Research Report
(Corrosion under insulation-Latest inspection techniques)

CHE 597-Professor Ray Mentzer
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Joseph Humes
Kai-Che Shen
CHE 597 Group 3

Executive Summary

Corrosion under insulation (CUI) is a major problem that plagues manufacturing facilities and refineries around the world. It is estimated that the damage caused by corrosion under insulation accounts for an estimated $2.2 trillion when considering repairs, pauses in production, and outside contract hirings. The main cause of CUI is water penetration of the outer metal cladding of the pipe. The water seeps through the insulation and contacts the temperature differential that is present at the interface between the pipe and the insulation. Over several heating and cooling cycles, the water evaporates and condenses. In conjunction with any anions present (chlorides, hydroxides, etc.), a salt forms, which is highly corrosive to stainless steel, which is a key material of choice for construction given its mostly unreactive nature. CUI is also problematic and complex to diagnose, given that the problem occurs under one or more layers of insulation and metal cladding. In the past, the primary method involved a trained operator spot checking key locations along the pipeline. However, modern techniques involve more complex, but reliable, methods to understand where CUI is occurring.

The CUI analysis revealed several new techniques that are saving manufacturing facilities millions of dollars by negating the need to strip the insulation to get to the affected area:

1) Radiographic techniques involve x-ray sensors placed at specified intervals down the length of the pipeline.
2) Ultrasonic thickness measurement (UT) involves using ultrasonic sound waves, similar to how SONAR operates.
3) Pulsed eddy current requires an electronic probe that can determine the average thickness of a given sample

During the course of the analysis, there were several recommendations that could minimize the impact of CUI on major refinery and manufacturing operations.

1) Coat the piping with an anti-corrosion spray, such as thermal sprayed aluminum, before the insulation is added
2) Make the piping out of one material to prevent galvanic corrosion
3) Use high heat-conductive metals to prevent stress cracking due to chloride degradation

Preventing corrosion entirely is impossible, as everything will corrode to some degree over the working lifecycle. However, due to the difficult and costly nature of corrosion under insulation, it is imperative that the effects be mitigated, such that repairs and maintenance can occur at more widely spaced intervals. If the effects of CUI can be mitigated, the manufacturing and refining industries can save billions of dollars over the lifespan of a facility.

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Introduction

Corrosion under insulation (CUI) is a major problem that plagues the refining industry. An insulated pipe experiences corrosion, much like all pipes and metal containers in the refining industry. These insulated pipes are numerous in a chemical manufacturing facility, and are installed usually for process reasons, but can also be installed to protect personnel. Spotting this corrosion is incredibly difficult.[6] The main method in the past was to strip the piping of the insulation, which involved stopping the flow of product in the pipe (which often meant shutting down units before and after the segment of piping being inspected).[2,6] This meant that the cost to check for piping corrosion could be enormous, which is just considering the pause in production. If the pipe needed repair, the costs could quickly reach dizzying levels.

Another facet of CUI is knowing where to check on the pipe. In refineries, there are miles of piping that connect various reactors, storage tanks, settling tanks, and columns. To remove the insulation from all of the pipes to check for corrosion would just not be possible, both on a fiscal level and on a time level.[1] In the past, spot checks were performed by experienced operators who knew where to check.[1,3] However, this method was extremely dependent on the skill of the operator. Also, the skill of an operator did not translate to a different facility, as a different piping layout, materials of construction, and environment varied from facility to facility.[3] Finally, relying on the skill of the operator also meant maintaining historical records, which often were neglected or lost.[2] This resulted in difficulty during training or historical data evaluation with the intent of determining trends or patterns.

A common cause of corrosion in insulated piping is water penetration. The insulation surrounding the pipe is usually clad in a metal casing to prevent environmental factors from deteriorating the enclosed piping.[5] This piping may crack, corrode, or deteriorate over time, allowing water to seep into the insulation. This water can come into contact with the heat differential produced between the pipe and the insulation, which can cause the water to condense over multiple heating and cooling cycles.[3] However, other factors, such as oxygen, salt electrolytes, alkaline or acid substances, and chlorides can also increase the severity of CUI. CUI is a common occurrence for most industries as the water can be acquired easily from rain water, washing water, leakage and flooding in the piping system.[3]

CUI is a serious problem, and can cause leaks of many different chemicals in the manufacturing industry. From the report of the World Corrosion Organization, corrosion under insulation costs around $2.2 trillion for the global economy every year, and almost 40 to 60 percent of maintenance costs for piping are caused by CUI.[2] Thus, an efficient approach to detect CUI is very important for chemical industries, and some inspection methods for CUI will be introduced in the following content of the report, including visual inspection, radiography, ultrasonic thickness measurement and pulsed eddy current.

Literature Review

Elsadig and Farayi published a literature review that considers the advancements and research conducted in the area of corrosion under insulation in the past thirty years.[5] It considers coatings under the insulation, causes of CUI (especially considering moisture and ion penetration on austenitic stainless steel cracking), and several techniques to combat CUI (including neutron backscattering, capacitive imaging and pulsed eddy current). This paper also includes several industrial standards that relate to CUI.[5]

Yuan-Hao and Jun publish a paper detailing a new method to detect CUI.[6] This novel method, known as Building-Information-Modeling (BIM), uses a number of RFID tags placed throughout the plant to collect site data to develop a building or facility-wide model. This can then be used to calculate a corrosion rate, which is a key metric in predicting corrosion. This paper mainly focuses on the theory and functionality of BIM, which makes it a useful source for future technologies.

De Vogelaere highlights several case studies related to CUI.[4] In doing so, he describes several root causes and recommendations to prevent CUI from ever occurring. One of the recommendations are risk-based inspections (RBI) and details on how RBI should be conducted in a chemical manufacturing facility.

Finally, Caines highlights several instances of CUI in marine environments.[7] Given the vast multitude of undersea cables that carry the world's information, maintenance is of the utmost importance. Additionally, given the difficulty in reaching these cables, methods of preventing CUI are critical. Caines proposes several types of corrosion tests, and in general describes the methodology to develop statistically significant data pertinent to CUI.

Problems to be analyzed

CUI is a severe problem to most chemical industries because it happens under the insulation, which makes it hard to detect and predict directly. The results of CUI can cause the shutdown of equipment, influence to the whole process in the plant, or worse situations that process safety incidents may be induced. Unfortunately, corrosion is unavoidable since the oxidation reaction tends to occur once the surface of pipes is exposed to the moisture. The oxidation takes place on the energized surface of metals and elutes metals as the ions where corrosion occurs. According to other factors stimulating the generation of CUI, corrosion can be classified into three types- galvanic corrosion, alkaline or acidic corrosion, and chloride corrosion. Galvanic corrosion would happen if pipes are built with dissimilar metals. Once metals are immersed in water with a salt electrolyte, one metal as the cathode is protected while another one as anode starts to corrode. The rate of corrosion for anode is accelerated compared to the corrosion rate for uncoupled one. Regarding alkaline or acidic corrosion, water dissolving alkaline or acidic chemicals can cause damage to aluminum or steel jacketing. Sometimes, if there are chloride ions in pipes, alkaline water may even produce etching and pitting, which are considered as more severe corrosion. With respect to chloride corrosion, it tends to happen for most austenitic stainless steel if the temperature of surface is above 60 °C. The source of chloride ions comes from the evaporation of rain water or process water, and the temperature governs the reaction mainly. To be more specific, if the temperature is below 80 °C, 100 ppm of chloride ions do not tend to cause corrosion; if the higher temperature happens, even lower concentration of chloride ions may give rise to the damage.

CUI actually has caused several process safety incidents and financial loss for chemical industries. For instance, on April 16, 2001, the leak of flammable gases from the de-ethaniser column overhead line caused the subsequent explosion and fire in the Humber refinery plant, United Kingdom.[4-] The root cause of this incident can be attributed to the corrosion of the 6 inch diameter pipe, which brings about the rupture of the pipe. Finally, this incident cost the company approximately 1 million euros for health and safety breaches. From the lesson of this incident, the insufficient inspection for corrosion and maintenance of equipment could lead to severe safety issues. Thus, efficient approaches to detect CUI and other measurements for mitigating corrosion should be emphasized more for chemical industries.

Analysis of the problem

Corrosion under insulation (CUI) is a complicated problem that is plaguing refineries and chemical manufacturers around the world. It accounts for trillions of dollars of product lost, revenue spent on repairs, and inspections. However, there are thousands of scholars and industry professionals working on understanding the complex corrosive processes that occur, in the hopes of mitigating the damage done or wholly preventing the processes from occurring. Understanding CUI requires engineering principles such as heat and mass balances, mass transfer, diffusion effects, and process safety analysis.

Elsadig notes several elements that have to be taken into account when considering CUI: anodic and cathodic reactions, the electrolyte, and metallic conduction.[5] To prevent corrosion, halting any of those four elements is crucial. However, preventing corrosion is nearly impossible, which is why most scientists and industry professionals are concerned with slowing down the corrosion process. Given the difficult nature of detecting corrosion under insulation, one of the major tasks for industry leaders is slowing down the progression of the corrosion, as well as finding new methods to easily detect corrosion.

Corrosion under insulation occurs due to the annular space created between the pipe and the insulation.[7] The interface between the two materials causes a temperature differential, which can cause any water vapor present to condense in the annular space, seen in Figure 1.

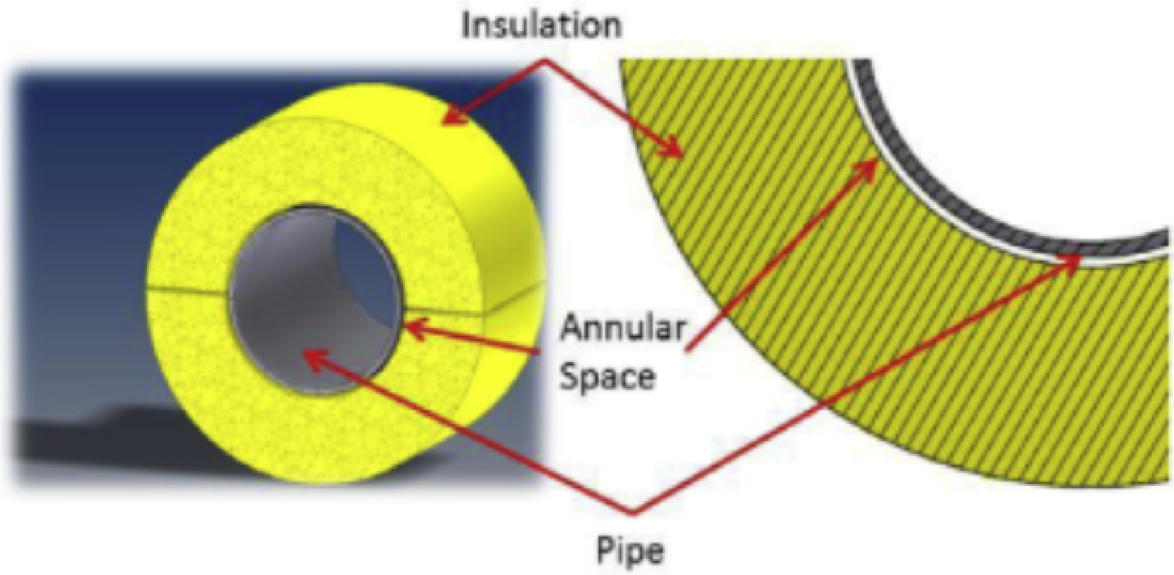

Figure 1. The annular space between a pipe and insulation is shown. Figure from Caines et al. [7]

Normally, piping is made of stainless steel, which is mostly chemically inert.[5] However, the condensed water can dissolve any salts present, forming a saltwater solution, which is highly corrosive to stainless steel.[5] This corrosion can be seen in figure 2.

Figure 2. Corrosion under the insulation of a pipe. Note the relative lack of corrosion on the exterior metal cladding compared to the inner pipe.[2]

It is imperative to find ways to keep water out of the insulation. One way to prevent this would be to increase the thickness of the insulation, making for a more difficult path for any water to reach the interface of the insulation and the steel.[5] However, difficulties in insulating joints in the insulation, bends in the steel, and removing defects in the insulation make this a more complicated problem.[5] Figure 3 highlights the joints in the material, making complete insulation difficult.

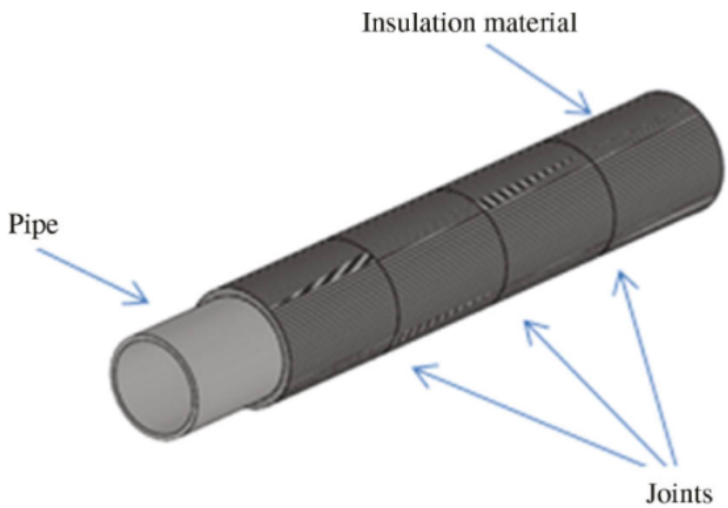

Figure 3. A schematic of an insulated pipe. Joints in the insulation make it difficult to keep all water vapor from reaching the pipe. Figure drawn from Elsadig.[5]

There are several areas that are expected to have high susceptibility to CUI. As mentioned, bends in piping are susceptible to CUI given the difficulty in casing bends in protective cladding and insulation. However, the API-570 (piping inspection code pertaining to in-service inspection, rating, repair, and alteration of piping systems) discusses several more areas that are susceptible to CUI.[5] These areas include fittings, hangers, platforms, areas that are exposed to mists from cooling towers, places close to steam vents, and areas exposed to high moisture and acid vapors.[5]

CUI is also particularly common in areas that have high operating temperatures. Elsadig mentions several areas that consistently have large temperature swings: carbon steel piping systems operating between 150°F and 400°F, deadlegs and attachments that protrude from insulated piping and operate at a temperature different than the active line, and austenitic stainless steel piping systems that operate between 150°F and 400°F.[5] These cyclical temperature cycles allow water to enter into the insulation as a liquid, which is much more likely to penetrate the insulation than water vapor. CUI is also common in areas that have high vibration (which could provide a pathway for moisture to reach the annular space) and some environments, such as humid or hot areas, marine spaces, or areas that have high atmospheric contaminants.[5,7]

There are many governmental guidelines pertaining to CUI. As mentioned, API-570 details how to properly inspect a pipe, including in-service inspection, rating, repair, and alteration. API-583 details maintenance, design, inspection, and mitigation techniques for pressure equipment, storage tanks and piping due to CUI. This is a particularly robust guideline, as it details all of the variables that would impact CUI and how they can be mitigated, such as temperature, pipe coating type and age, insulation types, climate effects, maintenance practices, and a way to rank the risk of equipment for potential CUI. ASTM C795-08 describes specification for thermal insulation for use in austenitic stainless steel, including physical and chemical parameters that must be met in the insulation design.[5] This standard makes note of the corrosive nature of ions that are left behind in the insulation by the evaporation of rainwater or firefighting water, which speeds up the corrosion process.[5] In conjunction with this standard, ASTM C692-13 and C871-18 detail standard testing methods to test the physical and chemical integrity of both the steel piping and the insulation surrounding the pipe.[5] The ASTM G189 guideline details a laboratory simulation of corrosion under insulation, which is important if standards are to be consistent across different industries.[5]

There are several cases that highlight the damage and danger of CUI.[4] In 2004, an ammonia leak occurred at one of Yara's ammonia production facilities. It was found that there was extensive damage due to corrosion in a four-inch elbow, as seen in figure 4.

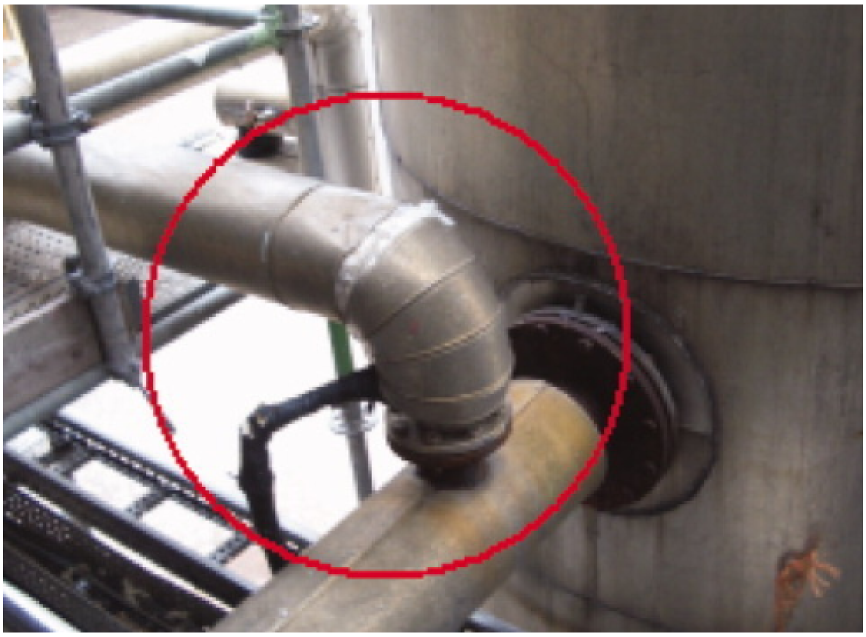

Figure 4. The damage in the elbow is shown. More frequent inspections could have caught this before it turned into a serious incident.[4]

The pipe was insulated, but the quality of insulation and steel cladding used was below the standard, which allowed water to enter.[4] Furthermore, infrequent inspections failed to see the damage present, which subsequently led to the leak.[4] Analysis of the incident found that the process conditions were optimal for CUI to occur, with operating temperature swings regularly between -5°C and 120°C.[4] The combination of a lack of integrity in the insulation/coating and process conditions led to a corrosion problem that ultimately was responsible for a massive ammonia leak. Following this incident, the Yara plant updated its inspection program and commenced a plant-wide analysis of the piping for potential missed conditions that could lead to CUI.[4]

Another incident took place at a different Yara ammonia plant in 2005, also caused by corrosion under insulation. In 2005, a gas fire occurred in a high-pressure synthesis loop bypass pipe. The bypass line was kept at 80°C, which resulted in condensation forming at the interface between the insulation and piping, causing CUI.[4] The inspection program at the plant did not include the analysis of small-bore piping, therefore had no maintenance program in place for such a pipe. The incident resulted in no casualties, but the Yara plant and the ammonia industry as a whole began an in-depth inspection program of bypass pipes, as well as a scheduled maintenance schedule for such pipes.

Strategies to detect CUI

Industries prefer nondestructive testing technology for CUI because it can prevent the time-consuming and laborious operation. As mentioned, past methods involve spot checking piping by an experienced operator, which involves removing the outer metal cladding and insulation to inspect the piping.[1,2,4,5] However, the inability to transfer this skill to other employees, lack of historical recordkeeping, and lack of transferability to other manufacturing facilities necessitates a more quantitative method to test for CUI. The following testing methods are often used in industries, and they can be combined for a more complete inspection.

Visual inspection:

Removing the covering of pipes is required during operating this method, and examiners can observe the surface visually to find the signs of corrosion.[1] Even though visual inspection is simple and obvious for discovering damage, examiners can only observe the outer areas of pipes without the inner inspection.[1] Furthermore, because the new insulation needs to cover pipes after testing, this inspection is more costly. The specimen also tends to be contaminated if examiners operate improperly.[1] This method also involves stopping flow in and around the pipe, which can be costly depending on the severity of repairs required.

Radiography:

X-ray technology can detect the change of thickness which can be interpreted as the form of corrosion, and then provides the outline of the diameter through the whole pipe.[1] Combining with other advanced software or digital imaging, examiners can acquire the best observation, and data is also portable, traceable and digital archiving, which makes the inspection more efficient.[1] This technique can be utilized in various approaches, including computed radiography (CR), real-time radiography (RTR) and digital detector arrays (DDA), which are applied in different situations.[1] Furthermore, CR requires the access to both sides of observed parts, and DDA is only applied properly to small structures while the performance would be reduced as the diameter of pipes increase.[1] Radiography scans of piping can be seen in figures 5 and 6 below.

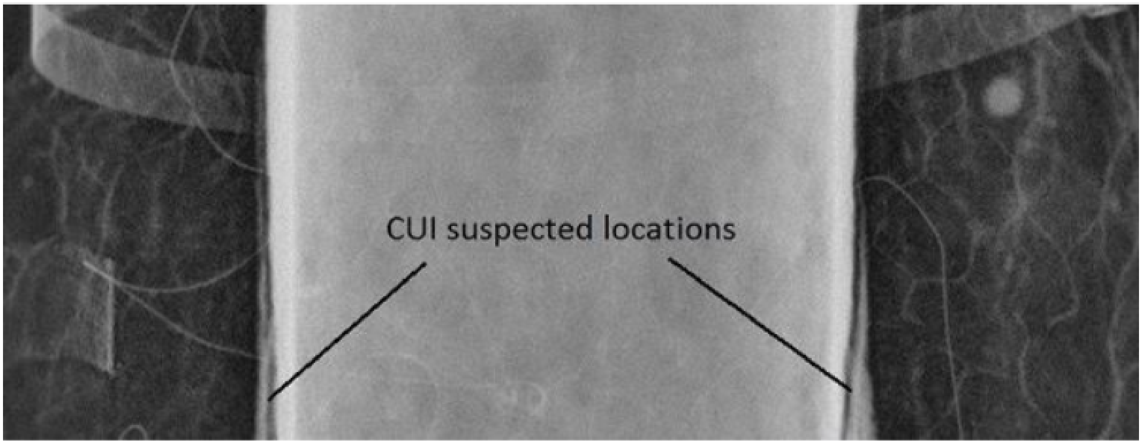

Figure 5. Radiography shows the scan of pipes, and indicates the suspected location of CUI.[11]

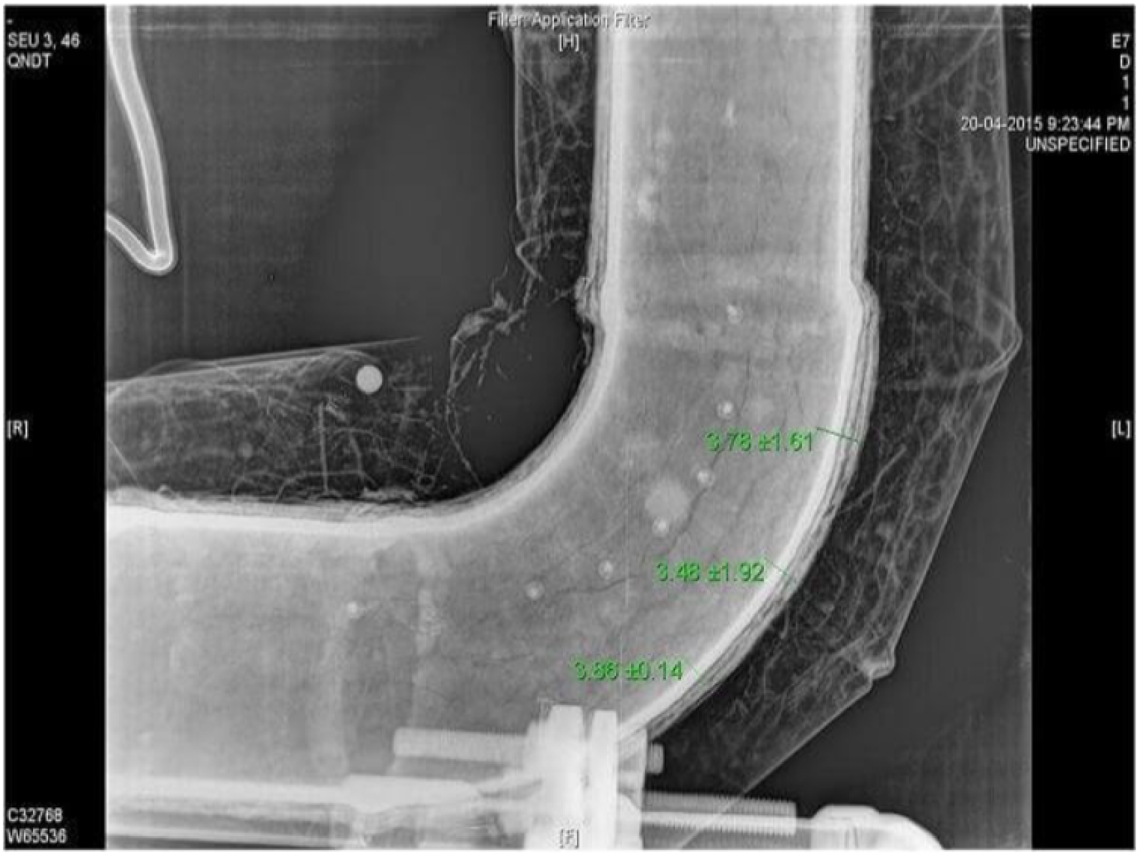

Figure 6. Computed radiography can detect the reduction of wall thickness of pipes.[11]

Ultrasonic thickness measurement (UT):

This inspection works with the measurement of how long it receives a reflected sound pulse from the sample.[1] Initially, one sound pulse will be spread from an ultrasonic transducer, travel through the inner tested pipes, and finally will be reflected back to the detector. The data of thickness of pipes will be calculated and be shown on the screen. However, the drawback of this measurement is that it can be only applied to the small region, and operators need to calibrate it for different materials.[1] Figure 7 shows how a UT instrument can be applied to an insulated pipe.

Figure 7. Applying long range ultrasonic testing to observe the situation of pipes.[11]

Pulsed eddy current:

This technique utilizes electromagnetic waves to detect the average thickness of pipes.[1,12] There's no requirement that the probe has to contact the sample, and it can track the rate of reduction of induced current and convert it to the data of thickness of the object. Although the measurement is accurate, the data cannot reflect the area of corrosion because it only provides the information of average thickness.[1] Furthermore, this inspection is also limited to carbon steel and low-alloy steel construction.[1] Figure 8 shows the relative ease at which a pulsed eddy current instrument can be deployed on a pipe.

Figure 8. How pulsed eddy current technique is used in the plant.[12]

Conclusion

It has been found that there are numerous causes of corrosion under insulation. The root cause is water entering into the annular space between the pipe and insulation. This area has a high temperature difference, which over several operating cycles, can cause the water to condense and vaporize. In doing so, ambient salts that may have been deposited on the pipe or in the insulation dissolve in the water and create a saltwater solution. This solution is highly corrosive to stainless steel and can cause structural failure as demonstrated in the cases studied. The salt solution can also cause galvanic corrosion (a form of oxidation and reduction reaction that occurs on the surface of the metal), stress cracking, and steel deformation.

One of the major concerns regarding CUI is the difficulty in analyzing suspect portions of pipe. In the past, CUI was determined by an experienced operator spot checking various pipes around a facility. Then, the insulation and metal cladding would be removed to inspect the pipe. Such a task is laborious, costly, and overall inefficient. However, there are a variety of new techniques available which promise to increase the efficacy of finding and repairing corrosion under insulation before a disaster occurs. These include radiography techniques, pulsed eddy current, and ultrasonic thickness measurements. Each of them can be combined with each other to use for more accurate observation. Furthermore, according to the reference we found, there is a novel detecting technique called Building Information Modeling (BIM). It can create the facility-wide model through utilizing a number of RFID tags placed through the plant. This model can calculate the rate of corrosion and predict the future situation.

Although CUI is an unavoidable damage for chemical industries, there are still several approaches to mitigate corrosion. Firstly, companies can increase the thickness of pipes, but they also need to take financial issues and mechanical requirements into consideration. Moreover, coating under the insulation is the great strategy since it can prevent the surface of metal pipes from oxidation reaction. Thermal spray aluminum (TSA) is common to use as coating material, and it can work as a sacrificial anode, which is protective for the underlying metal pipes. Also, engineers should emphasize the design of piping structures for mitigating corrosion. Complex shape and bends need to be avoided; higher heat-conductive and stress-resistive metals are suitable for the material of pipes. Finally, setting up the complete management for regular inspection and maintenance can mitigate the damage of CUI, and companies also have more time to prepare the measurement to improve the situation.

Recommendation

CUI is caused by the electrochemical reaction happening on the surface of metals, so the solution to corrosion is to prevent the progress of ions exchange from pipes. The first approach is the application of coating under the insulation. Thermal sprayed aluminum (TSA) is often used as protective material against corrosion, and this coating technique is suitable for carbon steel with a lifespan of over 25 years . Because TSA works as a sacrificial anode, it can prevent the underlying metals of pipes from electrochemical reaction, as seen in figure 9.

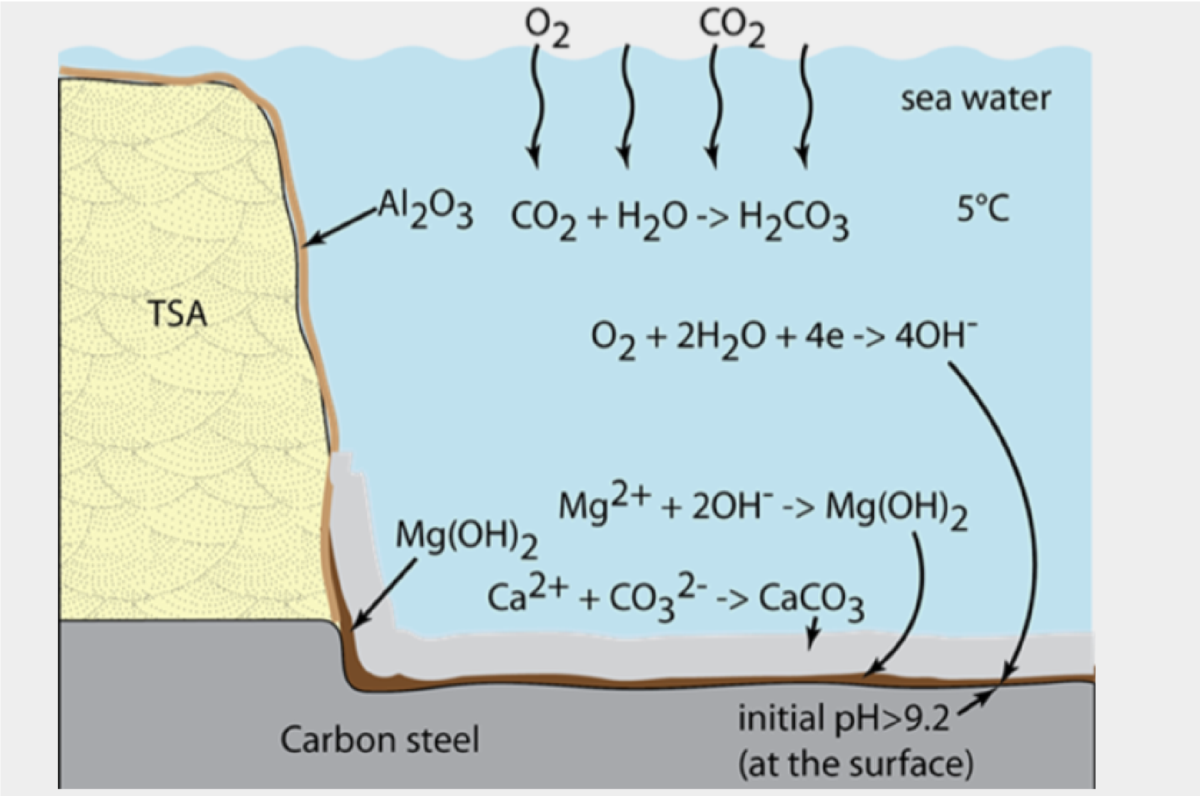

Figure 9. A mechanism of TSA coating on carbon steel in seawater. The surface of TSA is used as a sacrificial anode, and provides electrons to oxygen.[9]

The exterior coating of the pipe or vessel can have drastic impacts as to the severity of the corrosion. Figure 10 demonstrates the damage caused by corrosion on an uncoated metal surface.

Figure 10. Damage due to uncoated metal can be seen. Such damage can be prevented by applying anti-resistant sprays to metals before their service life begins.[4]

Furthermore, the proper design of pipe structure can also mitigate the corrosion. The most important factor is to avoid heterogeneity, including different metals constitution, uneven temperature distribution, and large pressure gradient. Consisting of different metals may cause galvanic corrosion; overheated spots of pipes may stimulate the corrosion while cold spots can lead to condensation of water vapor, which also enhance the corrosion; high stress can generate stress corrosion cracking if the pipe has been in the environment of corrosion. Therefore, choosing suitable materials is an important issue because it can improve the above mentioned problems. For example, engineers can select high heat-conductive metals as the material of pipes, and examine whether these metals are susceptible to stress cracking. Sharp corners and complex geometry of pipes should be also avoided because these designs may impede the coating treatment, and make cleaning or drying harder. Moreover, minimizing the turbulence is helpful for mitigating corrosion, so the design of sharp bend needs to be avoided in the piping system.

Finally, regular inspection and maintenance for CUI can also mitigate the severity of damage. Through non-destructive inspection techniques, engineers can find the problem before corrosion truly brings about extreme damage to the equipements. Moreover, utilizing some software with the results of inspection can help engineers evaluate the proper measurement and maintenance for the situation. For instance, applying the data of CUI inspection, mechanical integrity inspection, and thickness data to AsInt's CORE CUI App, it can perform the assessment of future planning and mitigating steps.

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