MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

Radio Frequency Identification (RFID) Smart Corrosion Coupon

CAAP Final Report

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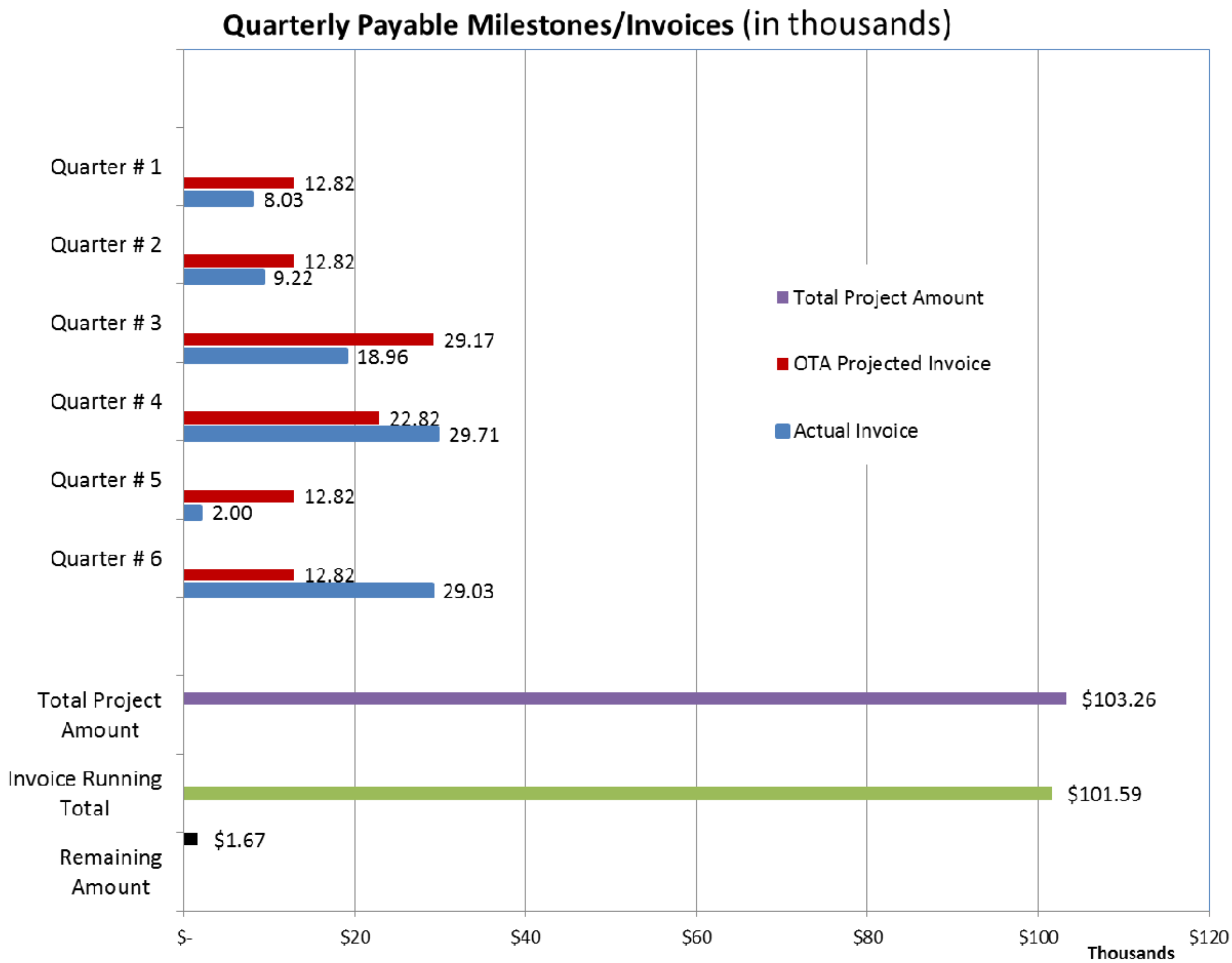
Funds and Work Completed During this Quarterly Period:

All teaming agreements were consistent with the last quarterly report. Some purchases were made in this period for the corrosion tests. Work broken out by task as defined in the award documents are described in the 'Technical Status' section.



Technical Status

Introduction

Corrosion is a major problem across industries with annual direct costs of approximately $1.8 *trillion*, equivalent to 3-4% of the Gross Domestic Product (GDP) of industrialized nations [1]. The U.S. Department of Defense estimated that its cost for corrosion is $22.5 *billion*, which accounted for 23% all of its maintenance costs in 2009 [2]. The study titled, "*Corrosion Costs and Preventive Strategies in the United States*", from 1999 to 2001 by C&C Technologies Laboratories, Inc., with support from the Federal Highway Administration (FHWA) and NACE International (National Association of Corrosion Engineers) shows that the direct cost for corrosion in the U.S. was $276 *billion*, approximately 3.1% of the U.S.'s GDP [3]. A recent report from the Office of Pipeline Safety, Pipeline & Hazardous Materials

Safety Administration (PHMSA) of the U.S. Department of Transportation shows that the total cost of pipeline corrosion is approximately $7 billion, including direct costs such as cost of capital, operation and maintenance, and cost of failure [4]. Indirect costs, particularly costs involving the loss of lives and properties resulting from incidents caused by corrosion are many times higher. A current statistic on significant pipeline incidents from PHMSA shows that from 1993 to 2012, there were 1,065 significant incidents involving pipeline corrosions [5]. These incidents resulted in 25 fatalities and 86 injuries, and caused more than $650 million in property damage. It is essential to recognize that significant incidents involving pipeline corrosion account for 18.9% of the total number of pipeline incidents.

While science and technology are advanced enough to control the corrosion problem, proper management is still the obvious solution for the controlling and mitigating problems that stem from corrosion. Having a proper corrosion management system will minimize possible indirect costs from incidents caused by corrosion, reducing the cost of corrosion to direct cost only. Good corrosion management starts with effective inspection techniques including effective corrosion monitoring and detection. However, it is extremely difficult to address all issues in practice, given the diversity of the materials, service conditions, and locations that need to be inspected and maintained. Corrosion can occur everywhere, which greatly complicates the issue of implementation. It is particularly true for pipeline systems because of factors such as corrosion under-insulation, pipelines situated in remote locations, and the complexity of underground or underwater environments.

There are multiple inspection methods available including contact methods such as voltage measurement and ultrasound, or non-contact-imaging methods such as X-ray; however, they are too expensive and complicated to be used as routine corrosion inspection methods. An ideal solution is a monitoring system that is:

(i) Continuous, such as a real-time monitoring system that streams constant signals regarding its current corrosion status from which appropriate maintenance decisions can be made; wireless or non-contact signals would be preferred;

(ii) Inexpensive, expendable, simple to be deployed without interfering with existing onsite activities and should be able to be monitored onsite on a regular basis without the need of complicated specialized equipment; and

(iii) Universal, deployable in all ranges of conditions including environmental conditions, operating conditions, geometries, locations and materials.

Available inspection methods that have been applied in corrosion detection, inspection, and management do not meet all the three criteria mentioned above. To overcome this challenge, the Mary Kay O'Connor Process Safety Center (MKOPSC) and RFID Technology Center of Texas A&M University proposed a research project for the development of a novel type of smart corrosion coupons using Radio Frequency Identification (RFID) technology for continuous real-time wireless monitoring of corrosion. This will combine the advantages of RFID technology and the corrosion coupon so that a better corrosion monitoring method can be developed. The central idea in this project is to create smart RFID corrosion coupons, which can emit signals indicating the corrosion status of the monitored points on demand, by placing the RFID coupons close to pipeline. The antenna material of the RFID coupon should be similar to the material that is monitored for corrosion; however, other types of materials can also be employed. Ideally, the smart corrosion coupons will monitor the entire surface for corrosion; however, in a more economical sense, strategic locations susceptible to corrosion. The continuous signals from RFID coupons are then monitored and used as corrosion indicators.

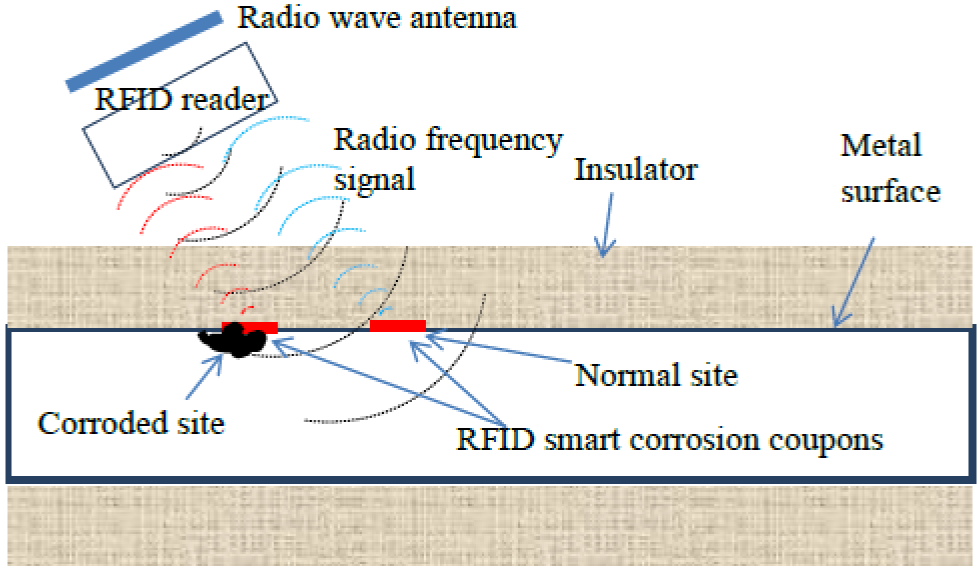


Figure 1. Conceptual representation of using integrated radio frequency identification (RFID) corrosion coupon for corrosion monitoring under insulation.

Figure 1 illustrates the conceptual representation of using integrated radio frequency identification (RFID) corrosion coupons for corrosion monitoring under insulation. The black wave represents the incoming radio wave from the radio wave emitting antenna, the RFID tag antenna picks up the signal and powers the microchip. The microchip at a normal site then responds with a normal radio frequency signal (green color); the microchip at the corroded site either responds with a different radio frequency signal (red color) or does not respond. The change in responding signal allows corroded sites to be detected. A description of the technical tasks as defined in the award documents and the status updates are provided in the following section.

Task 1 and 3 - RFID smart corrosion coupon design and Operational testing at laboratory scale

Task 1 is completed within the scope of the project. In this task, the objective included the completion of proof-of-concept of a novel Radio Frequency Identification (RFID) smart corrosion coupon system as a solution for effective corrosion management systems combining the advantages of the RFID technology and the conventional corrosion coupon. RFID coupons were developed and modified based on their performance as applied in the environmental chamber. Two types of RFID coupons have been designed and tested in this project, and the continuous improvement of the coupon design was described in the earlier quarterly reports. A description of the RFID coupon designs are provided in the following sub-tasks.

Task 3 is completed within the scope of the project. The objective of this Task was to investigate impacting factors on the performance of the designed RFID smart corrosion coupon such as antenna length and reading distance. Two versions of the chamber, alpha and beta, were constructed and one was placed in the RFID/Sensor Laboratory and the other in the Department of Chemical Engineering. Preliminary tests were conducted in the alpha and beta versions of the chamber to test the stability of the system. After the preliminary background tests of the stability of the system, experiments were conducted to test the RFID coupons with 6 variables, temperature, humidity, reader-coupon distance, length of the antennae, location, and acid concentration as shown in Table 1. The design of the RFID coupon was continuously revised based on the experiment results. The final design is an on/off RFID coupon design, which has proven very effective in corrosion monitoring through the laboratory scale testing.

Task 1 and task 3 are related tasks and a detailed description is provided in the following three sub-tasks: environment chamber establishment, RFID smart coupon design, and testing at laboratory scale.

A. Environment chamber

According to the standard ASTM B-117, a cost-effective corrosion environment chamber was designed and constructed with temperature, humidity, salinity, pH sensors, flow control and electronic control. Figure 2 shows the schematic of the environmental chamber and Figure 3 shows the picture of the real chamber in the lab of Department of Chemical Engineering. A maximum of six RFID coupons can be monitored each time in this chamber.

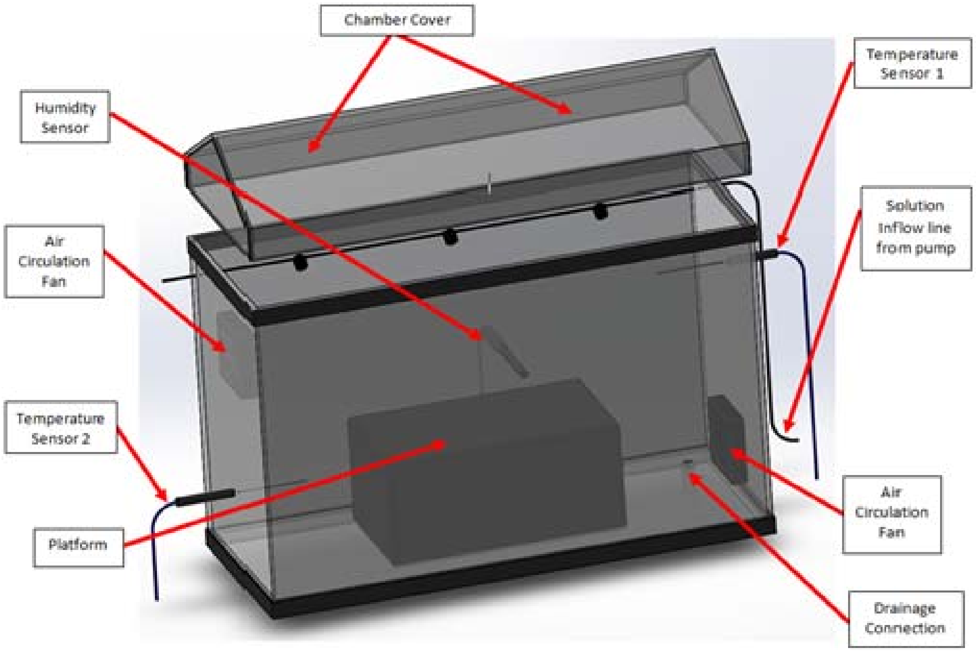


Figure 2. Front view of chamber design with mounting locations.

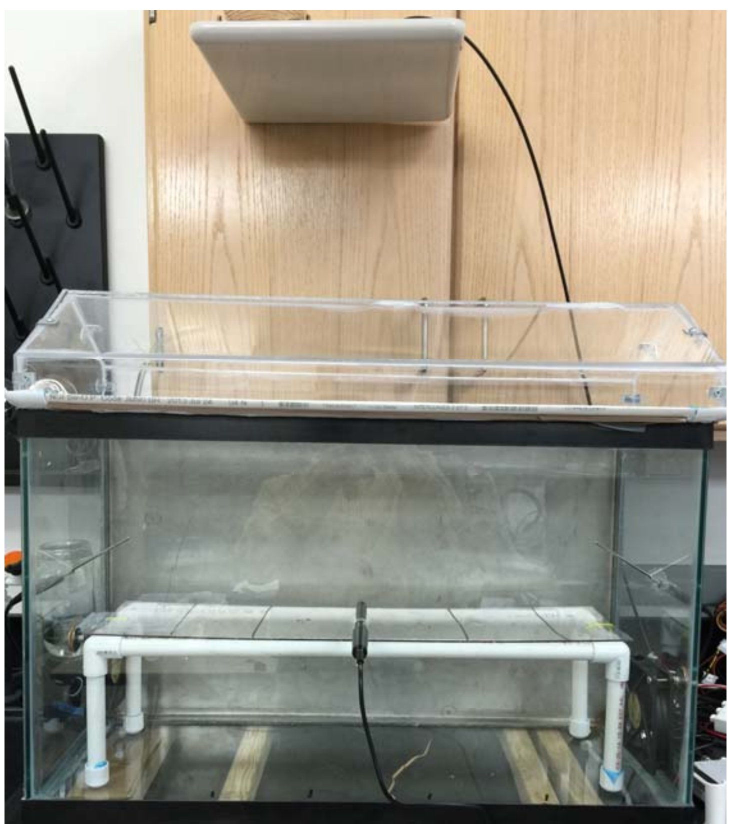


Figure 3. Front view of the environment chamber.

A user interface was designed based on LabVIEW for temperature and humidity control and continuous data acquisition as shown in Figure 4. The continual improvement of the environmental chamber was described in the earlier quarterly reports, and the final version has proven to be very effective through the preliminary testing and corrosion testing.

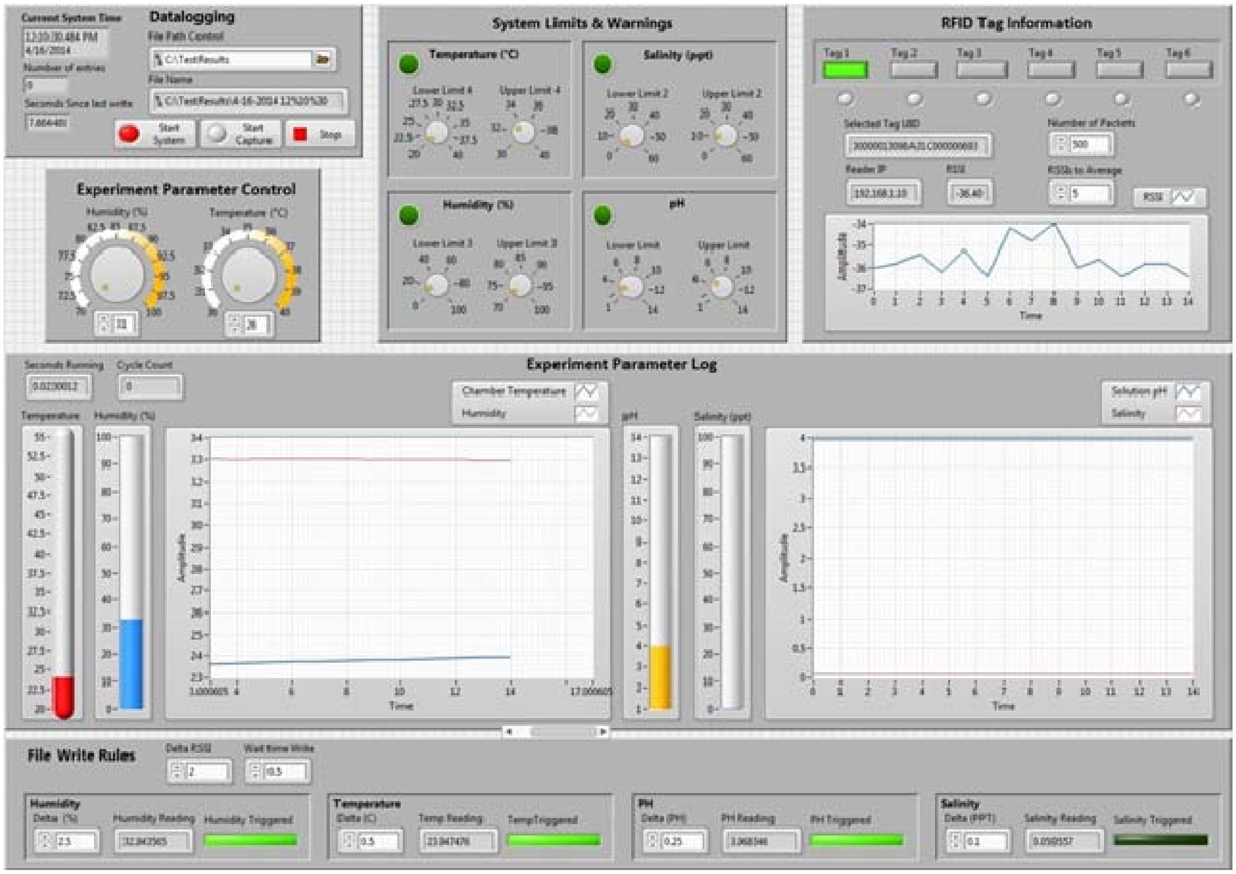


Figure 4. System user interface of the environment chamber.

B. RFID smart coupon design

Two main types of RFID smart coupons were designed and tested in this project. Figure 5 shows the first generation RFID smart coupon design. The chip is not protected and the antenna is made of tightly twisted metal wires. The signal strength of the RFID coupon was originally expected to correlate with the physical change of the antenna, such as length and thickness. However, the experimental results showed that such correlation is very weak. The strength of the signal of a single coupon will generally decrease upon the decrease of the antenna length, but the trend across different individual coupons is not clear due to large fluctuations. Moreover, the distance between the RFID coupon and the reader as well as the location of the coupon can affect the signal strength. These experimental results motivated us to continuously revise the RFID coupon design. It was found that no signal could be detected when the antenna was cut by more than 3 cm at both ends, when the distance from the reader was 26 inches. This was a very important basis for the design of on/off mode corrosion coupons. All the experimental details are discussed in the following sections.

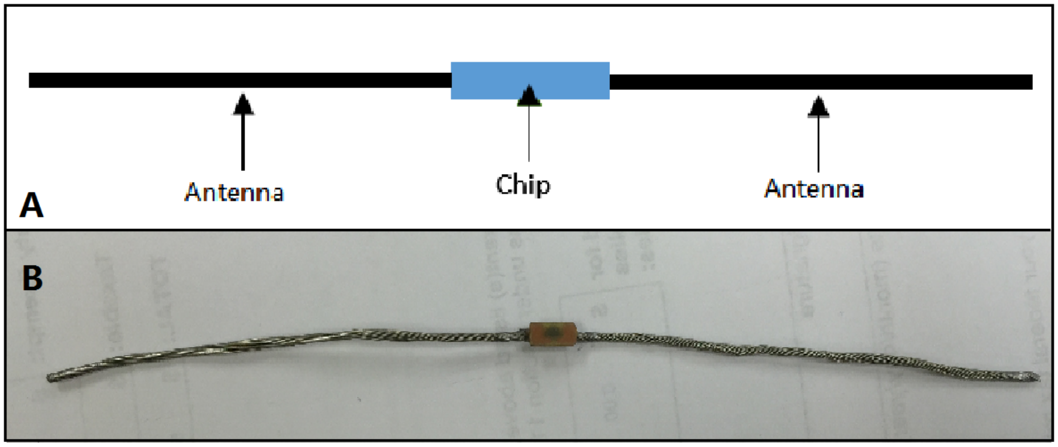


Figure 5. First generation RFID smart coupon design.

An on/off RFID smart coupon shown in Figure 6 was developed based on the result of the first generation RFID coupon. The materials of the antenna are alloys which are used in pipeline construction and hence the corrosion rate of the antenna is representative of a real pipeline. Additionally, these coupons have a polymer coating that is corrosion resistant covering both the chip and a majority of the antenna with the exception of a small section of exposed antenna immediately adjacent to the chip (the exposed section is approximately 2 cm long). This design allows for the on/off setup, because any corrosion that takes place close to the head of the antenna will kill the coupon.

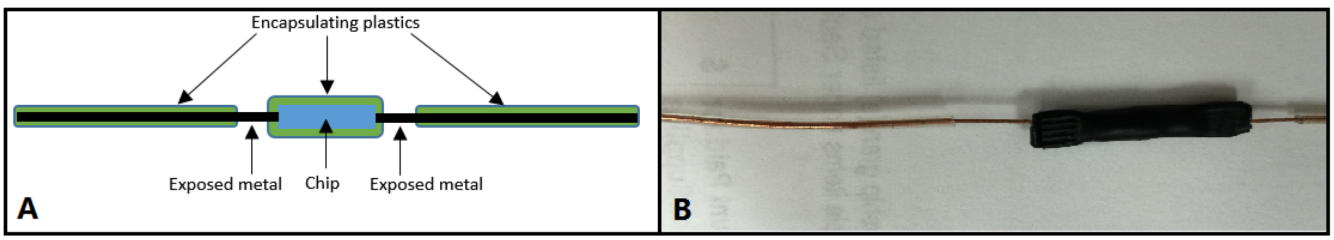


Figure 6. On/off RFID smart coupon design.

The first generation coupon design was enhanced by introducing corrosion resistive plastics to protect the chip and the end of the antenna, only exposing the metal very close to the chip to corrosion. In the first generation, the corrosion could take place randomly along the antenna if applied in a real situation. The on/off RFID smart coupon would be deactivated when both sides of the exposed metal were fully corroded and thus is able to detect corrosion. This design was proved to be effective in the laboratory testing.

C. Testing at laboratory scale

The schematic of the experiment set-up is shown in Figure 7. There are six locations from 1 to 6 in the sample stage and a maximum of six RFID coupons can be monitored in each experiment. The vertical distance from the reader to the sample stage is 26 inches. Characterization tests were conducted in order to study the effect of positional characteristics and reading environment on coupon response. In the preliminary stage, changes to the length and thickness of the antenna were achieved by cutting to simulate the corrosion procedure in nature. In the second phase of experiments, the RFID coupons were placed in an acidic environment to test the feasibility and effectiveness of corrosion monitoring. There are 6 experimental variables in the tests, which are shown in Table 1. There are totally around 100 first generation RFID smart coupons and around 60 on/off RFID smart coupons that have been tested to this point.

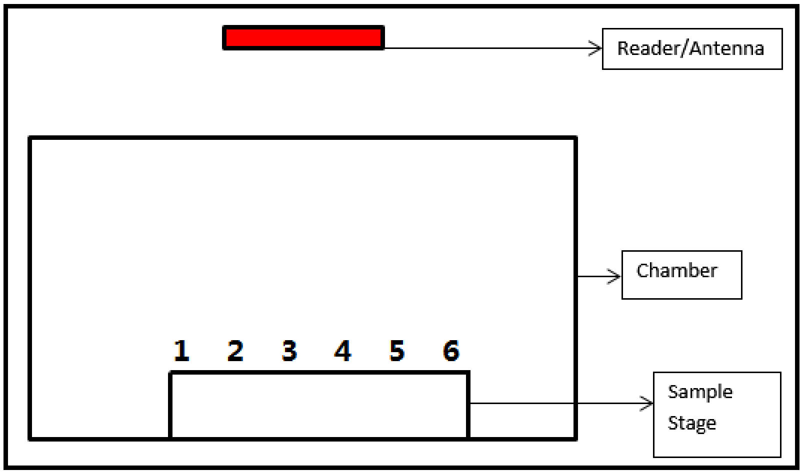


Figure 7. Schematic of the chamber.

Table 1. Experimental variables of the RFID coupon testing.

Variable	Descriptions
Temperature	20 ^{0}C, 25 ^{0}C, 30 ^{0}C, 35 ^{0}C
Humidity	30 %, 60 %, 100 %
Reader-Coupon Distance	20 inches, 26 inches
Length of the coupon	From 1 cm from each end to full antenna cut, one side and two sides
Location	Location 1, 2, 3, 4, 5, 6
Acid	1.25%, 2.5% and 5% H_2SO_4 Solutions, and acidified soil

The time of each experiment set is 2 hours and around 1,400 data points can be collected for each coupon. The data obtained from the experiments were analyzed. The signal was analyzed by taking the mean, the standard deviation and the range of the data. There are eight key observations based on the testing of two RFID smart coupon design.

Observation 1: The RFID reader implements FCC mandated frequency hopping in the 902-928 MHz band which causes slight variations in signal reading. Figure 8 shows a typical signal response in the experiment. In this experiment, the mean, the standard deviation and the range of the data is recorded.

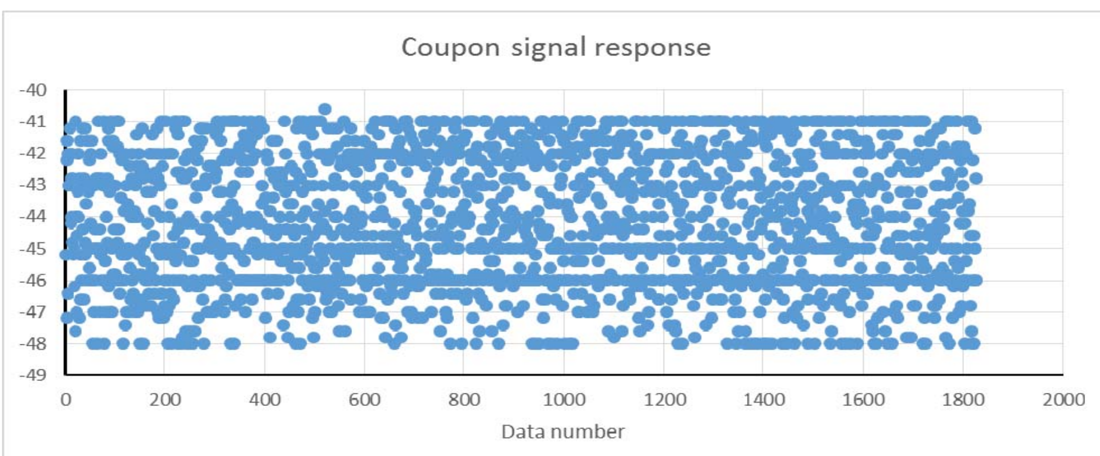


Figure 8. RFID coupon signal response

Observation 2: Multiple experiments show that the signal right below the reader (location 2-4) shows a smaller variance. Figure 9 shows an example of the mean and variance information of the on/off RFID smart coupon in six locations.

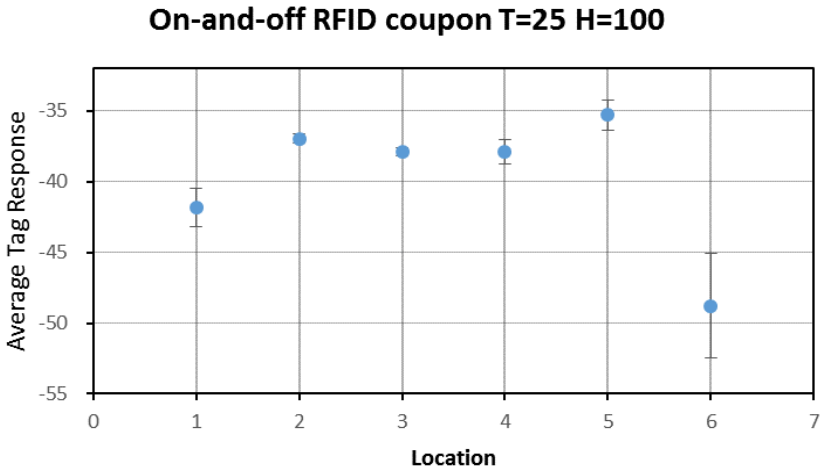


Figure 9. The signal of on/off RFID smart coupons in 6 locations.

Observation 3: The strength of the signal of a single coupon will generally decrease upon the decrease of the coupon length, but the trend across different individual coupons is not clear due to large fluctuations.

Observation 4: Temperature has no statistically significant effect on the reading in the range of 20-35°C. Humidity has minor influence in the range of (30%-100%). Figure 10 and Figure 11 show the reading of on/off RFID smart coupons in different humidity and temperature.

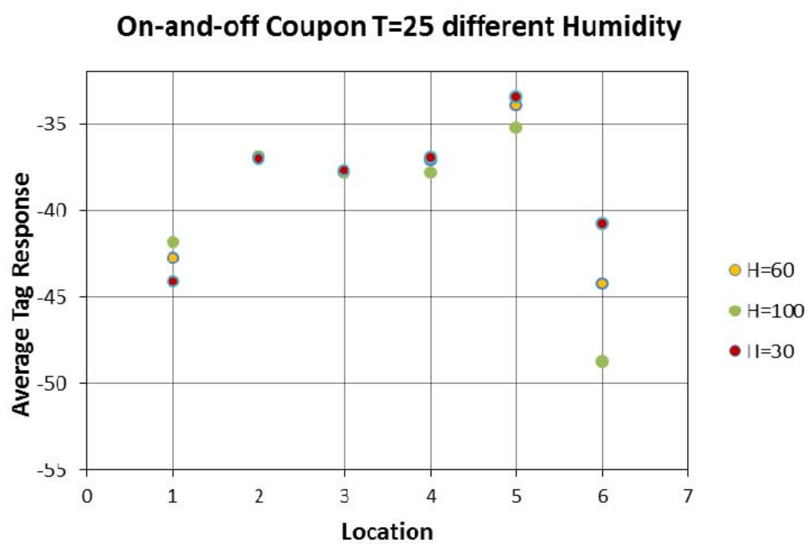


Figure 10. Signal of on/off RFID smart coupons in different humidity

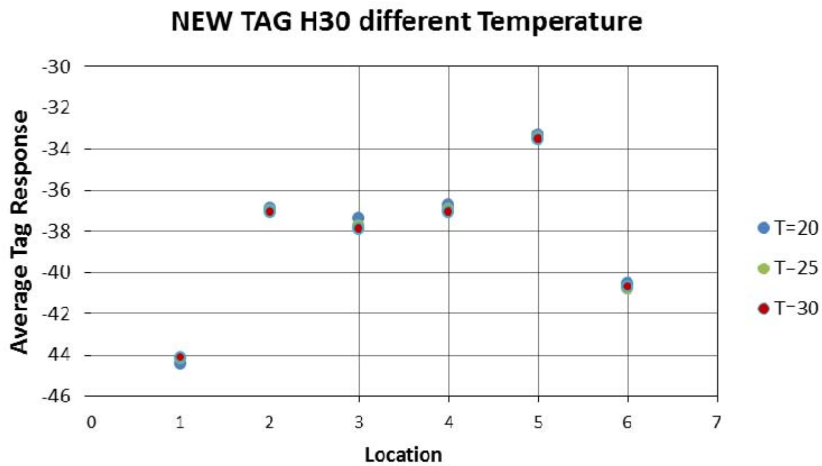


Figure 11. Signal of on/off RFID smart coupon in different temperature

Observation 5: The signal response of the same coupon in different locations shows that location can affect the signal but the influence from the location is very random. In Figure 12, six coupons give six different trends when location changes. In the beginning of this project, the signal strength of the RFID coupon was expected to be correlated with the length and thickness of the antenna. However, since location affects the signal, the correlation becomes less useful because the reader will be moving around to detect the signal of different coupons in the real application. A signal change caused by location could not be differentiated from a change caused by corrosion. This is another main reason that the first generation RFID coupon design was revised to an on/off design.

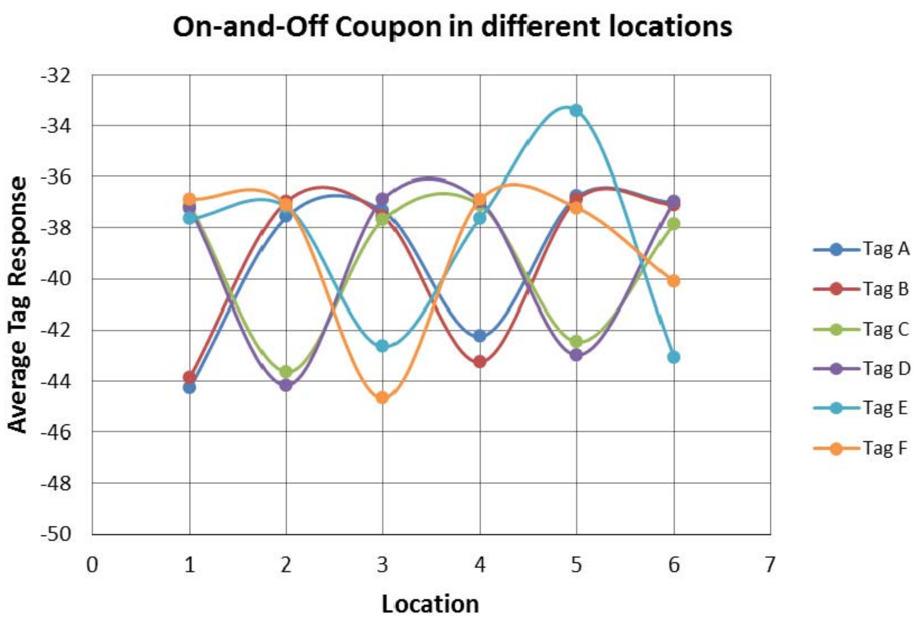


Figure 12. On/off RFID smart coupon in different locations.

Observation 6: The strength of the signal of a coupon will generally increase upon the decrease of the distance between the reader and coupon. However, the trend across different individual coupons is not clear due to large fluctuations.

Observation 7: When both sides of the exposed metal of on/off coupon are fully corroded, they coupon will be killed and no signal can be detected. However, when the distance between the reader and the chip is very close (≤ 2 cm), a very unstable signal was observed. A partial corrosion would not bring signal change. When only one side was fully corroded, the signal would decrease.

Observation 8: The corrosion test of the on/off RFID smart coupons in acid solutions showed that the coupons in 5% acid solution were killed in about 52~53 hours, and the coupons in 2.5% acid solution were killed in about 96-100 hours. The coupons in water showed evidence of corrosion but there were still signal readings after 150 hours. Figure 13 shows the pictures of two corroded on/off RFID smart coupons. The on/off RFID smart coupon buried in acidified soil could still be detected after 31 days.

Figure 13. Corroded on/off RFID smart coupons.

Task 2 – Corrosion testing

Task 2 is completed within the scope of the project. The goal of this task was to identify the corrosion rate of metal samples, which can be used as the material of the antenna. The data can be used to design the RFID smart corrosion coupon so that specific deactivation time can be achieved. The deactivation time is the time at which the RFID coupon is no longer functional. This time is an intrinsic property of a RFID smart corrosion coupon. The results of the corrosion testing of the metal coupons in acid solution and acidified soil give a great impetus to the design of RFID corrosion coupon.

USN G10200 and G10260 sample materials were selected to simulate the pipeline materials during the corrosion tests, due to the fact that they are the most commonly used materials for constructing pipelines. The metal coupon size was 3" x 1/2" x 1/16", and was procured from a commercial vendor. Metal corrosion coupons were immersed in mixtures with various acid concentrations for a variety of different times. Solutions with a very low pH create an aggressively corrosive environment. Gravimetric analysis was conducted to determine the extent of corrosion and rate of corrosion. The major findings from this experiment were that solutions with higher acid concentration increased corrosion rate and that corrosion rate decreased as corrosion time increased. Although both of these conclusions were to be expected, they provided baseline values that can be used for future comparison of RFID coupon corrosion. It should be noted that given the relatively short duration of the experiments, it was assumed that the change in surface area of the metal coupons was relatively small and hence held constant in the rate calculation. Also the density of the material was assumed uniform and was taken of mild steel (7.85 g/cc).

Additionally, experiments were conducted in acidified soil, which was used to represent a pipeline environment. In these experiments, soil was placed in a beaker and an acidic solution was added to the soil to both acidify it and remove any air pockets. Six different concentrations were tested, and each of these concentrations yielded three different time points. Experimental details and the preliminary results are presented and the data are attached in Appendices A and B.

A. *Corrosion testing of metal coupon in acid solutions*

Acid solutions with concentrations of 1.25%, 2.5% and 5% H_2SO_4 were prepared before the experiment. Prior to all measurements, the exposed surfaces of the metal coupons were mechanically abraded with 150 and 100 grain sandpapers, then washed thoroughly with Millipore water, degreased and dried with ethanol. The metal coupons were immersed in 200 mL of different acid solutions at room temperature (298 K) for a variety of times. Table 2 shows the various times and concentrations used in the experiment. The gravimetric measurements were carried out at room temperature (298 K) using an electronic balance. After the exposure time, the metal coupon was withdrawn, rinsed with Millipore water, washed with acetone, dried and weighed. Using the weight loss a corrosion rate in mm/year was calculated. The data is attached in Appendix A.

Table 2. Time and acid concentration variable

	Condition
Time point	4 hours, 6 hours, 24 hours, 48 hours
Acid concentration	1.25%, 2.5% and 5% H_2SO_4

It is observed that corrosion rate increases with concentration which is expected since the solutions become more aggressive with increased concentration as shown in Figure 14. There is a higher corrosion rate observed in the short-term tests. This is attributed to the presence of more exposed corrodible surface at the start of the experiment, and as corrosion product accumulates on the surface of the metal coupon, the direct exposure of the corrodible metal surface reduces.

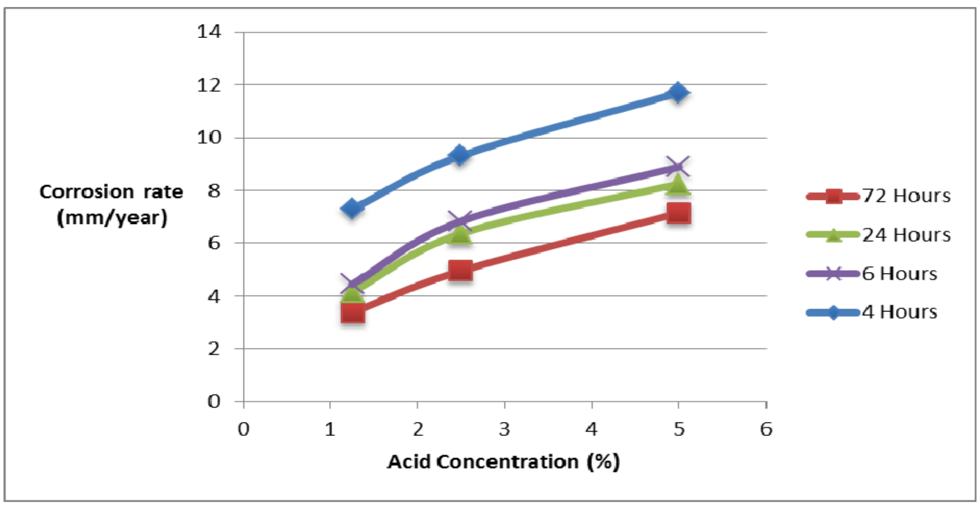


Figure 14. Variation of corrosion rate with concentration

The corrosion rate drops drastically as time progresses and then trends towards a stable rate in all the three concentrations of the acids as shown in Figure 15. The reason behind this is the same as above; as the corrosion products accumulate, the rate of corrosion stabilizes and electrochemical reaction stabilizes.

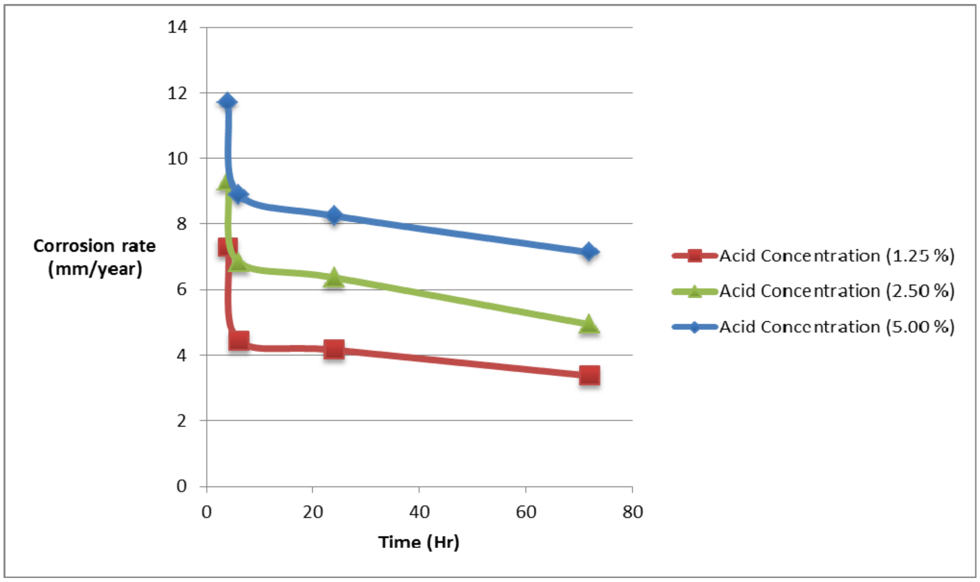


Figure 15. Variation of Corrosion Rate with time

B. Corrosion testing of metal coupons in acidified soil

The rate and type of corrosion in a liquid environment is often different from those in a porous solid environment. In order to get a representative idea of how the corrosion rate of pipeline materials would be in a porous solid environment similar to what would be found in the vicinity of buried pipelines; medium term lab-scale testing was done in lab with slightly acidified soil.

The soil used for the testing was mainly top soil taken from around Jack E Brown building on the Texas A&M University campus. 200 mL of soil was then placed in a clean glass beaker. The soil was then slightly acidified using various concentrations of H_2SO_4. The H_2SO_4 solutions were prepared in Millipore water and 40 mL of each solution was added to the soil at the start of the experiment. Since it was observed that there was a tendency for the soil to lose its moisture very rapidly given the laboratory environment, every seven days 20 mL of Millipore water (without acid) was added to the soil to keep a minimum level of moisture. The beaker filled with soil was then covered to prevent any external contamination and stored. The corrosion coupons were pre-treated by the same method described in the acid solution testing.

Gravimetric measurements were used in this experiment. The metal coupon was extracted at different time points as shown in Table 3 from each of the beakers. The metal coupons were then washed multiple times with Millipore water and sonicated. After the Millipore washing, the metal coupons were degreased and the remaining deposits were removed by light sanding and the samples were dried and weighed.

Table 3. Acid concentration added to soil and time points

Acid concentration added to soil (Set I)	10%	5%	2.5%
Time points for Set I (Hours)	144	360	504
Acid concentration added to soil (Set II)	1.25%	0.5%	0.25%
Time points for Set II (Hours)	264	456	672

The metal coupons kept in the less acidified soil concentration were kept for longer time given the (expected) lower corrosion rate. The metal coupons removed from the beakers presented some unique insights into the effect of the complex soil environments. Some of the observations include:

1. The observed corrosion was highly non-uniform with no particular pattern either spatially or with time.
2. There were areas of relatively uniform corrosion on one surface with non-uniform on the reverse side with extensive pitting.
3. An element of randomness was observed especially with the pitting corrosion. There were both areas which were closer to the surface and locations deeper in the soil showing pitting corrosion.
4. The corrosion products (by visual observation) were different at different locations on a single coupon, which may be attributed to the complex chemistry of the soil and also variation in oxygen levels in the soil.

The visual observations of the metal coupons give a great impetus to the corrodible RFID coupon design. The RFID coupons, if distributed in large enough numbers either underneath the pipe insulation or in the pipeline environment, would help overcome the inherent randomness and unpredictability of the corrosion processes. Also because of the nature of the RFID coupon design, the RFID coupon can monitor corrosion in highly aggressive and extreme local environments (pitting-prone), and thus may be very useful in pin-hole leak predictions.

Figure 16 shows the images of metal coupons extracted after 360 hours. They clearly exhibit the non-uniformity of the corrosion process. Figure 17 shows images of a metal coupon extracted after 144 hours. Similar non-uniformity was observed.

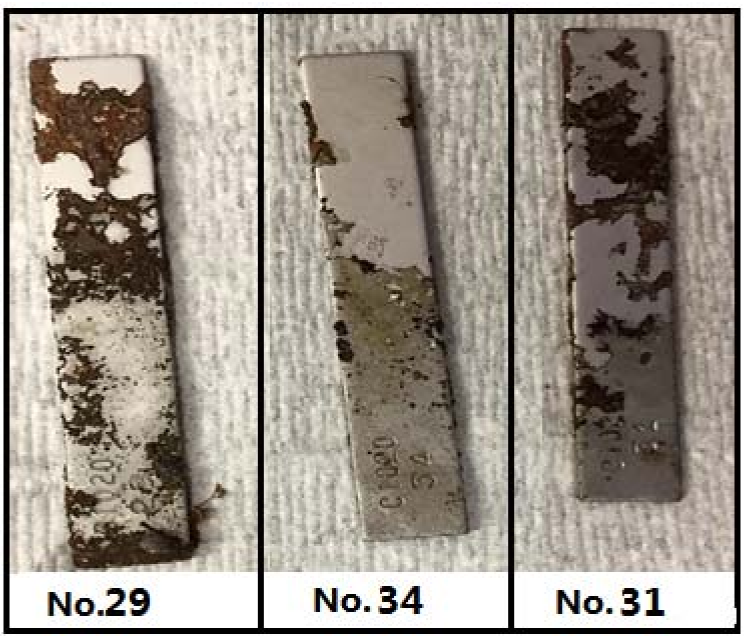


Figure 16. Metal coupon images after immersion in soil for 360 hours

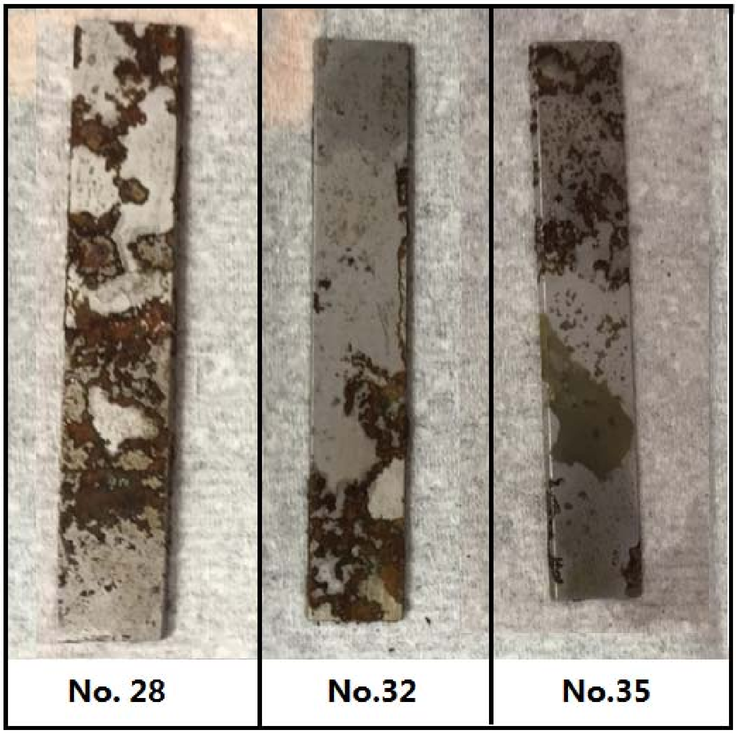


Figure 17. Metal coupon images after immersion in soil for 144 hours.

The experiment can be divided into two sets based on the extent of acidification: set 1 is the highly acidified soil (10%, 5% and 2.5%), and set 2 is the less acidified (1.25%, 0.5% and 0.25%). The data from the corrosion rate measurements was plotted with time.

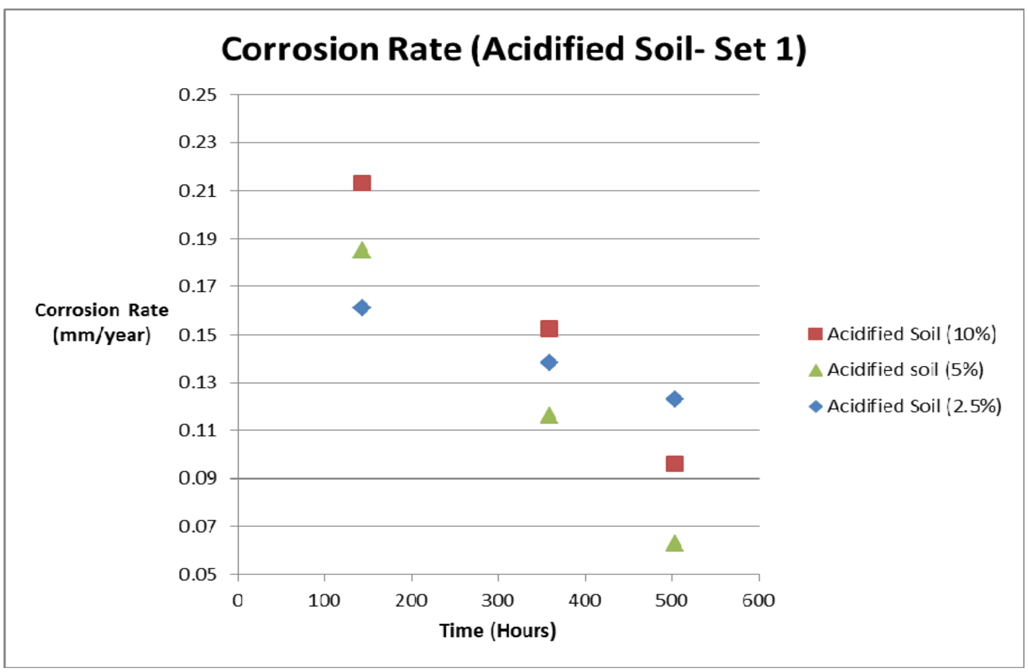


Figure 18. The corrosion rate of metal coupon plotted against time (Set 1).

Figure 18 represents the variation of corrosion rate with time. It is observed that there was a general decrease in the corrosion rate with time for all the three concentrations in the acidified soil. This may be attributed to the consumption of the more corrosive substances in the soil and also to the formation of a passive protective film. However, it should be noted that the samples were left in the soil with no mechanical vibration and in a stable environment. In the real world, many of the pipelines maybe buried under road or rail ways and be subjected to cyclical vibrations which may not allow for the passive layer or the corrosion product layer to stay on, thus eroding the surface away with time. Moreover, as mentioned in the previous section, the corrosion was highly non-uniform, hence even though the aggregate rate of corrosion may decrease, deep pits and indentation on the sample will occur, which in the case of an actual pipeline may lead to a pinhole. Also it is noted that there is no cathodic protection or coating applied on the metal coupons, which are the most commonly used methods to protect pipelines in the industry. Hence the rate of corrosion is more representative of unprotected metal.

The corrosion rate measurements from the second set show a more peculiar pattern as shown in Figure 19. It is observed that the corrosion rate increased and then decreased with time for the soil acidified with the 1.25% acid whereas the rate is stable for soil with 0.5% acid and decreases with time for the 0.25% acidified soil. Hence there does not seem to be any representative trend as seen earlier with the soil having higher amount of acidification. This is an interesting insight which adds to the inference from the visual observations of the highly non-linear and random corrosion events taking place on the metal coupons because of the complex chemistries in the local microenvironments of the metal coupon. Even in relatively controlled conditions of the lab and similar source of the soil we see that the trends of corrosion rate show significant differences.

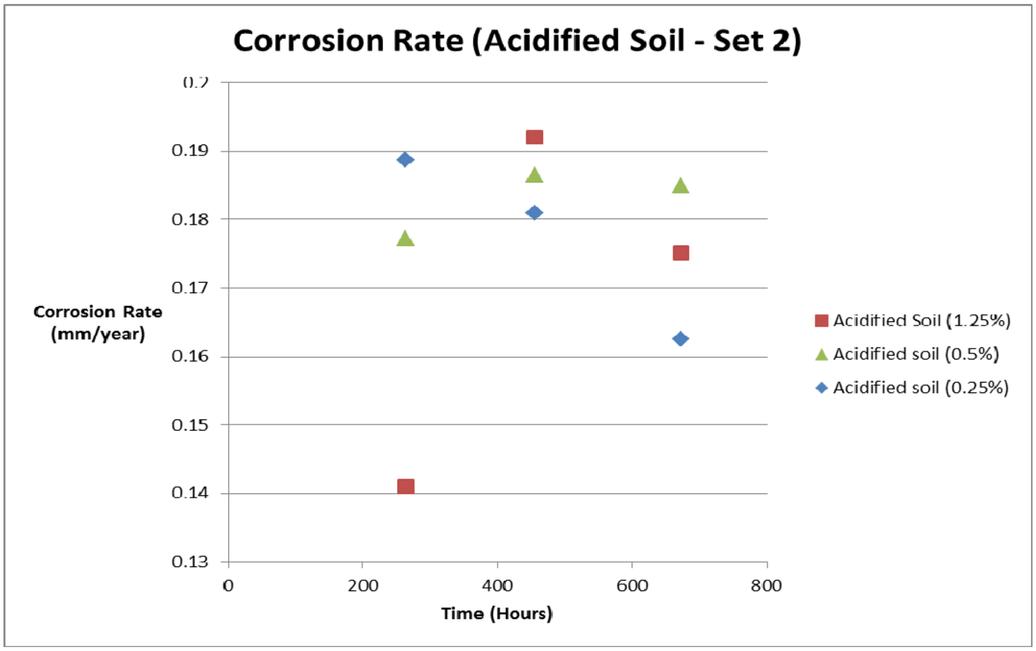


Figure 19. Corrosion rate of metal coupon plotted against time (Set 2).

The combined overlay of the corrosion rate from the different acidified soils over time, shown in Figure 20, gives an insight into the non-linearity of the corrosion process. We observe that at time points at more than 600 hours the relatively low acidified soil (0.5%) displays the highest corrosion rate almost comparable to rate that the highly acidified soil (10% - 20X more acidified) produced at the start of the experiment (~140 hours). Hence making conclusions based only on acidification would not be representative of the observed corrosion rates. Also, no general trend of overlap was found across all the data sets, although the data from set 1 displayed some amount of correlation (decrease of rate with time). These results indicate the need for a sensing/predictive mechanism that can overcome these difficulties by providing us local representative data about the microenvironment. This has been demonstrated by the modified RFID corrosion coupon which has been designed with the corrodible antenna design.

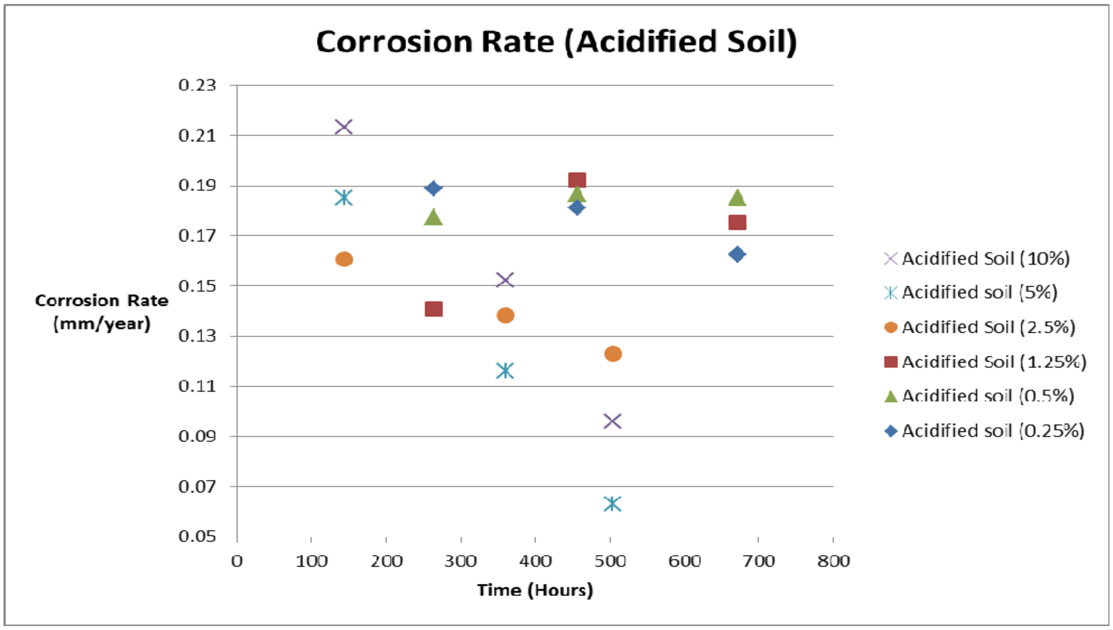


Figure 20. Corrosion rate of metal coupon plotted against time (Set 1 and Set 2).

Task 4 – Identify locations susceptible to corrosion

This task is complete within the scope of the project. The main goal of this task was to identify potential locations which are more susceptible to corrosion. Ideally, the RFID sensors should cover all surfaces for a complete monitoring of corrosion. However, in practice, for economic reasons, risk-based decisions should be followed; it is possible that only certain locations which have high probability of corrosion are selected for monitoring. Extensive corrosion literature was reviewed and analyzed. There are many different types of corrosion, such as general corrosion, pitting corrosion, erosion, galvanic corrosion, and so on. For pitting corrosion, the pitting spots tend to be more random and the rate of corrosion at different pitting spots varies drastically, thus it is difficult to predict the location of corrosion as well as establish a correlation between the pitting corrosion rate of pipeline and the corrosion rate of our coupon-encapsulating materials [6]. However, corrosion under insulation (CUI) tends to be general corrosion and the corrosion area is much larger and more uniform, compared with pitting corrosion in pipelines [7]. Additionally, general corrosion is easier to generate and tested in the laboratory, and the correlation between corrosion rates are easier to establish. The RFID coupon will be more effective at monitoring corrosion because the corrosion area is larger and especially because locations more susceptible to CUI are easier to identify. For these reasons, the corrosion environment of CUI was simulated in our corrosion tests.

Conclusions and Recommendations

Our work on RFID smart corrosion coupons was able to discover a suitable application for the coupons, develop a new coupon design that would accommodate the needs of the environment and the industry, and perform accelerated corrosion tests on the coupons. Additionally, corrosion tests using industry standard corrosion coupons allowed the comparison of coupon corrosion to pipeline corrosion to develop a basic relationship between coupon and metal coupon corrosion rate that is necessary for real-world application. The two potential applications of this technology could be in buried pipelines and in corrosion under insulation. Experiments were conducted to mimic these scenarios, and the results show that the coupon is able to perform well in both cases. The innovative design of the coupon allows a modified on/off response, which should reduce the dependence on signal analysis, and should simply provide an indication of the state of the coupon without extra effort from the end user.

Some recommendations resulting from the experiments are focused mainly on data analysis. During the experiments, the magnitude of the RF response was often not in line with what was expected. For example, the shorter the antenna, the lower the response should be. However, during the tests, there was no correlation between antenna length and signal strength until a certain threshold was reached. This result, in addition to the effects of location and distance on signal response, are the main reasons why the modified on/off setup is preferred. It is likely that a deeper understanding of RF and further data analysis could discover meaningful trends in the data. Another issue related to coupon cutting and data analysis is antenna detuning. This phenomenon is present in RFID coupons, and causes the optimum signal absorption to change as the length of the antenna changes. Because this variable is directly tied to antenna length, it is impossible to uncouple these variables in our setup.

References

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6. **Frankel, G. S.** "Pitting Corrosion of Metals." Journal of The Electrochemical Society 145.6 (1998): 2186.
7. **Vogelaere, Frank De.** "Corrosion under Insulation." Process Safety Progress. 28.1 (2009): 30-35.

Business Status

Per the contract cost sharing of salaries for the PI and Co-PI amounted to $42,799.85. Dr. Mannan's salary was cost shared for a total amount of $22,717 ($15,613 salary +fringes; $7,104 in kind indirect).Dr. Zoghi's salary was cost shared for a total amount of $21,178 (($14,555 salary +fringes; $6,623 in kind indirect).

Schedule

The project is on time. All the experiments and analysis were completed as planned.

Payable Milestones

The expected invoice in the last quarter will include personal time and materials cost as planned. Actual total invoice for the whole project is expected to be approximately $1.67 k less than the projected total cost. The remaining budget is due to the availability of the materials at a lower cost than what was originally anticipated.

Appendix A

Data from the corrosion rate measurements in the acid environment. (Liquid)

Solution Concentration	Time (hours)	Corrosion rate (mm/year)	Time (hours)	Corrosion Rate (mm/year) average
1.25	4	7.30	4	7.30
1.25	4	7.30	6	4.45
1.25	6	4.61	24	4.16
1.25	6	4.28	72	3.38
1.25	24	3.98		
1.25	24	4.34		
1.25	72	3.51		
1.25	72	3.26		
Solution Concentration	Time (hours)	Corrosion rate (mm/year)	Time (hours)	Corrosion Rate (mm/year) average
2.5	4	9.44	4	9.31
2.5	4	9.18	6	6.84
2.5	6	6.79	24	6.36
2.5	6	6.88	72	4.96
2.5	24	6.21		
2.5	24	6.52		
2.5	72	4.89		
2.5	72	5.02		
Solution Concentration	Time (hours)	Corrosion rate (mm/year)	Time (hours)	Corrosion Rate (mm/year) average
5	4	11.95	4	11.70
5	4	11.45	6	8.89
5	6	9.39	24	8.25
5	6	8.39	72	7.15
5	24	8.24		
5	24	8.26		
5	72	7.19		
5	72	7.16		

Appendix B

Data from the corrosion rate measurement in the acidified soil environment

Concentration 10 %		
Coupon #	Time (Hours)	Corrosion Rate (mm/year)
28	144	0.21
29	360	0.15
30	504	0.10
Concentration 5 %		
Coupon #	Time (Hours)	Corrosion Rate (mm/year)
31	360	0.12
32	144	0.19
33	504	0.06
Concentration 2.5 %		
Coupon #	Time (Hours)	Corrosion Rate (mm/year)
34	360	0.14
35	144	0.16
36	504	0.12
Concentration 1.25 %		
Coupon #	Time (Hours)	Corrosion Rate (mm/year)
37	264	0.14
38	672	0.18
39	456	0.19
Concentration 0.5 %		
Coupon #	Time (Hours)	Corrosion Rate (mm/year)
40	672	0.19
41	456	0.19
42	264	0.18
Concentration 0.25 %		
Coupon #	Time (Hours)	Corrosion Rate (mm/year)
43	672	0.16
44	456	0.18
45	264	0.19