. More long-term testing to observe the sensitivity of the sensor would be beneficial. Testing with more frequent humid air cycles would provide insight into the sensitivity. Refining the environmental chamber to allow more controlled, smaller steps in relative humidity would allow observations of how the corrosion rate changes with less direct humid air entering the chamber.

The quantitative results of the testing are most beneficial when compared with each other. However, expected and existing corrosion rates on the AWB are not known. Long-term monitoring of the cables would provide a baseline for expected corrosion before and after dehumidification. Corrosion rate is given in terms of mass of steel lost. By converting the LPR corrosion rate into thickness lost in the steel wire, strength projections could be made based on future cross-sectional loss. These projections could be used to predict the factor of safety in the future. This factor of safety could be compared with previous estimations to more accurately measure the safety of the bridge as it continues to age.

The AWB currently has an acoustic monitoring system installed. Past research at the University of Toledo studied the uses of these acoustic monitors in measuring corrosion. Future research monitoring corrosion with both the AN110 corrosion sensor and the acoustic sensors could further increase understanding of both technologies. Further, this combination of these sensors could allow a comprehensive monitoring system of the entire internal conditions of the cable. Corrosion sensors are localized, while acoustic sensors can monitor intervals of along the cable length. Together, these sensors could provide insight into the conditions inside the cable.

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