

Enabling Widespread Electronic Corrosion Monitoring in Marine Off-Shore Installations

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Introduction

What is corrosion?

Corrosion, to the lay user, is what happens to materials when they are exposed to the elements and left for a long time. When something is seen to be corroded it generally means that it is any or all of the following: of unattractive appearance, timeworn, out-of-date or no longer fit for purpose.

The official definition of corrosion, from the National Association of Corrosion Engineers (NACE) is as follows: “the deterioration of a material (usually a metal) that results from a chemical or electrochemical reaction with its environment”ⁱ. The International Standards Organisation (ISO) definition is: Physicochemical interaction between a metal and its environment which results in changes in the properties of the metal and which may often lead to impairment of the function of the metal, the environment, or the technical system of which these form a partⁱⁱ.

This impairment causes a need for corrosion to be sensed. In marine offshore installations, such as marine wind or wave energy farms, the remoteness of the structures means that inspection of each individual part for corrosion can be expensive and require highly trained and skilled staff. The human element also increases the risk of misidentification of corroded areas.

This report will concentrate on the effects and detection of corrosion that occurs in steel. The decision was made to focus on steel corrosion because of the following reasons:

- 1) The majority of marine and offshore installations are at the present time constructed from steel;
- 2) Steel is cheap and easily obtainable and therefore can be deliberately made to rust and tested.

Corrosion only becomes a problem when impairment of the metal's function occurs. However, if it can be detected and "flagged up" at a stage before impairment occurs, ameliorative action can be taken which may mean that the impairment does not occur at all, causing disruption to be avoided.

The purpose of this research is to investigate the possibility of detecting corrosion using electronic technology. If this is found to be possible and reliable, then it is envisaged that the sensor developed will be used in a wirelessly distributed system such that many sensors can be deployed and can monitor for corrosion remotely without the need for human input. The wirelessly distributed system was developed as part of research done by H.K. Twigg and Dr M. Molinari in 2015 in the WIDENSENSE projectⁱⁱⁱ and it is hoped that this research into Corrosion Monitoring will make use of the prototype that was developed for wireless distributed sensing.

The environment surrounding marine offshore structures presents additional problems to the development of a sensor system. Firstly, the sensors themselves would have to be waterproof, saline-proof and themselves corrosion-proof. They would also have to be resistant to marine creatures trying to eat them or make a home in them. Secondly, the water's edge / surface presents a particular problem in that the repeated action of covering with saline water followed by exposure to air, as happens at sea, creates an environment where corrosion is speeded up because of the chloride ions / oxygen interaction. Thirdly, even with waterproof, saline-proof and animal-proof sensors, it is very difficult to transmit data wirelessly when the transmitters are underwater. Power sources would have to be renewed more often than in a dry environment because the added attenuation when transmitting RF signals through water means that higher power levels are needed. The effect of having to renew or recharge the power sources continually may negate the usefulness of having an autonomous sensing system altogether. The frequency of replacement or recharging of the power source is currently outside the remit of this project but will have to be considered before a case is made to an industrial partner for investing in the development of this sensor system. Another factor that may reduce battery life is the marine environment itself. The batteries will have to remain dry within the waterproofing of the sensor, and safe from marine creatures, but they will not be immune to the effects of temperature extremes or temperature cycling.

Corrosion occurs because of both chemical and electrochemical reactions happening to an area of metal that is in contact with a non-metal (sea water in the case of marine structures). The combination of these reactions over time give the products of corrosion. When the metal in question is carbon steel, stainless steel or another iron alloy, the corrosion produces rust.

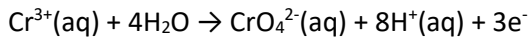
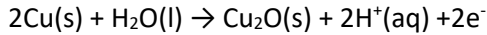
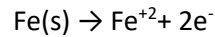
Electrochemistry of corrosion

Steel corrosion follows a series of chemical and electrochemical reactions (from Chandler (1985)^{iv}). In marine environments, the first stage of electrochemical change occurs separately at local anodes and cathodes.

Anodic reactions

Loss of metal occurs at an anodic site. This means that the metal changes to a metal ion. Electrons separate from the metal, so the metal becomes a positive ion and some free electrons. The products are therefore metal ions and electrons. This process is called oxidation because the metal ions are positive and electrons are produced. Any electrochemical reaction where the ions become more positive (including neutral → positive or positive → more positive) is oxidation, and in order for this to happen, electrons must be freed.

E.g.



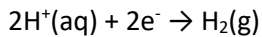
These last two are anodic reactions as there is a charge transfer that results in the oxidation number increasing (the metallic ion becoming more positive) and thus a release of electrons. However, they are not corrosive reactions because there is no transfer of mass.

Corrosion can be defined as the simultaneous transfer of mass and charge across a metal/solution interface.

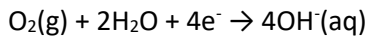
Cathodic reactions

Here the opposite occurs, i.e. there is a decrease in oxidation number (a given ion becomes more negative). There is a gain or absorption of electrons at the cathodic site.

E.g.



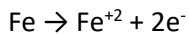
This is the usual cathodic reaction in acidic solutions. In neutral or basic solutions, a common cathodic reaction is:



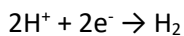
Both of the above two reactions are cathodic reduction reactions. Electrons are consumed and ions become more negative.

Coupled Electrochemical Reactions

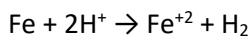
When a metal corrodes, anodic and cathodic reactions occur at different points on the metal's surface. For example, if iron is immersed in an acidic solution, at the anode the following will occur:



At the cathode,



So the overall reaction is:



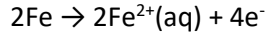
Note that the electrons freed in the anodic reaction are consumed in the cathode, so the overall equation does not record the electrons' movement.

Four conditions are therefore necessary for corrosion to occur:

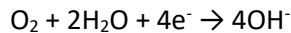
1. an anodic reaction
2. a cathodic reaction
3. a metallic path between anode and cathode
4. an electrolyte

In a neutral or basic solution containing water (aqueous), the following conditions and reactions combine to create rust (hydrated ferric oxide).

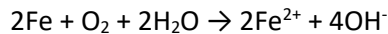
The anodic reaction is:



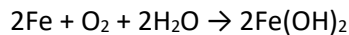
and the cathodic reaction is:



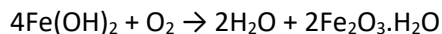
Putting the two reactions together results in the elimination of electrons as follows:



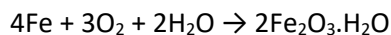
Above a low concentration, the ferrous and hydroxyl ions will combine to form ferrous hydroxide, $\text{Fe}(\text{OH})_2$. Low concentrations of Fe^{2+} and OH^{-} still exist in aqueous solution, but the reaction equation is more commonly written:



$\text{Fe}(\text{OH})_2$ reacts readily with dissolved oxygen in the water to form hydrated ferric oxide (rust) which has the formula $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$. So the next reaction equation in the conversion of iron to rust is as follows:



So the overall equation for metallic iron (in steel) converting to rust, leaving out the intermediate steps, is:



The water can evaporate if it has the opportunity (for example if it is at the water's edge on a boat or a pier) leaving the rust dry. The anodic and cathodic reactions and the formation of $\text{Fe}(\text{OH})_2$ may take place at different sites on the surface of the metal, and the precipitation of $\text{Fe}(\text{OH})_2$ may not even occur at the metal's surface, in which case it does not influence the production of rust. It is for this reason that the locations of patches of rust, certainly in the case of general attack corrosion, appear to be random and can be many metres or further apart.

The importance of cathodic reactions

Cathodic reactions do not produce corrosion products themselves, but are coupled to the anodic reaction. The rate of corrosion can be controlled by the rate of cathodic reaction. Also, cathodic reactions in certain circumstances can induce corrosion.

Types of corrosion

There are several different types of corrosion process that can occur to steel. The electrochemical reactions are similar, all producing the same outcome, but the physical circumstances, time taken to

occur, and structural danger posed by the end result, differ greatly from one another. Below is a summary of the types of steel corrosion that occur, particularly in marine environments, and the structural danger posed by them (summarized from ^v and ^{vi}).

General surface corrosion / Uniform attack

The metal is attacked more or less evenly over its entire surface. No areas are subject to preferential attack, so the metal is thinned away until it eventually fails. This is the visually most obvious form of corrosion, which causes the human description “rusty”. Local anodes and cathodes exist, and change places across the metal’s surface over time so that the overall effect is uniform.

Crevice Corrosion, Pitting Corrosion and Stress-corrosion Cracking

Local anodes and cathodes exist on the metal’s surface, but their locations are fixed so that corrosion continues into the metal, deepening rather than spreading across the surface. This means that the structural consequences are more dangerous than general attack corrosion, because the metal becomes significantly thinner at localized points, focusing strain and stress and weakening the metal at that point. In pitting corrosion, the protective oxide film that passivates the metal’s surface is broken down locally in one spot. This could occur because of various reasons, but in marine environments, a major culprit is the presence of the chloride ion Cl^- . Once the passive film is broken, the underlying metal is vulnerable to electrochemical corrosion. The surrounding metal still has its passive film protecting it so further corrosion occurs at the site of the pit, deepening into the metal structure, forming a discontinuity and therefore a weak point. This becomes a focal point for stress, leading to stress-corrosion cracking and ultimately structural failure.

Bimetallic Corrosion

Also called Galvanic or two-metal corrosion, this occurs where there is a junction of two different conducting materials immersed in an electrolytic solution. The materials do not necessarily have to be metals; graphite can be one of them. Usually, though, galvanic corrosion occurs between dissimilar metals. Alloys with the same constituent metals but differing proportions can also exhibit galvanic corrosion at the join.

The reason that galvanic corrosion occurs is that there is a measurable electrical potential between any metal and an electrolytic solution. In a given electrolytic solution, for example seawater, then the potential of each metal is known when compared to a standard electrode. For these purposes the electrode is made of calomel, a mercury chloride with the chemical formula Hg_2Cl_2 . Compared to the standard electrode, the electrical potentials of each metal can be measured. This gives rise to a known series called the Galvanic Series in Seawater, which orders commonly used marine metals according to their electrode potential, compared to the standard calomel electrode. The series is well known and appears in several places in literature. Not all versions of the series agree, but they are generally very similar to each other.

Essentially, looking at the Galvanic series in Seawater, the further apart two metals are in the series, the greater the galvanic corrosion that will occur between them. This is because the relative potential between the metals is greater the further apart they are in the series, and the greater the current that will flow between the two metals through the seawater. The greater the current, the greater the electrochemical breakdown on the metal’s surface and the greater the corrosion produced. The metal with the more negative electrode potential is the anode, and the one with the more positive potential is the cathode.

Galvanic corrosion products (rust, in the case where the anode is a type of iron or steel) occur at or near the junction of the two metals. The corrosion sites for this type of corrosion are not as localized as in the case of pitting or crevice corrosion, but they are more localized than in general or uniform attack.

Flow Induced Corrosion

Also known as Erosion-corrosion, this type of corrosion occurs because of the repeated movement of a corrosive electrolyte against a metal. In the case of marine structures, this most commonly refers to sea water waves against steel structures. The repeated mechanical action causes the corrosion to worsen and turbulent or irregular flow causes increased attack of the electrolyte against the metal walls.

Selective Leaching and Intergranular Corrosion

This is also known as selective leaching or de-alloying and occurs when corrosion affects one metal element much more than another in an alloy. The result can leave a frail, brittle compound devoid of its strength and structure. Weld decay (properly known as Carbide Precipitation) can be considered a form of de-alloying, or intergranular corrosion, which is described below. Carbide precipitation occurs in low-grade steel, near to a weld, when it is heated to gas welding temperatures (550°C – 850°C). At about 1-3mm away from the weld this range of temperatures is experienced, and while the metal cools slowly, chromium carbide forms at grain boundaries. This means in practical terms that the metal in these areas loses its resistance to corrosion and in certain situations has been known to crumble to powder^{vii}.

Hydrogen Embrittlement

Hydrogen molecules can be introduced into most metals due to their small size and high mobility^{viii}. These molecules can be present from various metal treatment methods such as melting, rolling, cleaning or electroplating, and they are the product of corrosion reactions. The inclusion of hydrogen in metals results in the loss of ductility of the metal and stress-corrosion cracking.

Corrosion Fatigue

Fatigue is the name given to the result seen in materials when they fail or fracture at loads below their ultimate tensile strength when a repeated cyclic stress is applied^{iv}. The effect is seen much earlier if the material is in a corrosive environment and so the term corrosion fatigue was coined to show that both corrosion and fatigue were occurring together.

Physics of Corrosion

Passivity

If a steel is alloyed with chromium at a proportion of greater than 10.5%, and the carbon proportion is less than 1.2%, then the steel is classified as stainless and is corrosion resistant under normal operating conditions. If the environment contains sufficient oxygen (either air or water), the chromium will form a layer on the surface of the steel of chromium oxide. The chromium combines preferably with the oxygen, thus preventing the formation of rust.

Current Corrosion Monitoring Technology

Corrosion sensing technology at the present time is to be reviewed as part of this project. There are several corrosion sensor systems currently existing, and in reviewing each one, consideration will be given to the suitability of the system to the needs of a marine offshore environment. The following criteria will be evaluated for each sensor:

1. Ease of manufacture. One of the principles of this sensor system is that it is distributed, meaning that several identical sensors will be scattered across an area and each one will report its findings to a base station. As a result, each individual sensor must be self-contained and must be capable of working autonomously. As such a system will require many such sensors, each one must be easily manufactured.
2. Small size. Each sensor must be small compared to the area being sensed, so that an array of them can cover a reasonable area.
3. Cost of manufacture. It is hoped that a market can be found for this system that does not preclude individual private users or small scale companies such as private boat owners or council-run harbours.
4. Scalability. The sensor must be capable of being reproduced many times to create a network.
5. External usage. The sensor must be capable of being used externally to the corroded area. It must be capable of being moved away from one area and towards another; it must not require embedding within a structure, nor to be attached when the structure is first built.
6. Capable of sensing through marine water. In the marine offshore environment, the medium between the corroded metal and the sensor is likely to be marine water.
7. Capable of sensing through a waterproofing medium. If sensors are to be placed on an underwater structure, the sensor package will have to be waterproofed so that the electronics can work. Inside the sensor package, all the components will have to be kept within some sort of waterproof medium. The same requirement applies to the networking system that the sensor uses to communicate within the distributed system.
8. Low power requirements. As mentioned above, if frequent battery changes are necessary this negates the effect of having an automatic corrosion sensing system. Another way of overcoming this problem is by using energy harvesting, so that the system is fully or partially self-powered.

These above requirements could relate only to part of the system: for example, a signal could be injected into an area of metal and the received signal from each sensor is evaluated.

The first stage of this project is to review current state-of-the-art in corrosion monitoring, and see if any current technology meets the above requirements.

A search of IEEE Xplore catalogue listing for “corrosion sensor” on 3rd November 2015 yielded 524 results. Understandably, a great deal of research has been conducted into this area and the timescale of this project dictates that only a portion of it can be reviewed.

Sun et al.^{ix} investigate the use of energy harvesting for embedded sensors in reinforced concrete. They examine the concept of utilizing the smelting process of the iron to release micro-currents that can be used to charge a battery to power the electronics of the system. They then continue to propose a network architecture for the distributed corrosion sensors.

Their idea is limited to sensors that are embedded into the steel structure when it is created, thus failing our criterion number 5 for external use. Also, in the available version of their paper, no experimental settings were given for reasons of restricted word count, but it does not seem viable that the smelting process, which happens only once at the start of the steel’s life, can produce enough stored electricity to power the sensor system throughout any significant portion of its life which may be as long as 50 years. Alternatively, if when using the term “smelting” the researchers were referring to the corrosion process

itself, then it seems from their description that they are both storing and sensing the same micro-fluctuations in current that occur because of the ion movement during the corrosion process. They also claim that this amount of harvested power would also be enough to power the radio frequency part of the wireless sensor network, and go into detail about the theoretical architecture of such a network. The network they describe is a standard wireless sensor network using a gateway system – data is handed across sensors to the closest sensor to the base station which then relays all the sensor data across. The timeslot notation that they use is a standard TDD data transfer technique. Experimentally, nothing was achieved beyond the first stage of energy harvesting, and from what they describe, corrosion sensing was not done concurrently with energy harvesting so it is disputable whether the two could be done at the same time. Splitting the tiny amounts of charge from ionic corrosion development into two for capacitor charging and sensing means that the amount that is sensed will often fall below the sensing limit, or it will be sensed wrongly because it is so minute.

The above paper does however raise an interesting point: corrosion occurs when a chemical change takes place involving the flow of ions. In the case of rusting corrosion, which is what the term “corrosion” usually refers to, iron is changing into iron oxide (rust). This process is a multi-stage chemical reaction^x during which iron and other elements gain or lose electrons and therefore become electrically charged. It is explained in brief above. Thus during the chemical process of rusting, it should be possible to electronically detect the fact that it is happening using suitable highly sensitive sensor systems.

Larsen^{xi} describes a system used increasingly in bridges in Florida, USA, where there are over 10,000 bridges constructed using either steel reinforced or pre-stressed concrete, a considerable portion of which are exposed to marine water. Her article refers again to sensors that are embedded into the steel when it is manufactured, and so are not immediately suited to our application. The sensors used are SAW (Surface Acoustic Wave) sensors which consist of a SAW crystalline device mounted on a tuned antenna. The SAW device also has a reflector array and a transducer deposited on the crystalline surface. The antenna receives an RF signal from an interrogating transceiver and converts the RF signal to an electrical shaped pulsed (in effect, demodulating the signal). The signal then travels across the crystal and bounces back from the reflector array. Any change in temperature, pressure or humidity will cause a shape change in the crystal due to the mechanical strain that the crystal is now under, and this will be shown as a phase change in the returned signal. The returned signal is re-modulated onto an RF pulse and this is transmitted back to the transceiver showing that the sensor has undergone some sort of shape change. With careful data analysis and signal processing, phase changes due to corrosion-induced shape changes at the crystal can be monitored. The sensor system is still at research stage but shows a great deal of promise as a corrosion sensor for internal steel structures when the SAW sensors are embedded at the time of manufacture.

An example of using change in capacitance to monitor corrosion can be found in the research done by Chen et al. (2014)^{xii} where it was found that a capacitive sensor constructed from the same material as that being monitored for corrosion would reliably increase in capacitance proportionally to the amount of corrosion that had occurred. The researchers also found that the resistance of the sensor decreased proportionally to the amount of corrosion. The research was excellently documented and supported by scientific observations and electrochemical facts throughout. The main difference between this example and the sensor that it is intended to develop as part of this research is that our team hope to

create a sensor that does not corrode itself but that can be used externally, outside the corrosion, to monitor what is happening to the metal.

Rinaldi et al.^{xiii} describe a “multi-parameter integrated corrosion sensor” which uses many different COTS and bespoke sensors to form an overall corrosion warning sensor system, in order to reduce the cost and unreliability of inspection in the corrosion monitoring process in aircraft. As part of this sensor system, they employed a passive electrochemical sensor made by Aginova Inc. called an XCorr. The paper states that the XCorr sensor measures corrosion through the anodic – cathodic current sites on a metal’s surface. Although the paper was concerned with aircraft monitoring and therefore primarily corrosion of aluminium rather than steel, the XCorr was considered to be worthy of further investigation later on in this project. Another part of their sensor, used by them for humidity monitoring, was an interdigitated capacitor. This device is used for example under rubber or plastic buttons, for example on computer keyboards or calculators, to detect when a button is pressed. An image is shown below:

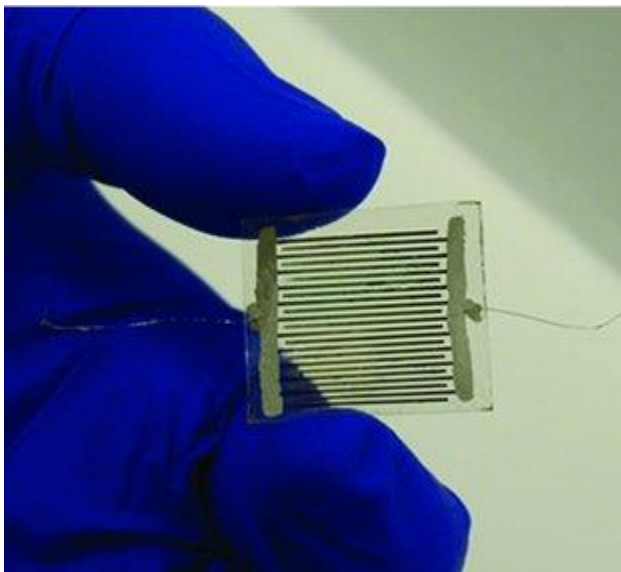


Figure 1: Interdigitated Capacitor, from onlinelibrary.wiley.com

An interdigitated capacitor consists of two metal conductors etched on to two (usually clear) plastic substrates. The capacitance is dependent on the distance between “digits” and any interdigital dielectric substance injected between the substrates. These capacitors could also be used as corrosion sensors, because their capacitance value is affected by the distance between the digits. Usually, one side (one of the plastic substrates) is stuck to a surface to be monitored and the other floats freely close to it. If the surface moves, the capacitance changes. In the case of corrosion monitoring, if the surface expands because corrosion occurs, that would cause a measurable change in capacitance that could be used as a sensor.

Bray et al.^{xiv} describe a corrosion detection system using K Band (24 GHz) radar. This utilises the difference in reflectivity due to the presence or absence of corrosion products on the metal’s surface. As this paper is written for the purpose of evaluating the K band detector’s usefulness in detection of corrosion in aircraft materials under different coatings, they are primarily concerned with aluminium corrosion. The usefulness of this type of detector in sensing steel corrosion would be the subject of a whole new investigation. However, this type of detector fails the criteria 1, 3, 6 and 8 as it is neither

easy nor low-cost to manufacture, requiring specialist equipment and fine tuning at that high frequency. Also it would not work through water due to the high absorption level of water molecules to K band radio waves, and it would require high power because of this. However, the principle that radar reflectivity changes due to the dielectric properties of the surface is as valid for rust as it is for aluminium corrosion.

Qi and Gelling^{xv} look at corrosion monitoring and detection state of the art in 2011 and review technologies including optical fibre, acoustic, electromagnetic, eddy current and galvanically coupled sensors. In their paper they mention a sensor based on an LC electrical circuit where phase, frequency or magnitude change of an RF signal is used to monitor progressive change of corrosion.

Yonemoto and Shida, in their two papers^{xvi,xvii} look at the capacitive and inductive properties of rust vs. metal surfaces and propose a dual mode sensor looking at both inductance and capacitance. They are concerned with very thin rust films (0.04 μm) and are trying to minimise the effect of avalanche breakdown of the rust layer on sensor circuit switch-on. Their circuit imposes an AC current and measures the impedance that is returned, at various thicknesses of rust from 0.001 to 1 μm .

From the above papers and from looking at the chemistry and electrochemistry of corrosion, the following sensor technologies are currently considered worthy of further investigation for the purposes of sensing early stage corrosion:

1. Pulsed RF energy. This system is envisaged to contain an active part, through which pulsed RF energy is passed, and a passive sensing part that responds to the active RF signal. From brief initial lab experiments, it was found that a square wave of frequency 1kHz when passed through an inductor of value 0.7mH produced a signal consisting of higher order harmonics at the transition of the square wave. This provided pulsed RF energy. Theoretically, these harmonics would induce magnetic fields in nearby metal that would differ if the metal were corroded from if it were uncorroded. The passive sensor, an identical inductor, would then detect a difference in the signal induced from corroded versus uncorroded metal. Initial experiments showed promise but the difference in signal was tiny and would have to be very carefully filtered to make obvious the change seen.
2. Capacitance change. It can be seen from the above papers that capacitance alters as metal corrodes. It is intended to use an interdigitated sensor to measure the change in capacitance between corroded and uncorroded metal. One possibility of relaying this change into an RF network is to use a 555 timer circuit where the capacitance change modifies an RF signal's modulation by changing the mark-space ratio or similar. Currently this sensing technique is only at the idea stage; future work will be necessary.
3. Acoustics / ultrasonics. It is envisaged that by using sonic waves, possibly pulsed, and received by a network of tuned microphones, any discontinuities caused by crevices and pits filled with corrosion will show up as reflections or attenuations and differ from the expected signal. Guidance will be sought from the Acoustics research department and Solent Acoustics.
4. Optical. In one instance of visible spectrum monitoring, seen in use at Southampton University, a wireless webcam was used to look at a projected pattern of white light on a surface. If corrosion or other displacement occurred, the pattern would change and image processing would pick up the variation.

5. Heat / IR imaging / Thermography. It was noticed while using a soldering iron with a less-than-optimal tip that rusty areas do not radiate heat as efficiently as healthy metal does. Although this method of corrosion detection should not be discounted, it is considered that for an autonomous discrete distributed sensor system, the costs and power requirements for heating the metal sufficiently would be too high, especially in a remote offshore environment.

Capacitance Change Monitoring

The consensus was reached that, given the time and resources available during this project, the way forward and a novel way of detecting and reliably sensing corrosion was to investigate the capacitance variation between corroded and uncorroded surfaces.

When the iron or steel undergoes surface corrosion, a layer of rust appears on its surface. In corrosion that is not within pits or crevices, the corroded metal's surface provides a flat surface onto which a sensor can be placed. The rust itself has dielectric properties that differ from those of the metal, so it should be possible to measure and detect the presence of corrosion by detecting the difference in dielectric properties of the surface itself. The dielectric layer can form the centre region of a capacitor and then the sensor is detecting a change in capacitance. This sensing method is limited to types of corrosion that present a flat surface on which the sensor can be placed; pits and crevices cannot be evaluated for corrosion using this method. However, the capacitance change across a crevice due to the presence or absence of corrosion products is potentially a measurable quantity and is worthy of future work.

Another change caused by the transition of steel to rust is a change in volume. Rust takes up more volume than uncorroded metal and swelling occurs during the rusting process. This change can be monitored using an interdigitated capacitor covering the metal's surface. The capacitance value is determined by the proximity of the digits and this proximity will change when the surface turns to rust and swells in the process. Thus, in theory, a capacitance change will occur. Further work is required to determine if this capacitance change, which would happen over a long period, could be monitored.

Changes in capacitance can be monitored using a 555 timer circuit. The 555 timer itself is a very versatile integrated circuit, used extensively in electronics, which can be configured as a monostable, bistable or astable voltage level generator, depending on external circuitry. The 555 timer IC has been around since 1971 and is now manufactured by many different companies. Market forces have pushed down the unit price to about 20 pence per unit. Using it as an astable device would mean that it could give an output clock signal with a frequency depending on the capacitance connected between Ground and the IC's "Threshold" level.

Although the 555 timer itself is not capable of generating frequencies high enough to be used in a wireless sensor network, the signal generated by the 555 timer circuit can be modulated onto a radio frequency signal to form part of the wireless sensor network. This method fulfils all the criteria mentioned on p6 and p7, especially the cost criterion; as a result, the decision was made that the 555 timer method is the essence of the sensor system that will be presented in this project.

ⁱ JACOBSON, G.A., Date Unknown, *Corrosion 101: Corrosion - A Natural but Controllable Process* [viewed 6th November 2015]. Available from: <https://www.nace.org/Corrosion-101/>

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