OKLAHOMA TRANSPORTATION CENTER

PASSIVE, WIRELESS CORROSION SENSORS FOR TRANSPORTATION INFRASTRUCTURE

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16. ABSTRACT
Many industrial segments including utilities, manufacturing, government and infrastructure have an urgent need for a means to detect corrosion before significant damage occurs. Transportation infrastructure, such as bridges and roads, rely on reinforced and prestressed concrete for structural reliability but corrosion of the reinforcing steel in structural concrete can significantly lower the structural capacity. This proposal aims to develop an inexpensive wireless corrosion sensor that does not require any external power supply. Such a sensor would be very useful tool in evaluating the structural health of the nation's infrastructure and in turn make our highway travel safer. These sensors will be based on radio-frequency identification (RFID) tags that are used to track consumer goods and are extremely low-cost. The ubiquity of RFID tags in the consumer market allows for the use of proven, off-the-shelf technology and translates into a lower per unit deployment cost. These sensors would be situated on the steel rebar either directly on the metal or over the epoxy coating. They could be fixed to the rebar in the field using a plastic ring that snaps onto the rebar or supplied pre-affixed to the rebar using an adhesive such as epoxy glue. Alternatively, they could be placed at different depths in the structure allowing the monitoring of the diffusion or seepage of corrosive salts into the concrete and provide early detection of potential structural problems. The location and degree of corrosion may be used to intelligently schedule maintenance to optimize resources or to modify the current uses of the structure to prolong the life. The development of such a sensor will allow the engineers to employ "best maintenance practices" that are estimated to save 46 percent of the annual corrosion cost of a black steel rebar bridge deck, or $2,000 per bridge per year.

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Wireless communication systems, Wireless sensor networks, Sensors, Corrosion, Prestressed concrete, Radio frequency identification, Bridge decks, Reinforcing bars

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units				
Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units				
Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

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Passive, Wireless Corrosion Sensors for Transportation Infrastructure

Final Report

July 31, 2011

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Executive Summary

Early detection of corrosion of steel reinforcement in concrete, through the use of sensors, can help to preserve structural integrity and reduce the risk of substantial section loss or fatigue failure that is initiated by corrosion damage. Currently, it is not feasible to locate corrosion on reinforcing steel until corrosion has already developed and caused cracking of the surrounding concrete from the rust products. Once surface cracking of the concrete has occurred, an investigation into the deterioration is time-consuming and destructive to the element as cores are taken to investigate the surface of the reinforcing steel. This work requires lane closures, causes traffic delays, and involves elevated safety risks for maintenance crews and the traveling public. Thus, wireless monitoring will increase the safety of the workers and reduce delays, as well as provide the owner with crucial information about the health of the structure. This information may be used to intelligently schedule maintenance to optimize resources or to modify the current uses of the structure to prolong its life.

This research project met the objective to develop and validate of extremely inexpensive passive wireless corrosion sensors. These sensors are based on passive radio-frequency identification (RFID) tags that are used to track consumer goods and are extremely low-cost. Once embedded in a structure, a technician will be able to detect areas of corrosion through the change characteristic identification number from the RFID tag by waving a wand-type RFID tag reader in the vicinity of the tag. Alternatively, a transceiver could be mounted on a vehicle and the tags read as the vehicle drives across the bridge or road at highway speeds.

Corrosion can be a slow and random process. Thus, the testing methodology must provide an answer in a reasonable amount of time and accurately represent the actual performance of the sensors in the field. The triggering mechanism was initially investigated by measuring the corrosion rates of iron wires of various thicknesses in a 5% sodium chloride solution using a newly designed and manufactured automatic corrosion testing apparatus. Subsequently, tests of the sensor triggering mechanism were performed in actual concrete. In these samples, several sacrificial wires were embedded using a custom holder. At the time of triggering, the chloride content of the concrete near the surface of the sensor was quantified. This data allowed us to correlate the triggering in the prototype sensor and the chloride content of the powder near the surface of the sensor. This allowed an accelerated corrosion testing protocol to be used below to verify the validity of the sensors.

Low-frequency 125 KHz RFID tags were determined to be the best fit for our application. Early on reliability issues were encountered with sensors constructed using commercial RFID integrated circuits or chips. To avoid these issues, an emulated common RFID chips using low-voltage, ultra-low power microcontrollers was used. The footprint or size of the final systems was similar to that of commercial RFID devices. Feedback from contacts with possible customers and investors indicated that it is highly desirable to have the sensor always responds when they are queried. In addition, the threshold or degree of corrosion required to trigger the sensor can be controlled using an internal voltage reference on the microcontroller or wires of different thickness. With this new design, we avoided difficulties found in current RFID circuits and added useful features into the design.

Upon completion of the design, approximately thirty sensors were constructed for testing. To ensure the reliability, environmental and material tests were conducted. The sensors were exposed to approximately 80 cycles of temperature changes from 23^{o}C to 80^{o}C and from 23^{o}C to -20^{o}C. Failures in the hardware were found and the sensor design was improved. The impact of the sensors on the mechanical properties of concrete was also investigated. To investigate the impact, the sensors were placed at the center and top of a concrete cylinder and tested. In addition concrete beams were cast with the sensors near the bottom fiber. In all of these tests the strength impact was found to be less than 10%. This is significant as these sensors were placed in the most critical areas within these members and tested. This is a big success for the sensors. The technology is now mature enough to be used in actual structures.

In conclusion, prototype wireless passive corrosion sensors have been developed and tested. These sensors will find their way into actual structures in the immediate future. The results obtained from this product were critical to provide the chemistry and engineering required to take our corrosion sensors from an idea to a working and verified prototype.

Introduction

Problem

Many industrial segments including transportation, utilities, manufacturing, government, and infrastructure have an urgent need for a means to detect corrosion before significant damage occurs. According to one study, the annual cost of corrosion among five key industrial segments in the United States exceeds $279 billion per year.[2] For the target market, bridges and overpasses, the annual direct cost of corrosion is estimated to be $8.3 billion, consisting of $3.8 billion to replace structurally deficient bridges over the next ten years, $2 billion for maintenance and cost of capital for concrete bridge decks, $2 billion for maintenance and cost of capital for concrete substructures, and $0.5 billion for maintenance painting of steel bridges.[3] The estimated indirect costs to the user due to traffic delays and lost productivity is more than ten times the direct cost of corrosion maintenance, repair, and rehabilitation. According to a 1997 report, of 581,862 bridges in the U.S.A. about 101,518 bridges or 17% were rated as structurally deficient.[3] While the majority of these bridges were not in danger of collapse, they were likely to be load posted so that overweight trucks are required to take longer alternative routes. Corrosion of the reinforcing steel in these bridges is a major contributor to these structural deficiencies.[3] A complicating factor with this corrosion is the extreme difficulty of its detection because the steel rebar is embedded within the concrete. The lack of viable low-cost non-powered corrosion sensors is a hindrance to effective scheduling of maintenance to optimize resources or to modify the current uses of the structure to prolong their service life. Therefore, the advent of a new non-powered, inexpensive wireless corrosion sensor could tremendously reduce these expenses and make our highways safer.

Early detection of corrosion of steel reinforcement in concrete, through the use of sensors, can help to preserve structural integrity and reduce the risk of fatigue failure that is initiated by corrosion damage. If corrosion persists, the increase in volume as steel is converted to rust causes concrete to crack and eventually spall, posing danger to passing cars and exposing the rebar to further corrosion. Finding corrosion before spalling occurs generally involves time-consuming activities in which the decks are actually cut open by chaining or coring. Due to the lack of a viable sensor, this activity typically occurs after a problem has been found and work requires lane closures, causes traffic delays, and involves elevated safety risks for maintenance crews and road users. In addition to increased safety, a viable method for the remote sensing of corrosion can assist in determining corrosion mitigation schedules by focusing costly labor-intensive inspection and repairs where they are most required. Importantly, a simple low-cost binary sensor that can be easily and economically placed at many locations within the concrete has greater utility over more expensive sensor designs that report the degree of corrosion from a limited area.

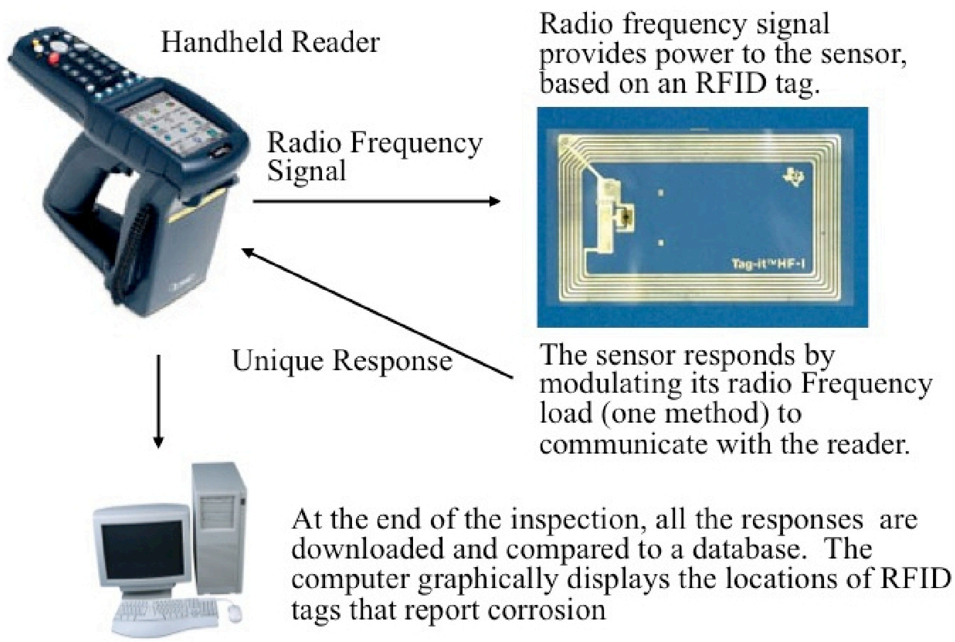

Figure 1: Graphical illustration of our approach for early corrosion detection.

Background and Proposed Technology

Figure 1 illustrates the proposed solution for the early detection of corrosion. The enabling technology is the use of passive non-powered radio-frequency identification (RFID) tags that have been modified to respond to corrosion. Since the sensors are based on passive radio frequency identification (RFID) tags that are used for theft prevention of consumer goods, there is a significant cost advance of this design. In this system, each sensor has a unique identification number allowing additional recordkeeping. In addition, standardized communication protocols and the available inventory tracking software significantly lower the information-technology cost of our proposed sensors. This ubiquity allows for the use of proven, off-the-shelf technology and translates into a lower per unit deployment cost. The use of available low-cost RFID readers significantly impacts the total cost of the system.

For reinforced concrete applications, these sensors would be situated on the steel rebar either directly on the metal or over its epoxy coating. They can also be fixed to the rebar with plastic rings. To monitor the diffusion or seepage of corrosive salts into the concrete and to provide early detection of potential structural problems, the sensor could also be placed at different depths within the structure. A technician would be able to detect areas of corrosion, by the loss of the characteristic signal from the RFID tag, by waving a wand-type RFID reader in the vicinity of the tag. Alternatively, a transceiver could be mounted on a vehicle and the tags read as it drives across a bridge or other concrete structures. While there are alternative sensors for detection of corrosion in reinforced concrete bridges, none of them has the simplicity, low cost, and lack of need for external power or wiring as our proposed solution. The lack of a power source is significant. It allows the sensor to be directly imbedded in the concrete structures without extra infrastructure and worries about failures due a finite to battery life.

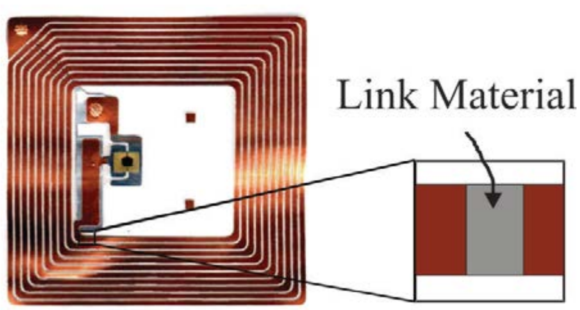

Figure 2a: Modified 13.6 MHz RFID tag for corrosion sensing with no corrosion detected.

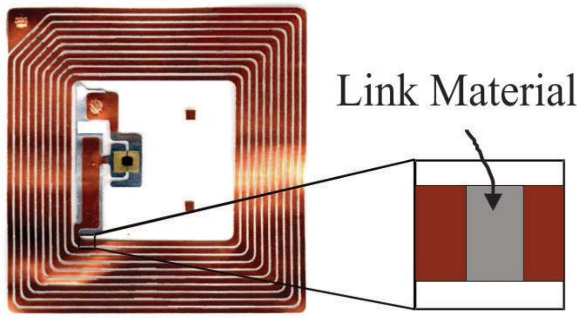

Figure 2b: A modified 13.6 MHz RFID tag for corrosion sensing after exposure to a corrosive environment.

Prior to the submission of this proposal, the PIs had developed a simple proof-of-concept by turning a commercial RFID tags into a corrosion sensor by replacing part of the connection conductor with a strip of corrosion-sensitive metal (Figure 2a). The creative aspect of this design is the corrosive link and the chemistry employed to enable it to reliably and passively integrate the corrosive events. Corrosion of this strip (Figure 2b) by direct exposure to a corrosive environment will prevent the device from absorbing the RFID reader's radio frequency radiation causing the sensor to not respond to the RFID reader. Thus, in this simplest design, the RFID reader will respond only if corrosion is not present. In a sense, these proof-of-concept sensors are analogous to the "check-engine" light in modern automobiles, saving time and money by eliminating unnecessary inspections. The seriousness of a triggering event will then be confirmed by a field inspection. Depending on the design of the link, the sensor will indicate a range of corrosion, from "inspection is warranted" to "inspect immediately" to "imminent system failure."

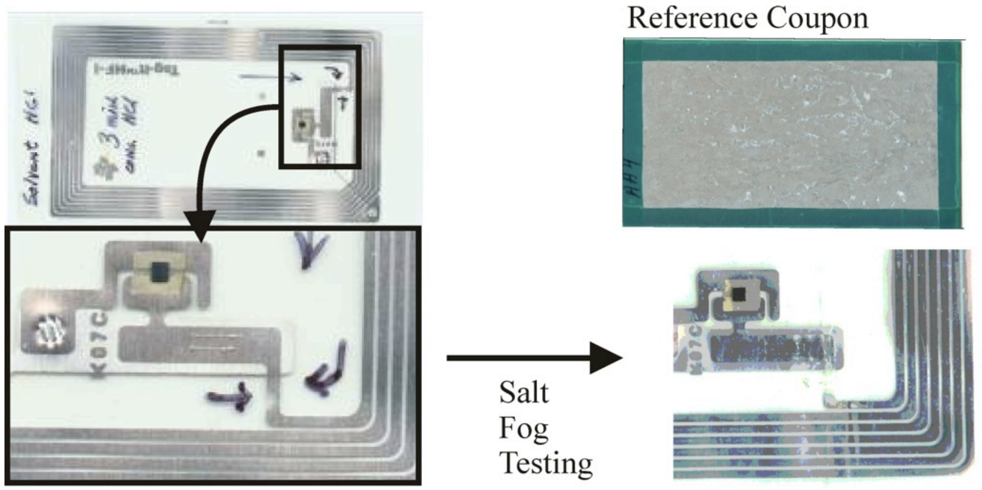

Figure 3: A physically modified RFID tag before and after 3 days of salt fog testing. An aluminum reference coupon after salt fog testing to judge the degree of corrosion.

The researchers have had much success in creating passive corrosion sensors based on this simple idea. The images on the left of Figure 3 show a top view of this type of sensor and a blowup of the thinned link. The right top of Figure 3 is an aluminum reference coupon after three days of salt fog testing that clearly displays the effect of corrosion due to the salt fog exposure. Below the coupon, the image shows a sensor that has triggered at this degree of corrosion.

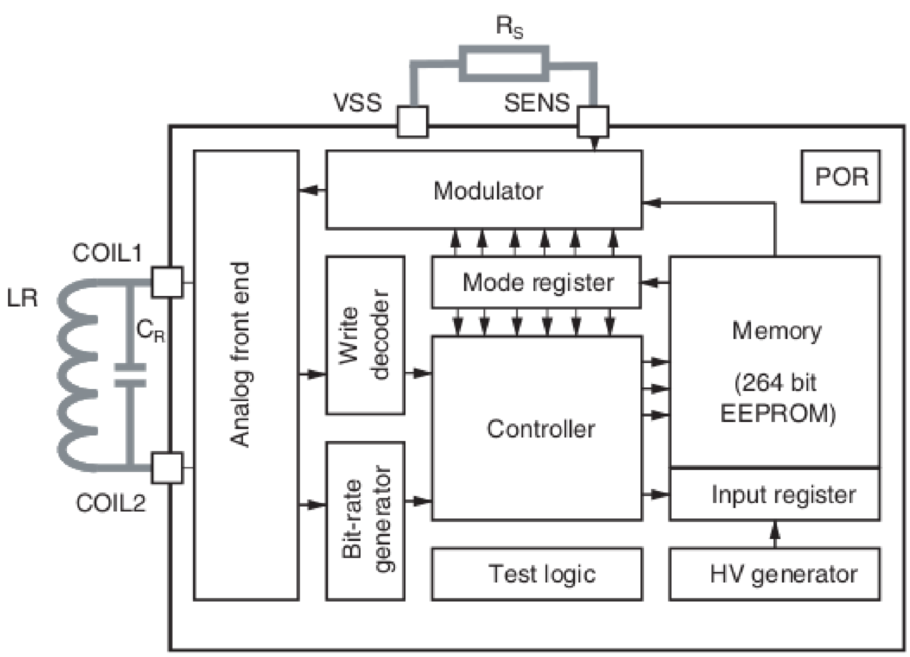

Figure 4a: Block diagram of the ATA5570 device.

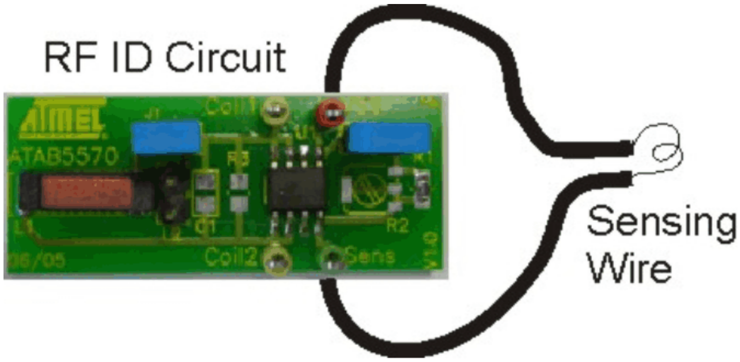

Figure 4b: Simple diagram for a prototype RFID corrosion sensor.

Even though the prior work has been extremely successful, the cost of a false positive is very high and must be avoided. Relying only on commercial technology, one could use a dual RFID tag combination in which one tag is modified into a corrosion sensor while the other provides the identification response. In this manner, it is extremely likely that corrosion has occurred if the sensor tag goes silent while the identification tag remains responsive. Alternatively, one could utilize a novel commercially available RFID chip that has an external circuit that has the ability to change or invert the unique code sent in the tag's response if corrosion is present. Initially, we proposed the use of an Atmel ATA5570 RFID tag or equivalent that has a switchable sensor resistor (Figure 4). Until it was discontinued, the Microchip's MCRF202 RFID integrated device was another option. Notably, this device has previously been used in other types of commercial sensors. For both devices, the data stream containing the unique RFID number is inverted based on the state of an external circuit. The ATA5570 device inverts its data stream when the resistance of the external circuit (labeled R_s in Figure 4a) is greater than 100 kΩ. Thus, placement of a corrosion sensor wire in the external circuit will create a sensor that will change its response to the tag reader when corrosion is present rather than just simply turning off.

However, there are a number of clear drawbacks associated with reliance on commercial RFID technology. There are several reasons that, despite all the advantages of RFID-based transponders, this technology has not yet made a significant impact on sensor design. Current RFID devices for sensor applications have major limitations, the most important of which are restrictions on what data can be returned to the reader and the reliability of the datastream. For commercial RFID devices mentioned above, the datastream containing the unique RFID number is inverted based on the state of an external circuit. We have identified major issues with the ability of commercial readers to reliably respond to the inverted data stream. This may be one of the possible reasons that sensors based on these devices (e.g. Smart Pebbles™, developed and commercialized by SRI International) have not been successful. Indeed, examining Atmel's RFID product line, transponder support chips designed to interface with low-power microcontrollers and other devices with RFID circuitry have not been successful and have planned obsolescence without replacement. In addition, the reliability of the data stream is of utmost importance. Depending on the application, proper inclusion of error checking and correcting bits in to the data stream is critical to establish reliability at different reading speed and distances. A significant component of this project is the development custom RFID circuitry to overcome these disadvantages.

Corrosion Sensing Technology

As discussed above, transportation infrastructure, such as bridges and roads, rely on reinforced and prestressed concrete for structural reliability, but corrosion of the reinforcing steel in structural concrete can significantly lower the structural capacity and can seriously degrade the roadway surface through spalling of the concrete. The steel sections of bridges are also prone to corrosion and would benefit from the use of a sensor, as reviewed by Song *et al.*[4] and Martinez *et al.*[5]. Many of these sensors are based on fiber optics, electrochemical measurement, segregate corrosion and many other techniques.[6-37] Unfortunately, the widespread use of many of these sensors is hindered due to the expense of the associated electronics and the clumsiness of the probe and associated wiring. For example, complex wiring is required for many modern sensors that utilize voltage drops across multiple electrodes to detect and localize the corrosion. Several wireless, but powered, corrosion sensors have now been developed and successfully deployed in the field. In many applications, replacing a battery is unfeasible. A good example is a sensor used by the Naval Air Warfare Center for monitoring of corrosion in aircraft.[38] Another example is the wireless corrosion sensor developed for concrete bridges by Carkhuff *et al.* at Johns Hopkins University's Applied Physics Laboratory.[39] This sensor is powered through induction and transmits the conductivity and the temperature of the concrete. However, a corrosion sensor must integrate corrosion events even while unpowered. Fiber optics based corrosion sensors have also been investigated. Such systems are based on either metal dissolution from the fiber, deposition onto the fiber or detection of corrosion products.[40-42] Although these systems require no power and integrate corrosion events, the requirement of laying delicate fiber cables and the difficulty of coupling light into and out of the sensor may prevent routine use. In addition, damage to the cable may inaccurately reflect a corrosion event.

Powered RFID tags that can transfer data and can also be used as sensors are commercially available. As noted above and discussed further below, for our specific applications, the requirement for a power source has prevented the widespread use of corrosion sensors. Based on our patent searches and a review of current availability of commercial sensors, the use of unpowered RFID technology to query sensors is unique. The complexity of coupling a transducer with sufficiently low power has been a major hindrance for RFID sensor development. Nevertheless, there are two passive wireless sensors for corrosion detection in concrete that are similar in application to our sensor. At the University of Texas, Austin, Dean Neikirk and co-workers have developed an unpowered binary sensor based on a radio frequency resonance phenomenon.[6-7, 11-12] However, we have found no evidence that this technology has been transferred from the laboratory to a commercialized sensor, possibly due to the difficulty of measuring the frequency response of a device whose quality factor in the resonance circuit changes with corrosion. The other sensor is Smart Pebbles,™ developed and commercialized by SRI International. These sensors are unique in that they utilize passive wireless RFID technology to measure chloride concentration in bridge decks, which can, for concrete members, be correlated with potential corrosion of the reinforcing rebar. Smart Pebbles™ relies on Microchip's MCRF202 RFID integrated device leading to problems, as discussed above, with many commercial tag readers.

Objectives and Scope

In this research project inexpensive passive wireless corrosion sensors were developed and validated. These were based on passive radio-frequency identification (RFID) tags that are used to track consumer goods and are extremely low-cost. As discussed above, the basic idea is that a technician will be able to detect areas of corrosion through a change in a unique identification number returned from the RFID tag by waving a wand-type RFID tag reader in the vicinity of the tag. Alternatively, a transceiver could be mounted on a vehicle and the tags read as the vehicle drives across the bridge or road at highway speeds. This information can be used to intelligently schedule maintenance to optimize resources or to modify the current uses of the structure to prolong its life. We hope that engineers will utilize our sensors to employ "best maintenance practices", minimize and control maintenance cost and ensure the safety of the public.

Accomplishments

There are three main components of this work. The first four sections discuss the development of the testing methodology and verification of the basic concept. The next two sections report on the corrosion sensor development and construction. The final two sections discuss the environmental and structural evaluation and the final testing being performed.

Establishment of Correlation between Wire Thickness and Degree of Corrosion

The correlation between the time to triggering of the wire and the extent of corrosion of a structural element is important information that allows the manufacture of sensors with varying indications of corrosion from “this is an area of concern” to “failure is imminent” for the two target applications. For materials utilized to manufacture rebar and pipelines (principally iron and steel alloys), the corrosion of 1-in^2 metal coupons were utilized. Figure 5 shows the mass loss with respect to time for 1-in^2 coupons of mild steel placed in 5% sodium chloride solution. The insert shows the metal coupon after about 60 hours of exposure, illustrating the degree of corrosion following exposure to 5% NaCl. The corrosion rates obtained in a similar fashion for aluminum, rebar data and mild steel are also shown in Figure 5.

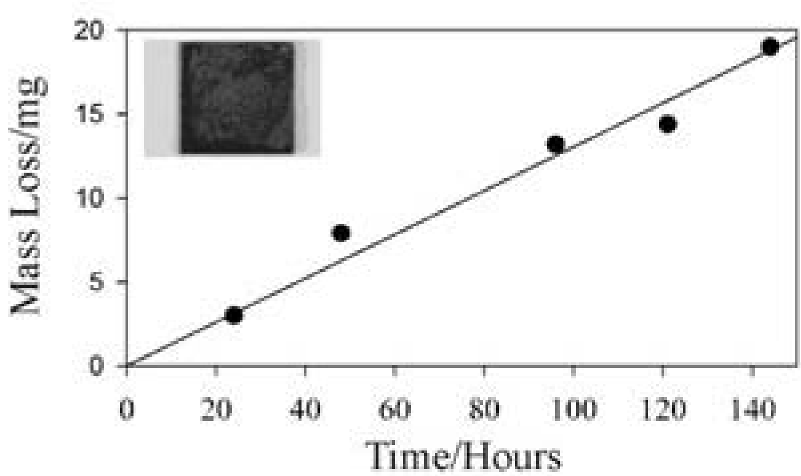

Figure 5: Weight lost vs. time for mild steel in a 5% sodium chloride solution.

Table 1: Baseline corrosion studies on various materials in a 5% sodium chloride solution. The slope is the weight loss per hour for a 1 in^2coupon.

Material	Slope (g/hr)
Aluminum 2024	$(4.4 \pm 0.09) \times 10^{-5}$
Aluminum 6061	$(1.3 \pm 0.1) \times 10^{-5}$
Aluminum 7075	$(4.5 \pm 0 .2) \times 10^{-5}$
Rebar	$(1.7 \pm 0.06) \times 10^{-4}$
Mild steel	$(1.3 \pm 0.09) \times 10^{-4}$

The correlation between the time to triggering of the wire and the extent of corrosion of a structural element is important information that allows the manufacture of sensors with varying indications of corrosion from “this is an area of concern” to “failure is imminent” for the two target applications. For materials utilized to manufacture rebar and pipelines (principally iron and steel alloys), the corrosion of 1-in^2 metal coupons were utilized. Figure 5 shows the mass loss with respect to time for 1-in^2 coupons of mild steel placed in 5% sodium chloride solution. The insert shows the metal coupon after about 60 hours of exposure, illustrating the degree of corrosion following exposure to 5% NaCl. The corrosion rates obtained in a similar fashion for aluminum, rebar data and mild steel are also shown in Figure 5.

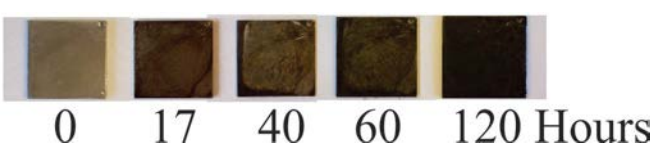

Figure 6a: Corrosion in a 5% NaCl solution with Corrosion as a function of time for 1-in^2 mild steel coupons.

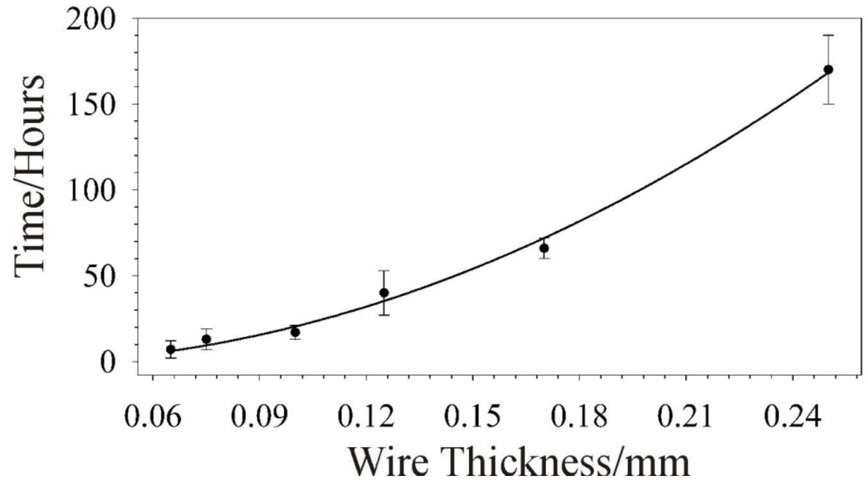

Figure 6b: Plot of the trigger time in hours verses the diameter of the iron wire in mm.

Our trigger mechanism is based on a thin wire that is expected to corrode similarly to the structural element. In general, high-quality corrosion measurements for thin wires are difficult to obtain due to the time-scale and mechanical issues with the measurement. We have developed an automatic system to test our triggering mechanism based on a microcontroller manufactured by Microchip Technology. In addition to the electronics, this system involves a specialized wire holder to hold the triggering wire without inducing undue stress, a phenomenon that proved to be major problem. Figure 6 shows the results for pure iron wires. The failure time can be correlated with the mass loss data to set the triggering point of our sensors.

Sodium Chloride Concentration Profiles in Concrete

There are a large number of accelerated tests that could be used to investigate the performance of the sensors. The ingress of corrosive agents into the concrete is responsible for the corrosion of the rebar and is therefore the best target for testing. It was also necessary to choose a test that would be able to give answers in a reasonable amount of time, but would also represent the actual performance of the sensors in the field. A test of this nature also builds confidence within the Civil Engineering community. Thus, the research team decided to use ASTM C 1556 “Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by

Bulk Diffusion” to accomplish this goal. This test is widely used to investigate the diffusion coefficient of chloride within a concrete mixture. The benefits of the test are that it is standardized and recognized by many as a standard method to expose concrete to chlorides in a very controlled manner. This test was utilized to determine the concentration profiles of chloride in concrete. In this way, the amount of chloride at the sensor at the time it triggered could be quantified.

Figure 7: A powder sample being collected from a concrete sample after being exposed to a sodium chloride solution for a given time.

This test involves filling a plastic container almost full of concrete, with or without rebar, and then coating the sides with impermeable caulk. After this, a sodium chloride solution is used to fill the container, which is than sealed with its lid. The specimen is then placed in a temperature-controlled room and allowed to sit for 35, 70, or 105 days. The container is then removed and the sodium chloride solution is poured off. The sample is allowed to sit out in the lab air for a day so that the surface dries. Next, powder samples are taken from the sample at different depths by drilling into the concrete with a diamond coated drill bit. Figure 7 shows the powered sample being collected at a specific depth within the concrete. After the powder is collected, it was titrated to determine the concentration of chloride ion at the collected depth.

Tests have been completed with concretes prepared using 0.5 and 0.7 water/cement (w/cm) ratios. Powder samples have been collected from specimens that were allowed to pond for 35, 70, and 105 days and are about to be titrated. This information will allow the research team to choose a desirable depth to place the sensors and have an estimate of the chloride content at that depth for the two different concretes. These samples were used to determine the concentration profile of the water-soluble chlorides.

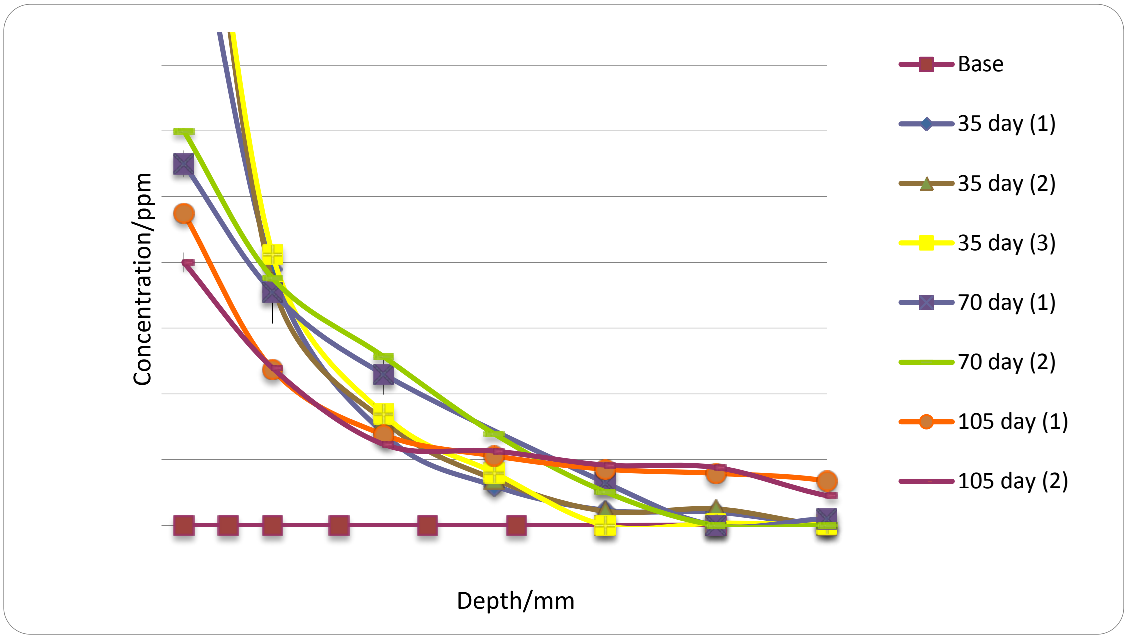

Figure 8: Titration results from powder collected from a concrete sample that was ponded in a 5% NaCl solution for 35, 70 and 105 days.

Figure 8 shows the results of these measurements. The shapes of the diffusion curves are what one expects from this measurement and validate our technique. The longer the time, the further the chloride diffuses into the sample. The data also shows a high degree of reproducibility. These concrete samples are an excellent testing platform for the ingress of corrosive agents and to test the sensor and triggering mechanism.

Evaluation of the Sensor Trigger when Embedded in Concrete

The triggering system was tested using a specialized wire holder to hold the triggering wire in the concrete samples while they are initially being cast. Wires extend outside the specimen and the resistance can be measured. The microcontroller was utilized to monitor the concrete test samples and report the time of failure. After trial and error, the wire holder design evolved to become robust enough to survive being embedded in concrete.

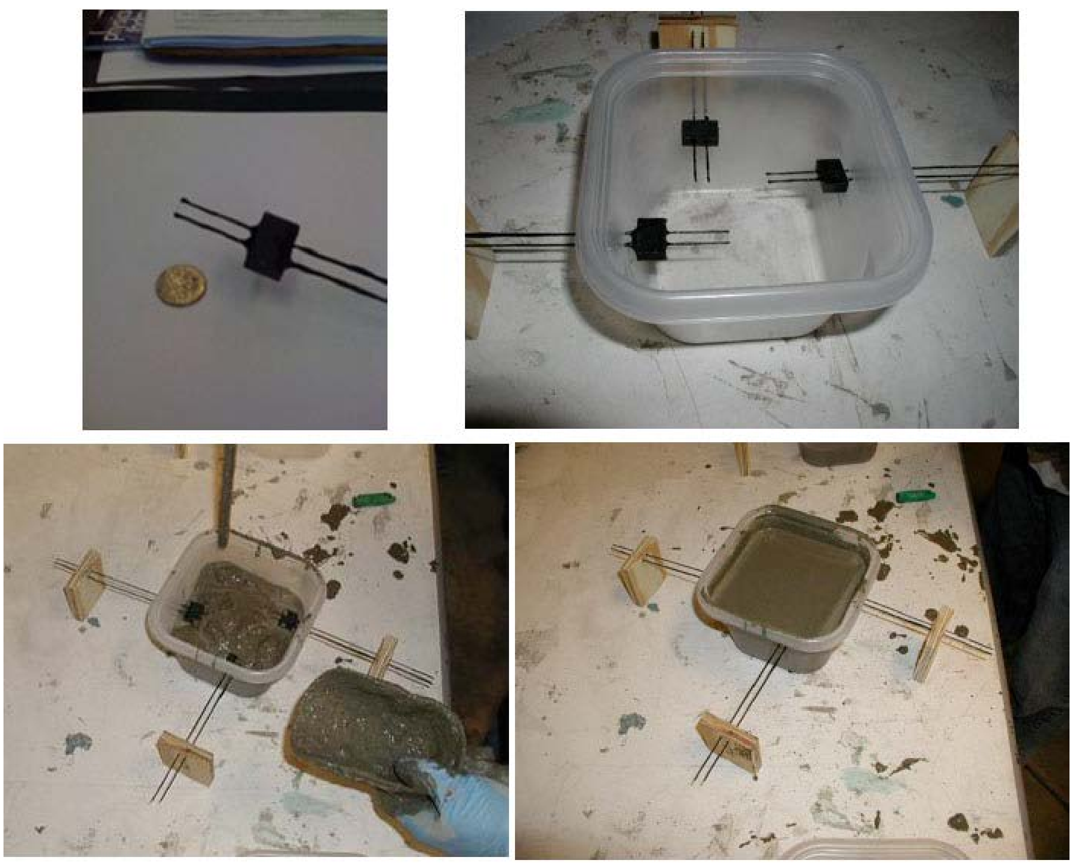

Figure 9: The wire holder for testing our triggering system is shown on the top left. The next pictures show three of these holders being embedded in concrete for accelerated corrosion testing.

Initially, a 0.125mm diameter wire was embedded into a concrete sample using five wire holders. Later tests involved a 0.065mm diameter wire to increase the sensitivity to chloride. Figure 9 shows a typical test setup. The concrete sample with three wire holders underwent the accelerated corrosion testing. The other concrete samples with two holders were controls. In addition, several samples were poured to provide backup samples for the chloride depth profiling of chloride concentration and one sample was prepared with a section of rebar to correlate the corrosion with a structural element.

Table 2: Summary of the trigger time for various concrete samples and wire thicknesses. The 10/8/2009 specimen was microcracked to accelerate the test.

Date Ponded	Number of Days Ponded	Storage Temperature/^{o}C	Depth/mm	Chloride Level at Failure/ppm	Wire Diameter/mm
5/29/2009	291	23	12.5	2900	0.125
8/7/2009	167	23	12.5	2500	0.125
10/8/2009	54	80	9.4	1050	0.065
11/23/2009	no failure	80	9.4	--	0.065

Table 2 summarizes the trigger time for various concrete samples and wire thicknesses that underwent the accelerated corrosion tests. The later samples were stored in an oven to increase the diffusion rate and shorten the test. In addition, the 10/8/2009 specimen was micro-cracked to accelerate the test. Thus, the similar sample that was ponded on 11/23/2009 should trigger at a later date but at an equivalent chloride level. Each failure data represents the time to trigger from multiple wires within the ponded sample (see Figure 9). The similarities of the trigger times along with the ppm data clearly demonstrate that our trigger wires can monitor the ingress of corrosive agents.

Initial RFID Corrosion Sensor

A crude prototype sensor was initially developed using a commercial RFID card in which a section of the receiver coil was replaced with either a 0.125 or a 0.065 mm diameter iron trigger wire. The cards responded to the RFID reader and were embedded in concrete (see Figure 10). Please note that the size of the sensor in our final prototype is significantly smaller. After being embedded, these samples underwent accelerated corrosion testing. As above, to decrease the time to failure, we embedded the sensor very close to the surface of the concrete and subjected it to higher temperatures to further enhance the corrosion rate. In a reasonable time, the sensor trigger failed and the RFID tag stopped working, indicating sufficient chloride ingress to cause corrosion. Future sensors (see below) will return a different ID to the reader, eliminating possible false positives due to electrical failures. Further analysis indicated that corrosion of the wire trigger was responsible for the cessation of the response of the sensor. The time to trigger was slightly faster than that determined for the wire sensor triggers, due to the lower threshold of resistance at which the triggering of the RFID sensor takes place. Nevertheless, the chloride concentration values were consistent at the point of triggering.

Figure 10: Larger RFID based corrosion sensor being embedded in concert for accelerated corrosion testing.

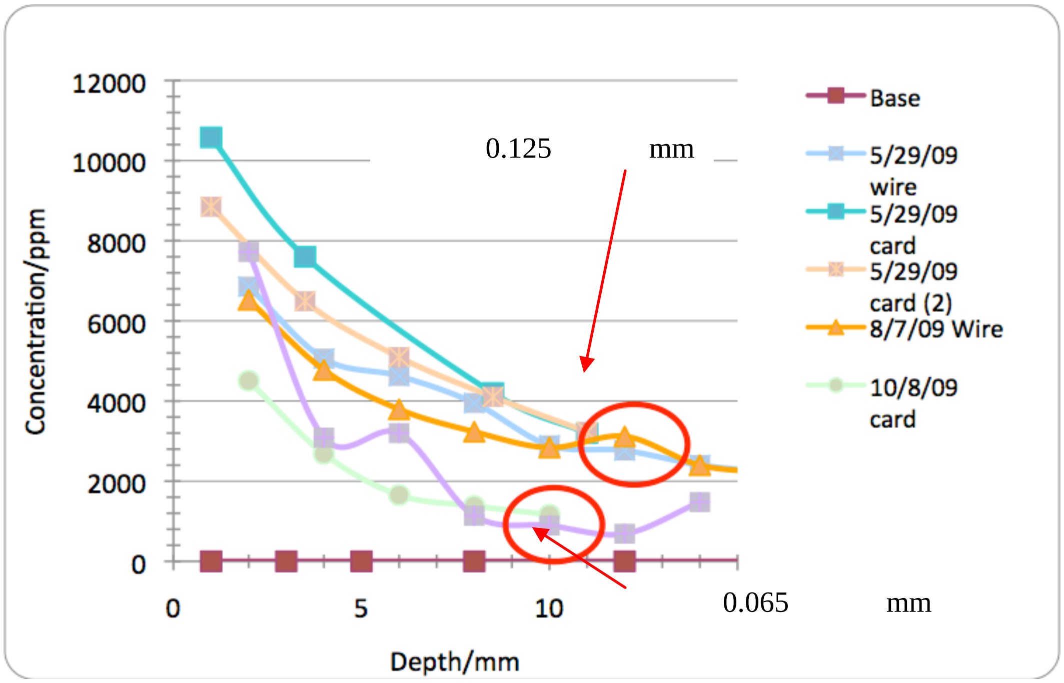

Figure 11: Titration results from the powder collected from both the concrete samples used to test the wire trigger and those used to test RFID sensor

Figure 11 summarizes the titration results from the powder collected from both the concrete samples used to test the wire trigger and those used to test RFID sensor. Results for both the 0.125 mm and the 0.065 mm diameter wire triggers are shown. As mentioned above, the similarities of the trigger times along with the concentration data clearly demonstrate that our trigger wires can monitor the ingress of corrosive agents.

Corrosion Sensor Development

The crude prototype sensor shown in Figure 10 was sufficient to prove the basic functionality. However, the sensor size is not optimal for embedding in concrete. Thus, a smaller more compact sensor was desired, an objective we achieved by manufacturing a custom RFID tag. Initially, we focused on the coil design with a commercially available RFID integrated circuit.

Figure 12a: New RFID sensor body, prototype coil and sensor body and coil.

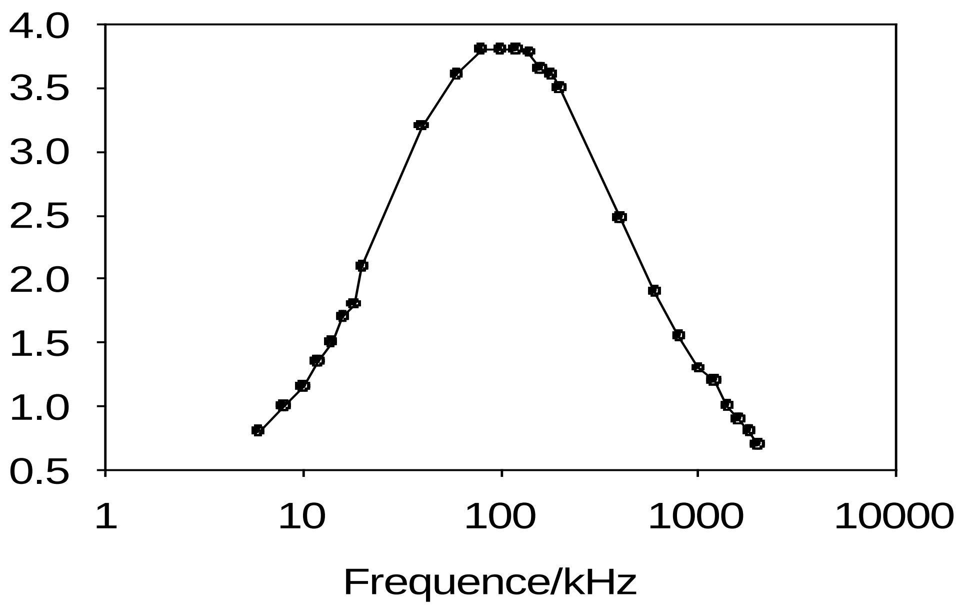

Figure 12b. The response frequency of the coil to RF over the range required to be an RFID tag showing the maximum in the response at about 125 kHz.

The Chemistry and Physics Mechanical shop at OSU constructed a sensor body based on our new design (Figure 12). The mechanical design of the sensor body was time consuming but the final result is easy to manufacture. Figure 12 also shows the final coil design and its electrical response. The modulation of the current induced by the reader requires a relatively low Q coil. The response of the current coil allows reading through at least 12" of concrete.

Figure 13: New RFID sensor with a commercial RFID chip and a quarter for size reference.

Figure 13 illustrates the basic size of the sensor and shows the installation of the commercially available RFID integrated circuit. The next step involves sealing the internals of the sensor within a Delrin body and coating the sensor with a flexible plastic coating (tool dip) to eliminate any stress points that can result in cracking of the concrete.

The use of the commercial RFID chips introduced additional problems. The reliability of reading of the tags with a commercial reader was poor. Initially, we believed this was a problem with our coil design, which is one reason we carefully measured its electric properties and compared them to our theoretical predictions of these characteristics. In actuality, the problem was found to be with the RFID chips obtained from two suppliers. Our sensors worked fine with RFID chips salvaged from commercial tags. The difficulty involved the RFID writer used to initially configure these devices. At the same time, feedback from potential customers indicated that it is highly desirable to have the sensor always respond in real-world applications. This feature will eliminate false positives due to sensor failure. To this end, we originally planned on using Atmel's ATA5570 RFID tag (Figure 4) or equivalent that has a switchable sensor resistor (see Background). However, we also found issues with the ability of our commercial reader to reliable respond to the inverted data stream.

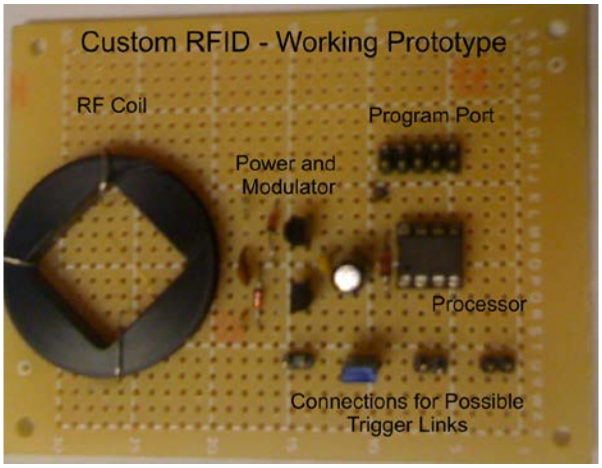

Figure 14: Initial prototype RFID emulator for sensor applications.

Many designs can be found for RFID emulators. However, we found that many of these are not reliable, especially with long-range readers that can saturate the radio-frequency coil. In our design (Figure 14), the induced current in the inductor is rectified utilizing a Graetz bridge composed of the internal diodes in a N-channel MOSFET and two low-forward voltage diodes. The rectified signal is filtered by a small capacitor and s regulated by a Zener diode. The N-channel MOSFET can modulate the load on the radio-frequency coil in a very symmetrical fashion without discharging the small capacitor. A small amount of code, running on a Microsystem PIC processor, is used emulate the EM4001 series RFID chip. In addition, the status of the sensor link, connected between two I/O pins on the device, can be used to change the return value. The EM4001 device returns 64-bits of data (Manchester encoded) which contains 40-bits of information as well as the header and parity bits to ensure correct transmission of the data. We determined that the inclusion of the parity bits is vital for making the device extremely reliable. Finally, we found that we had to modify the circuit and code on the sensors to provide a fixed trigger at a known resistance of the trigger wire. Corrosion of the trigger wire increases its resistance. The first generation sensors waited until the wire was completely broken before changing their response. The current version under testing waits until a predetermined resistance, increasing the reliability of the device.

Sensor Construction

Based on the prototype design discussed above, we had 50 pc-boards for the prototype sensor constructed. Once the pc-boards arrived we built and tested several sensors and validated the design. The picture shown in Figure 15 illustrates the various steps in the construction of a complete final sensor. This sensor is operational and is only missing the final encapsulation in epoxy and silicon before it can be embedded in concrete.

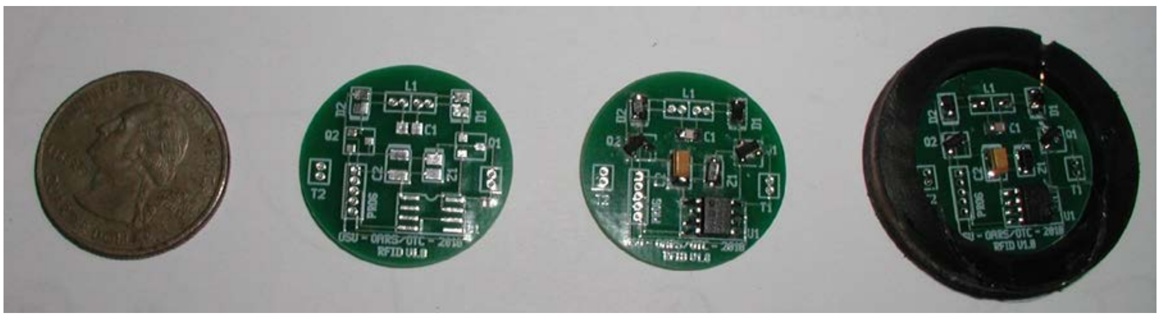

Figure 15: Second-generation prototype RFID emulator based sensor. The quarter is to reference the size, the blank pc-board, an assembled pc-board and the final sensor.

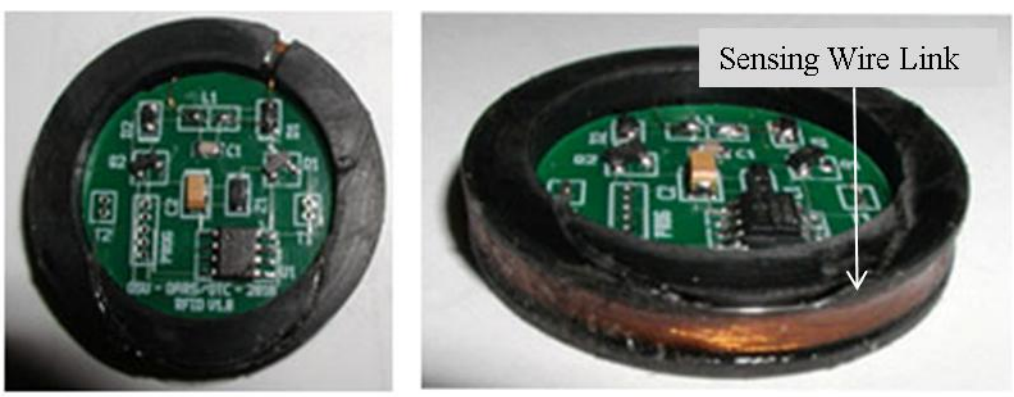

Figure 16: Detailed views of the sensor and sensor wire.

Figure 16 shows the details on the trigger wire used to detect the corrosive agents. We have considered adding an additional guard for the sensor link. However, these wire links proved to be surprising resilient during testing.

Once the first sensor was operational, the major task was to produce a large number of sensors. Numerous sensors were required to assess the electronics, the potting component, and the coating for long durability. To this end, our machine shop produced 30 sensor bodies from PET. With these bodies, we confirmed that we had calculated the correct number of windings for the RF link.

Figure 17a: Sensors after the coils have been wound and attached to the electronics.

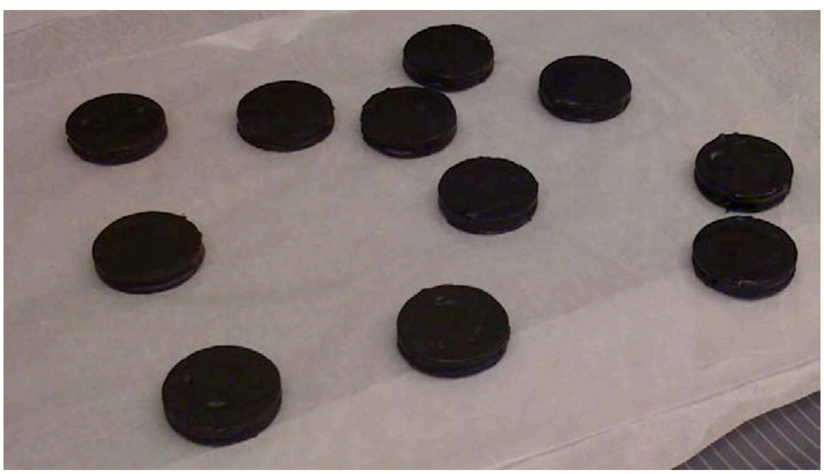

Figure 17b: Sensors after the encapsulation step and application of a rubbery coating.

After the electronics were attached, each sensor was programmed with a unique number, which changes when the sensor triggers trips. At this stage, the sensors are shown in Figure 17a. The next step is encapsulation. We found that a high quality electronic grade epoxy gives the best performance and ease of application. This picture shows some of our final sensors after applying a rubbery coating, as shown on the right panel of Figure 17b.

Environmental and Structural Evaluation

The impact of the sensors on the mechanical strength of concrete was measured. To investigate this, sensors were placed at the center and top of a concrete cylinder and tested. In addition concrete beams were cast with the sensors near the bottom fiber. In all of these tests the strength impact was found to be less than 10%. This is significant as these sensors were placed in the most critical areas within these members and tested. Next the response of the sensors to temperature cycles was investigated.

The sensors were exposed to approximately 80 cycles of temperature changes from 23^{o}C to 80^{o}C and from 23^{o}C to -20^{o}C. Failures in the hardware were found and the sensor design was improved. It was found that the resonance capacitor was not able to withstand the combination of temperature, voltage and time. It was replaced with a high-quality high-temperature radio-frequency grade device. In addition, the modulation frequency, which is based on the internal clock of the microcontroller, drifted slightly with temperature. This drift prevented one of the two RFID readers being able to quarry to the tag. Although additional circuitry can be utilized to lock the tag frequency to that of the reader, a better solution to select a reader that can compensate for small drifts in the tags frequency with temperature. The sensors and reader were pre-testing with a 90^{o}C oven over the course of one month with no failures. The successful completion of this testing was a big success for the sensor development.

Final Corrosion Testing

Three of the corrosion sensors have been placed in concrete for long-term corrosion testing at moderate temperatures. These sensor are currently being monitored daily but are not expected to trigger until several months after the completion of this project. At the time of triggering, we plan to measure the chloride content of the powder near the surface of the sensor to quantify the response to corrosive agents.

Additional sensors are currently undergoing accelerated testing. We expect that the final corrosion testing will be successful based previous studies of the sensor link.

Technology Transfer

Oklahoma State University received a US utility patent application for our "Passive Wireless Corrosion Sensor," number 767529, on 3/9/2010. For sensors embedded in concrete, an invention disclosure was submitted and was approved by the Oklahoma State University Office of Intellectual Property. An additional patent application (Docket number: 71683/10-209) titled "Embedded Wireless Corrosion Sensor" was filed. In addition, one paper was submitted to the 18th World Congress of the Intelligent Transportation Society of America. Presentations were made at the American Ceramic Society, American Concrete Institute, and ODOT-OkTC Transportation Research Day. In addition, this project also supported a research symposium organized between OU, OSU, and Langston Universities. This First Annual Oklahoma Transportation Center Summer Symposium was held in Oklahoma City on July 26, 2010 and featured 17 different technical presentations. It was attended by over 60 people from the OkTC partner institutions.

Technology transfer efforts are now focused on sensor manufacturing. We hope that the body and electronics can be outsourced. However, the winding of the coil and the final connections will be initially performed by the research team. We estimate that approximately 50 sensors can be manufactured in a reasonable time frame using the facilities at OSU. We will obtain assistance the New Product Development Center at Oklahoma State University to find partners to construct addition sensors. Having a large number of sensors to perform mechanical and accelerated corrosion tests is critical in establishing their effectiveness in real structures.

Field studies were not part of the original scope. However, the success has led to several future opportunities to install sensors in a bridge deck and concrete pavement which we plan to explore. One opportunity is near Ft. Worth, Texas. The TxDOT pavement project is funded by the Federal Highway Works Association (FWHA) Highways for Life program. The goal of this program is to promote the use of highways that have a service life much longer than current pavements. To accomplish this goal a number of new monitoring, and maintenance technologies will be used. The inclusion of the research team's sensors will provide outstanding exposure for the technology.

Dr. Ley has been working closely with ODOT to find projects where the sensors would be of great interest and are close to the OSU campus. One project appears to show promise for the first implementation of the sensors is a bridge deck resurfacing repair in Ripley, Oklahoma. This is about 20 minutes from Stillwater. This bridge is the primary mode of transportation in and out of the city and sees a tremendous amount of deicing salts applied to the bridge. The sensors may be used in several key areas of the bridge where the intrusion of chlorides has been seen to be the most prevalent. This application will provide extremely useful information to both ODOT about their bridge and also to the research team about the performance of their sensors. This is a positive situation for both parties.

The research team is also in talks with Kellog, Brown, and Root (KBR) from Dallas and the CTL Group out of Chicago about using these sensors in different repairs in bridges that they are designing and specifying. Early discussions with these groups have been very positive and they are actively looking for projects where these sensors would best fit. The research team has also been taking with OSU about embedding the sensors in different sidewalks on campus that are deteriorating because of corrosion problems. This is a good test for our corrosion sensors as the main sidewalks on the OSU campus are religiously salted to insure that they are safe for walking. In addition, the concrete used to construct sidewalks is not the same quality as concrete used for transportation applications. This means that the salt will permeate this concrete faster and therefore cause the sensors to trigger faster. This application of the sensors would also provide substantial data on the performance of the sensors in concrete under real conditions. This will be invaluable information to help get a wider use of these sensors.

Summary and Conclusion

The report discusses the successful development of an inexpensive wireless corrosion sensor that does not require any external power supply. This corrosion sensor is useful tool to evaluate the structural health of the nation's infrastructure and in turn make our highway travel safer. These sensors are based on radio-frequency identification (RFID) tags that are used to track consumer goods, are extremely low-cost, and use proven, off-the-shelf technology. In a structure, sensors would be situated above the steel rebar.

This project established a correlation between wire thickness and concentration of salts. This work was extended to the development of methodology based on a previous ASTM standard to measure the sodium chloride concentration profiles in concrete. The work allowed us to provide an answer in a reasonable amount of time and accurately represent the actual performance of the sensors in the field. We used this methodology to evaluate the sensor trigger embedded in concrete and validate the sensor concept by embedding a simple prototype into concrete.

For the sensor, low-frequency RFID tags at 125 kHz were determined to be the best radio-frequency range for this application. A prototype sensor that requires no power source to monitor corrosion was designed and constructed based on a programmable microcontroller. These sensors passed the environmental and material testing and are currently undergoing corrosion studies in concrete. The technology has resulted in two patents. Oklahoma State University was granted a US utility patent application for our "Passive Wireless Corrosion Sensor". A patent application for sensors embedded in concrete was also filed (Docket number: 71683/10-209) titled "Embedded Wireless Corrosion Sensor".

The next step is scaled up production of the sensors and their placement in the field. Recently, we have received seed money from OSU to build a larger number of prototype sensors for testing and demonstrations. We hope that these corrosion sensors will be used to intelligently schedule maintenance to optimize resources or to modify the current uses of the structure to prolong the life.

References

1. Yunovic, M.; Thompson, N. G.; Vanyos, T. B.; Lave, L., "Cost of Corrosion: Highway Bridges, " 2010, http://www.corrosioncost.com/infrastructure/highway/index.htm

2. Koch, G. H.; Brongers, M. P. H.; Thompson, N. G.; Virmani, Y. P.; Payer, J. H., Corrosion Cost and Prevention Strategies in the United States, CC Technologies and NACE International in cooperation with the U.S. Department of Transportation, Federal Highway Administration, Sept. 30, 2001. http://events.nace.org/publicaffairs/images_cocorr/ccsupp.pdf

3. The Status of the Nation's Highway Bridges: Highway Bridge Replacement and Rehabilitation Program and National Bridge Inventory," Thirteenth Report to the United States Congress, Federal Highway Administration, Washington, D. C., May 1997.

4. Song, H.-W.; Saraswathy, V., Corrosion monitoring of reinforced concrete structures - a review. *Int. J. Electrochem. Sci.* 2007, *2* (1), 1-28.

5. Martinez, I.; Andrade, C., Examples of reinforcement corrosion monitoring by embedded sensors in concrete structures. *Cem. Concr. Compos.* 2009, *31* (8), 545-554.

6. Andringa, M. M.; Puryear, J. M.; Neikirk, D. P.; Wood, S. L., Low-cost wireless corrosion and conductivity sensors. *Proc. SPIE-Int. Soc. Opt. Eng.* 2006, *6174* (Pt. 1, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems), 61740X/1-61740X/9.

7. Andringa, M. M.; Puryear, J. M.; Neikirk, D. P.; Wood, S. L., In situ measurement of conductivity and temperature during concrete curing using passive wireless sensors. *Proc. SPIE-Int. Soc. Opt. Eng.* 2007, *6529* (Pt. 2, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2007), 65293M/1-65293M/10.

8. Blumentritt, M.; Melhorn, K.; Flachsbarth, J.; Kroener, M.; Kowalsky, W.; Johannes, H.-H., A novel fabrication method of fiber-optical planar transmission sensors for monitoring pH in concrete structures. *Sens. Actuators, B* 2008, *B131* (2), 504-508.

9. Broomfield, J. P.; Davies, K.; Hladky, K., The use of permanent corrosion monitoring in new and existing reinforced concrete structures. *Cem. Concr. Compos.* 2002, *24* (1), 27-34.

10. Dantan, N.; Habel, W. R., Monitoring of corrosion protection. A concrete-embeddable pH optode. *Betonwerk Fertigteil-Tech.* 2006, *72* (3), 48-50, 52-55.

11. Dickerson, N. P.; Andringa, M. M.; Puryear, J. M.; Wood, S. L.; Neikirk, D. P., Wireless threshold sensors for detecting corrosion in reinforced concrete structures. *Proc. SPIE-Int. Soc. Opt. Eng.* 2006, *6174* (Pt. 1, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems), 61741L/1-61741L/8.

12. Dickerson, N. P.; Simonen, J. T.; Ardringa, M. M.; Wood, S. L.; Neikirk, D. P., Wireless low-cost corrosion sensors for reinforced concrete structures. *Proc. SPIE-Int. Soc. Opt. Eng.* 2005, *5765* (Pt. 1, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems), 493-503.

13. Du, R.-G.; Hu, R.-G.; Huang, R.-S.; Lin, C.-J., In Situ Measurement of Cl- Concentrations and pH at the Reinforcing Steel/Concrete Interface by Combination Sensors. *Anal. Chem.* 2006, *78* (9), 3179-3185.

14. Duffo, G. S.; Farina, S. B.; Arva, E. A.; Giordano, C. M.; Lafont, C. J., Development of an integrated sensor to monitor the corrosion process of reinforced concrete structures. *RILEM Proc.* 2007, *PRO 56* (Integral Service Life Modelling of Concrete Structures), 167-173.

15. Fernandes, B.; Miller, G.; Gaydecki, P.; Quek, S., Damage and corrosion visualization of reinforcing bars embedded in concrete using a new solid-state inductive scanning sensor. *AIP Conf. Proc.* 2002, *615* (Review of Progress in Quantitative Nondestructive Evaluation, Volume 21B), 1233-1238.

16. Grahn, W.; Makedonski, P.; Wichern, J.; Kowalsky, W.; Wiese, S., Fiber optic sensors for an in-situ monitoring of moisture and pH value in reinforced concrete. *Proc. SPIE-Int. Soc. Opt. Eng.* 2002, *4480* (Imaging Spectrometry VII), 395-404.

17. Lam, C. C. C.; Rajesh, M.; Sun, T.; Grattan, K. T. V.; Grattan, S. K. T.; Taylor, S. E.; Basheer, P. A. M., Calibration of optical fiber refractive index sensor with potential for structural corrosion monitoring. *Am. Concr. Inst., SP* 2008, *SP-252* (Health Monitoring Systems and Sensors for Assessing Concrete), 73-84.

18. Lee, H. S.; Shin, S. W.; Ahn, J. M.; Kim, Y. C.; Kho, Y. T., Development of corrosion sensors for monitoring steel-corroding agents in reinforced concrete structures. *Mater. Corros.* 2003, *54* (4), 229-234.

19. Leung, C. K. Y.; Wan, K. T.; Chen, L., A novel optical fiber sensor for steel corrosion in concrete structures. *Sensors* 2008, *8* (3), 1960-1976.

20. Lu, S.; Ba, H.; Wang, A.; Yang, Y., Tower type sensors for monitoring corrosion risk in cover-zone concrete. *Adv. Mater. Res. (Zuerich, Switz.)* 2010, *97-101* (Pt. 5, Manufacturing Science and Engineering I), 4305-4308.

21. Lu, S.; Ba, H.-J., Corrosion sensor for monitoring the service condition of chloride-contaminated cement mortar. *Sensors* 2010, *10*, 4145-4158.

22. Montemor, M. F.; Alves, J. H.; Simoes, A. M.; Fernandes, J. C. S.; Lourenco, Z.; Costa, A. J. S.; Appleton, A. J.; Ferreira, M. G. S., Multiprobe chloride sensor for in situ monitoring of reinforced concrete structures. *Cem. Concr. Compos.* 2006, *28* (3), 233-236.

23. Muralidharan, S.; Saraswathy, V.; Madhavamayandi, A.; Thangavel, K.; Palaniswamy, N., Evaluation of embeddable potential sensor for corrosion monitoring in concrete structures. *Electrochim. Acta* 2008, *53* (24), 7248-7254.

24. Nieves-Mendoza, D.; Almeraya-Calderon, F.; Uruchurtu-Chavarin, J.; Martinez-Villafane, A.; Chacon-Nava, J.; Baltazar-Zamora, M.; Gaona-Tiburcio, C.; Menchaca, J. L., Evaluation of reinforced concrete structures by means of a novel electrochemical noise corrosion sensor. *Corrosion (Houston, TX, U. S.)* 2008, *64* (12), 920-928.

25. Park, Z.-T.; Choi, Y.-S.; Kim, J.-G.; Chung, L., Development of a galvanic sensor system for detecting the corrosion damage of the steel embedded in concrete structure. *Cem. Concr. Res.* 2005, *35* (9), 1814-1819.

26. Pereira, E. V.; Figueira, R. B.; Salta, M. M.; Fonseca, I. T. E., Embedded sensors for corrosion monitoring of existing reinforced concrete structures. *Mater. Sci. Forum* 2008, *587-588* (Advanced Materials Forum IV), 677-681.

27. Pereira, E. V.; Figueira, R. B.; Salta, M. M. L.; Elias da Fonseca, I. T., A galvanic sensor for monitoring the corrosion condition of the concrete reinforcing steel: relationship between the galvanic and the corrosion currents. *Sensors* 2009, *9* (11), 8391-8398.

28. Popovics, J. S.; Gallo, G. E.; Shelton, M.; Chapman, P. L., A magnetic sensing approach to characterize corrosion in reinforced concrete. *Proc. SPIE-Int. Soc. Opt. Eng.* 2007, *6529* (Pt. 1, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2007), 65291A/1-65291A/7.

29. Qiao, G.; Hong, Y.; Ou, J.; Leng, J.; Asundi, A. K.; Ecke, W., Corrosion monitoring of reinforcing steel in RC beam by an intelligent corrosion sensor. *Proc. SPIE* 2009, *7493* (Pt. 1, Second International Conference on Smart Materials and Nanotechnology in Engineering, 2009), 74930C/1-74930C/7.

30. Qiao, G.-F.; Hong, Y.; Ou, J.-P., Corrosion monitoring of reinforcing steel in concrete by electrochemical sensors. *Proc. SPIE* 2010, *7647* (Pt. 1, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2010), 76471G/1-76471G/6.

31. Rajabipour, F.; Weiss, J., Parameters affecting the measurements of embedded electrical sensors for concrete health monitoring applications. *Am. Concr. Inst., SP* 2008, *SP-252* (Health Monitoring Systems and Sensors for Assessing Concrete), 7-22.

32. Raupach, M.; Weizhong, G., Corrosion monitoring systems for design verification - application at the 36 km Hangzhou Bay Bridge. *RILEM Proc.* 2007, *PRO 56* (Integral Service Life Modelling of Concrete Structures), 159-165.

33. Schneck, U.; Winkler, T.; Mucke, S., Integrated system for corrosion monitoring of reinforced concrete structures. *Eur. Fed. Corros. Publ.* 2007, *38* (Corrosion of Reinforcement in Concrete), 146-158.

34. Short, N. R.; Page, C. L.; Glass, G. K., Design and operation of a galvanic sensor for in-service monitoring of the corrosion of steel in concrete. *Proc. SPIE-Int. Soc. Opt. Eng.* 1994, *2361*, 172-5.

35. Sorensen, R.; Buhr, B.; Rostam, S., Sensors for detection of corrosion. *Concr. Eng. (Farnham, U. K.)* 2002, *6* (1), 53-56.

36. Tamura, H.; Nagayama, M.; Shimozawa, K., Rebar corrosion monitoring using embedded minisensors. *Spec. Publ. - R. Soc. Chem.* 1996, *183* (Corrosion of Reinforcement in Concrete Construction), 294-302.

37. Yoo, J.-H.; Park, Z.-T.; Kim, J.-G.; Chung, L., Development of a galvanic sensor system for detecting the corrosion damage of the steel embedded in concrete structures: Part 1. Laboratory tests to correlate galvanic current with actual damage. *Cem. Concr. Res.* 2003, *33* (12), 2057-2062.

38. Yang, L.; Sridhar, N.; Pensado, O.; Dunn, D. S., An in-situ galvanically coupled multielectrode array sensor for localized corrosion. *Corrosion (Houston, TX, U. S.)* 2002, *58* (12), 1004-1014.

39. Carkhuff, B.; Cain, R., Corrosion sensors for concrete bridges. *IEEE Instrumentation & Measurement Magazine* 2003, *6*, 9.

40. Mendoza, E. A.; Lieberman, R. A.; Prohaska, J.; Robinson, D., Distributed fiber optic chemical sensors for detection of corrosion in pipelines and structural components. *Proc. SPIE-Int. Soc. Opt. Eng.* 1998, *3398* (Nondestructive Evaluation of Utilities and Piplines II), 136-143.

41. Tanaka, S.; Imaizumi, H. Corrosive liquid leak detecting sensor. US Patent 4,710,353, December 1, 1987.

42. Triques, A. L.; Silva, M. F., Jr.; Gonzalez, D. M.; Celnik, J.; Schlueter, V. G.; D'Almeida, A. R.; Pereira, F.; Valente, L. C. G.; Braga, A. M.; Dias, M. L., Fiber Bragg grating sensing for indirect evaluation of corrosion in oil and gas facilities. *Proc. SPIE-Int. Soc. Opt. Eng.* 2004, *5502* (Second European Workshop on Optical Fibre Sensors, 2004), 283-286.