Corrosion Under Insulation

Michael Cordon
David Harvey
Matthias Kiesel

ChE 597
Team 2G
December 4, 2017

Executive Summary

Corrosion under insulation (CUI) is a major safety threat to chemical processes with pipes and pressure vessels for moving and storing fluids where anions and cations are transported via water to pipe surfaces to corrode away pipe surfaces. Since insulation is necessary for minimizing energetic losses to the environment and therefore can significantly affect the economic feasibility of processes, insulation is required for economic optimization yet insulation hinders the ability to visibly monitor corrosion to external pipe surfaces. CUI is responsible for up to 60% of corrosion related incidents and the direct damage done by CUI is estimated to be $276 billion per year as of 2005. This report discusses CUI causes and types of damage to pipelines, different techniques of CUI detection, and the strengths and weaknesses of each of these techniques. It was determined that a combination of several existing techniques is required as the most efficient way to prevent and mitigate CUI from both an economic and time standpoint. Finally, this report looks at several experimental techniques that are being studied for the improvement of CUI detection.

Besides physically removing the entire swaths of insulation from pipes which is extremely costly, four other technologically sophisticated possibilities are discussed here. Neutron backscattering is an inexpensive screening method for detecting moisture in insulation while X-Ray radiography can be used for real time scanning in small appliances and also in more complex settings to create a detailed picture of the pipe or vessel. Ultrasonic thickness measurement (UTM) uses soundwaves to measure the thickness of the pipe and is especially helpful when dealing with difficult geometries as a secondary measurement method. Pulsed eddy current (PEC) utilizes electromagnetic effects to generate an eddy within a flowing fluid and then measures decay rate of the magnetic field to calculate the wall thickness. Combining these methods efficiently is essential for cost effective CUI detection with recommendations given at the end of this report for the most effective combination. Research in the field of CUI aims at providing steady state screening methods to eventually make in person measurements unnecessary. These techniques could significantly improve the cost effectiveness of CUI detection and reduce the risk of incidents caused by CUI.

Introduction

Insulation has been widely used for decades to maximize energy conservation and maintain temperatures in flowing fluids. However, effective insulation requires complete encapsulation of metal pipe and tank walls which can cause a hidden corrosion danger under said insulation. These same concerns can also be applied to fireproofing materials which protect pipes and tanks in case of fire[1]. Corrosion under insulation (CUI) is becoming a common safety issue as metal wall failures have become increasingly prevalent within aging chemical plants, resulting in fluid releases from piping and tanks. This in turn can result in the release of flammable compounds and explosion and fire hazards. From an economic standpoint, CUI is responsible for roughly 40-60% of all pipe maintenance costs which can total around 10% of a facility's overall maintenance budget if left unchecked[2]. Overall, this issue has been identified to cost as much as $276 billion per year for the chemical and petrochemical industries, with up to 60% of corrosion-related incidents occurring on pipelines.

Traditional CUI is caused by the aqueous intrusion into insulation (or fireproofing[1]) surrounding process pipes. As water diffuses inwards, anions (alkali, alkaline) and/or cations (halogens, nitrates, sulfates, etc.) dissolve and diffuse into water as it moves towards pipe surfaces, leading to the eventual buildup of highly corrosive solutions in close proximity to pipe walls. These corrosive solutions can be of much lower (or higher) pH than bulk fluid measurements and will begin to break down protective coatings given enough time and high anion or cation concentrations. Higher temperatures also lead to higher corrosion rates until water evaporation eventually occurs. Upon additional water intrusion, anions and/or cations in the newly made solution continue their localized attacks on the pipe's structural integrity[3].

Localized attacks on pipe walls typically occur through either pitting or stress-corrosion cracking (SCC). Pitting refers to the localized attack of a corrosive agent on passivating films which first ruptures protective passive films prior to forming holes in metal walls, allowing for small fluid leaks and releases. Released corrosive fluids typically result in significantly more severe pipe damage as the corrosion spreads radially, increasing the pit size over time[4]. Stress-corrosion cracking of alloys and metals (stainless steel by chlorides, alkali and/or nitrates on steel, ammonia on copper) is often caused by conditions well below those of traditional fracture formation. Microscopic cracks permeate throughout the piping due to only mildly corrosive conditions but remain imperceptible to the human eye until the pipe becomes quite brittle and cracks. This behavior is caused by localized attack from corrosive agents and can happen both on exterior and interior pipe surfaces[4].

CUI safety incidents and near misses caused by the factors mentioned above have been studied for over 50 years now with many explicit safety incidents occurring globally. Notable incidents include the oleum release at a DuPont plant in 2010 caused in part by pitting from CUI[5], the hydrocarbon explosion and resulting fire at a Williams Olefins petrochemical plant in 2013[6], and an explosion at a DOW light hydrocarbon plant in 2008[7]. These incidents are by no means limited to the United States though with lists of CUI incidents occurring under EU and OECD jurisdiction[8] or in specific countries such as Japan which date back to at least 1965[8]. These incidents are a conglomeration of pitting and SCC incidents and often result in explosions and/or fires. Statistically, the most commonly released compounds are hydrogen and hydrocarbon products which easily lead to explosions and fires and are arguably the most dangerous component of CUI incidents[8].

Some preventative measures are known and globally used to mitigate CUI concerns overall. To some extent, these preventative measures are dependent on the material of construction of the pipes and tanks in question. Organic coatings are often applied to external metal surfaces to hinder CUI through unfavorable interactions between the organic film and the aqueous solutions. However, these films degrade over time with lifetimes lasting from 5-13 years on average[2]. Since this is often a lower lifetime than the equipment they protect, the organic coating must be maintained and reapplied periodically[1]. As the film breaks down, the potential for pit or crack formation increases significantly. In addition to the organic films, aluminum foil has been widely used as a protective anionic layer to prevent against cationic attack. This preventative measure is commonly used due to its immediate accessibility, low initial cost, and simple installation. Aluminum can also be applied through thermal spray aluminum which applies an aluminum coat of increased thickness to withstand more severe CUI environments for longer durations. Improvements in the inherent design of insulation and the associated appropriate installation to eliminate water presence and buildup is also a critical preventative method[2]. This combination of preventative techniques serves to lengthen the lifespan of pipe and tank walls from CUI but is not useful for directly detecting piping sections where CUI is occurring. Additional details and risk analysis equations have been published by the American Petroleum Institute for analyzing CUI requirements and concerns[9].

Objective of Report

The objective of this report is to understand the scale and severity of corrosion under insulation in the chemical and petrochemical industry with regards to both the inherent safety concerns and the economic costs. Current detection methods are discussed for identifying potential CUI occurrences and analyzing the severity of these situations. Strengths and weaknesses of each technique will be discussed including detection limitations, applicability to tanks, pipes, or both, and their relative costs. Additional discussion will focus on the desired attributes of an ideal CUI detector along with the research needs necessary to support the development of this type of technology. Then, recommendations are provided for which current techniques should be used in tandem to best collect CUI data and prevent potential CUI incidents from occurring.

Literature Review

CUI has become increasingly concerning as chemical manufacturing facilities age. CUI incidents discussed above focus primarily on relatively recent release scenarios within the United States. Here, the Chemical Safety Board acts as a primary source for individual, full-scale CUI incident investigations[5,10] with news report and journals providing more easily digestible stories[6,11]. In addition, companies will occasionally publish their own findings and reports on release or near-miss scenarios[7]. Since CUI is a global issue though, foreign governmental and regulatory agencies from both Europe and Asia have also investigated CUI incidents looking for general trends in CUI-related incidents[8,12].

There is a wide body of literature, both peer-reviewed and otherwise, looking at the various types and underlying causes of CUI in industrial applications. Notable publications include reports from the National Board of Boiler and Pressure Vessel Inspectors[3], NACE International[13], and ASM International[4] written on corrosion methods, detection, and mitigation. These sources go into detail regarding how CUI rates are affected by a number of variables including temperature, humidity, and anion and cation content. More simplified approaches come from professional presentations[13,14] or shorter articles[15]. This provides a general overview of CUI issues and the parameters known to increase CUI rates, forming a broad understanding of CUI concerns.

CUI risk-based inspection technology guidelines have been previously published by NACE International[1] and by the American Petroleum Institute[9] since many CUI incidents occur in petrochemical applications. Comprehensive reviews and presentations are available for predicting CUI occurrences[16] and predicting areas likely to experience more rapid CUI rates[15,17]. Economic comparisons for some general CUI prevention methods were reported by ExxonMobil in 2005 with a focus on simple preventative measures[2]. Each of the budding detection methods discussed below (neutron backscatter[13,15,17], radiography[13,15,17], pulsed eddy current[18–20] , and ultrasonic thickness measurement[21]) have detailed technical specifications reported along with their strengths and weaknesses which are summarized in Table 1. Newer techniques currently being developed for CUI applications include microwave detection[22] and fiber optic acoustic emission sensing[23,24] with sources providing both details on each technique's technical capabilities along with how they can be utilized for identifying minute cracks in pipes.

Current Detection Methods Overview

Some generalized preventative measures for protecting pipes and tanks from CUI are already in place in many chemical plants which include the implementation of organic coatings on pipe surfaces, thermal spray aluminum or aluminum foil wrapping for protection against cathodic attacks, and the use of personnel protection cages in place of insulation when the primary goal of insulation is personnel protection rather than energy conservation and temperature consistency. Next, detection methods will be discussed as ways of identifying potential CUI occurrences prior to failure scenarios occurring. Each method is discussed with its strengths and weaknesses which are collected together in Table 1 below.

Table 1: Qualitative comparison of CUI detection method strengths and weaknesses.

Technique	Damage to Insulation	Detection of Hotspots	Screening Ability	Applicable to Vessels	Applicable to difficult geometry
Insulation Removal	Not Applicable	Yes	No	Yes	Yes
Neutron Diffraction	No	No	Yes	Yes	Yes
X-Ray Scanning	No	Yes	No	No	Limited
Ultrasonic Thickness Measurement	Minor Damage	No	Limited	Yes	Yes
Pulsed Eddy Current	No	No	Yes	Yes	No

Method 1: Visual Inspection of Metal Surfaces

The most obvious method for detecting CUI instances occurring on tank surfaces or sections of piping is through direct physical inspection. By necessity, this means removing the insulation or fireproofing from the suspected section of metal wall and physically analyzing the potentially affected areas. This most likely coincides with a halt in operations since the temperature could not be easily maintained while the insulation is relocated. Insulation removal is a slow and therefore expensive process and must be reinstalled with great care to ensure that water remains outside of the insulation and away from the pipe surfaces. This method is the most direct means of detection but may lead to false negatives since SCC fissures and cracks (and even pits in some cases) are often invisible to the naked eye. This method also requires significant time and understanding for determining which pipes are most likely to experience CUI incidents and requires developing and implementing a rigorous preventative maintenance program to ensure that release scenarios do not occur. For instance, more regular visual inspections would be required for pipe and tank sections that are exposed to the weather, especially in locales with higher precipitation rates. This doubly applies in naturally humid climates where water accumulation occurs more readily or in particularly hot environments where CUI occurs more rapidly. This is often considered the most expensive method for determining and predicting CUI incidents[2].

Method 2: Neutron Backscatter

Neutron backscatter is a technique that can be used to detect moisture in the insulation of pipes and vessels[13,15,19]. It operates by sending a beam of high energy neutrons through a pipe or vessel. If there is moisture in the insulation, the hydrogen atoms in the moisture will reduce the energy of the neutrons and they backscatter in such a way that they come back to the detector. The detector counts the number of low energy neutrons where the number of counts is proportional to the amount of water in the insulation[13]. The neutrons are produced using a radiation source, and because the high energy neutrons do not show up on the detector it gives an accurate measure. This technique was first introduced for monitoring liquid levels in ammonia tanker cars as it detects any hydrogen-rich solutions[17].

The biggest drawback of this technique is that it does not detect corrosion directly. It can only indicate where corrosion could occur more readily[13]. This means that further investigation of direct methods is necessary to determine if corrosion is occurring. Additionally this technique can give false positives for corrosion depending on the conditions and must be calibrated based on dry samples[14,19]. The advantage is that this technique is very fast, versatile, and small[13,15,19]. This technique can be used to scan a lot of pipe quickly and can give potential problem areas for CUI[13]. Because it is light, it can be used without additional scaffolding[13,19]. Additionally, this technique can be used for both piping and vessels[15].

Method 3: X-Ray Radiography

Radiography is another nondestructive technique used for the detection of CUI. Radiography utilizes x-rays to create images and profiles of the piping. There are 3 common techniques for radiographic use of x-rays: real-time radiography, computed radiography, and digital detector arrays. Real time radiography uses an x-ray source or radiation source with a detector to create a profile of the outside of the pipe[13,14]. Computed radiography and digital detector arrays work slightly differently by creating a profile of the entire pipe. These can be used to not only detect corrosion but measure corrosion levels quantitatively[13]. Computed radiography uses an imaging plate to digitalize the images from the x-ray source[19]. The image plate uses a "photo stimulable phosphor" and can produce an image in between 1-5 minutes[13]. Digital detector arrays are similar to computed radiography only instead of a film or plate, flat-panel detectors are used to detect the x-ray radiation from the source. This method is quite sensitive so they require less radiation than a film dependent technique.

These techniques have similar pros and cons compared to each other. All of them provide imaging that is fast and quickly analyzed[19]. They also require radioactive sources and are more accurate on smaller pipe diameters as the signal is stronger[13,19]. Additionally they are more difficult than other techniques to use in tight spaces because they require access to both sides of the piping and thus are difficult to use on vessels or even pipes located in spots that are hard to reach[14]. Each of these techniques can provide quantitative measurement of wall loss within a pipe, however computed radiography and digital detector arrays give more detailed and sharper images which translates to more powerful information. When deciding between these techniques, cost and time are the distinguishing factors between these similar x-ray techniques.

Method 4: Pulsed Eddy Current

The pulsed eddy current (PEC) method relies on the induction of an eddy current within a pipe caused by a magnetic field generated by an excitation current. Figure 1[18] shows the circular excitation coil wrapped around two anisotropic magneto-resistive sensors (AMR) on top of the test object such as a pipe. The test object remains in a multi-layered state, meaning that the PEC method does not require the removal of insulation or protective coatings from the pipe surfaces though it does require the pipe to be filled with fluid. Each of these layers may have a different thickness, electrical conductivity, and relative magnetic permeability. For theoretical simplicity, the test object is assumed to be planar if the excitation coil diameter is smaller than the pipe diameter[18]. During PEC testing, the excitation coil generates an eddy current in each of the mentioned layers until a steady state flow is achieved. The excitation then stops and the sensor measures the decay of the magnetic field generated by the eddy current[18]. The desired output is either the maximum peak height for non-conductive pipe materials or the decay rate of the magnetic field for conductive pipe materials[20]. Additional repeat measurements can be obtained from changing the polarity to generate either positive or negative excitation currents[18]. Plugging in the known parameters and the measured magnetic field behavior, the wall thickness can then be calculated explicitly.

PEC application can be limited by insufficient information on the magnetic and electrical properties of each material of construction. Thicknesses of protective coatings and insulation must also be precise for reliable measurements. Therefore, this is not an infallible technique since this information must be accurately supplied. Furthermore, the resulting signal is averaged over an area of pipe and ultimately assumes an even wall thickness distribution in this area, meaning that the technique cannot locate small points of acute corrosion. This also limits its ability to detect CUI on equipment fittings which may have difficult geometries[19]. Overall, PEC is a noninvasive and cheap method to accurately measure wall thicknesses of industrial piping given adequate constants which does not require removal of insulation or protective coatings.

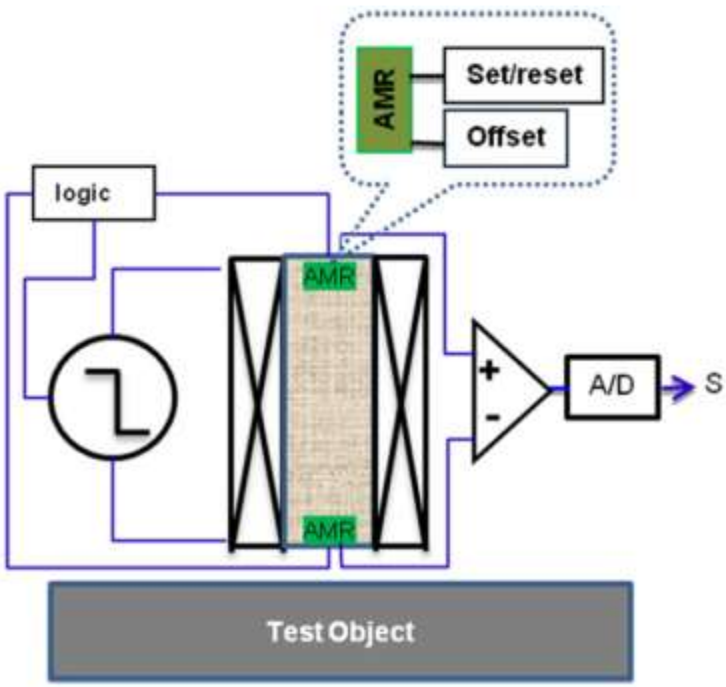

Figure 1: Structure of a PEC measurement device[18].

Method 5: Ultrasonic Thickness Measurement

Ultrasonic thickness measurements (UTM) make use of the fact that soundwaves have a characteristic velocity in each material and additionally are reflected on boundaries between different materials[21]. UTM operation occurs by emitting ultrasonic soundwaves into a pipe and measuring multiple echoes as the soundwave passes through the leading and lagging edges of each pipe wall. The time required to record these echoes can then be used along with the speed of sound through the fluid and the pipe material of construction to calculate the wall thickness for both sides of the pipe using the following equation: $l = \frac{ct}{2}$. Here, l is the wall thickness of the pipe, c is the celerity of sound through the metal, and t is the time it takes to measure the echo. These measurements are conducted in a pulse/echo mode in order to reduce the noise in the measured signal and can be repeated rapidly.

Important measurement parameters include the soundwave wavelength (ranging between 50 kHz and 20 MHz) and the transducer type. Longer wavelengths may be required for thicker pipes due to penetration depth concerns, but short waves yield more accurate measurements overall. Therefore, an optimal wavelength can be determined for a given starting thickness. More important is the choice of the transducer which emits the soundwaves and receives the echoes. Transducer choice and transducer mode will alter the measured timespan which is the critical measurement for determining the wall thickness. The simplest method measures only the time between the initial pulse and the first backwall echo. More advanced methods use a transducer which is slightly lifted off the surface to measure the time between the echo from the soundwave first entering the wall and the first backwall echo or the time between two backwall echoes as the soundwave bounces back multiple times[21]. These measurements therefore require accurate time measurements and accurate speed of sound values. Time measurements can be improved using multiple repeat measurements while the speed of sound through the metal or alloy may be generated by measuring the pipe prior to initial insulation placement and flow operations but held at the operating temperature (temperature will alter the speed of sound through the material).

The practical strength of UTM lies in its quick scanning nature and response time. The technique can also handle difficult geometries with minimal difficulty and relays accurate wall thickness measurements. However, two major weaknesses should be mentioned. First, the speed of sound through the wall is a function of temperature which much be rigorously accounted for to avoid systematic errors in wall thickness measurements. Since temperatures will vary throughout the plant, this may introduce sampling difficulty. Second, UTM typically requires direct contact between the transducer and the pipe wall, meaning that the surrounding insulation must be punctured prior to collecting measurements. This makes it critical to reseal insulation punctures appropriately to avoid water ingress and therefore mitigate higher corrosion rates after measurement. This resealing leads to higher costs with increasing sampled area, limiting the technique applicability.

Current Research Directions

The current techniques for detection of CUI typically are very accurate for a short distance of piping or are a screening method that can cover a lot of piping quickly while sacrificing accuracy or quantitative information. An ideal detection method would both give accurate information in terms of the location and severity of corrosion and monitor large sections of piping in real time. Several experimental techniques are being researched for this purpose.

One possible technique for this purpose is the use of microwave signals through insulation to detect water in the insulation. Microwave antenna can be placed throughout the insulation creating a network of water detectors within the insulation. If water is in the insulation it absorbs some of the microwave energy, causing an amplitude difference that can be tracked to roughly the spot of the wet insulation[22]. This technique would however still only screen for water in insulation much like neutron backscatter and thus would still only act as a screening technique.

Another promising area of research uses fiber optic acoustic emission sensors to detect corrosion in piping. An acoustic emissions sensor can be calibrated to give different signals based on the acoustic inputs. As pipes corrode the signal through the pipes tends to change[23,24]. By monitoring the frequencies, the corrosion can be tracked. While in its current state, this technology can't pinpoint the corrosion, it can be used to find problem areas in piping networks.

By pairing these future experimental technologies that can monitor pipelines with the current technology that can be used to pinpoint locations of CUI, problems can be prevented before they occur. Additionally, better prediction methods and models for CUI are being developed to assist in determining high risk pipes[16]. By predicting areas that are most likely to suffer from CUI, additional monitoring can be done in these areas. Implementing the technology based on risk allows for more efficient allocation of resources that could prevent CUI incidents. This also can allow for better planning of mitigation strategies especially in cases with toxic or flammable chemicals.

Recommendations

In the previous sections, the different techniques for detecting CUI were examined. Clearly each technique has its own benefits and disadvantages and is optimally used for different purposes within the field of detecting CUI. We recommend an approach with many different layers of detecting CUI. First of all, areas susceptible to CUI have to be identified and prioritized for detection measures. This step is not only performed within plant planning but also updated throughout the plant's lifetime. Susceptible areas should be updated as screening information becomes available over time. Additionally, when changes to the process or the equipment are made, CUI should be considered within a management of change procedure.

The second step in detecting CUI consists of utilizing scanning techniques. Scanning techniques are cheap and fast in comparison to other techniques, but at the cost of quality of information. Probably the cheapest and fastest technique is neutron backscatter, which has the ability to scan long stretches of piping or large vessels. Because of the previously discussed disadvantages of this technique, it should not be the only technique utilized but it remains as a strong example of a scanning technique to be used in the second step of the recommended approach. Other examples of scanning techniques that could be used are PEC and real-time radiography. These techniques could also be used to scan depending on the piping layouts and structures, as well as the cost to perform each technique.

The third step is to utilize more expensive quantitative techniques on problem areas identified by the scanning techniques to characterize the corrosion in these areas. Because changing equipment is expensive, quantitative data will allow for the exclusion of false positive results and determine the severity of CUI. The most reliable method for this task would be X-ray radiography to obtain a more complete picture of the extent of CUI. Unfortunately, this is not applicable to big vessels and reactors as both sides of the equipment have to be accessed. A cheaper measurement method is UTM. UTM is more applicable to difficult geometries and vessels but eventually has to be applied in a narrow grid to investigate CUI hotspots. Therefore, UTM is recommended for in-depth examinations since it is accurate and comparably easy to apply. Removal of insulation does not give strong advantages over any of the methods in this paragraph due mostly to its high cost; however, during planned plant shutdowns and revisions, removal of insulation can give accurate CUI measurements. Because each technique has strengths and weaknesses that are specific to the application, it is recommended that each technique be examined in both the scanning and quantitative categories before a selection is made.

Conclusions

Corrosion under insulation will continue to occur for the foreseeable future, making preventative maintenance and CUI detection methods of critical importance. Because insulation is a key part of the energy conservation strategy in many chemical processes, it will remain an important challenge in the near future. When combined, current techniques can be used in both screening and quantitative diagnostic capacities. By utilizing cheaper screening techniques such as neutron backscatter on large sections of pipe to identify areas of concern and then following up with more quantitative techniques that can be used to pinpoint and diagnose the damage to piping and tanks, damage due to CUI can be effectively detected. Through regular screening and data collection, effective predictions of problem areas can be used to determine the likelihood and frequency of necessary maintenance based on the surrounding conditions.

Experimental research in the area of CUI is moving toward a more ideal system where larger sections of pipe can be monitored in real time to pinpoint points of corrosion. Work is still needed to quantitatively track the corrosion of large sections of pipe in real time and it will be a long time before the ideal corrosion tracking systems are developed. By embracing the newest prediction algorithms for corrosion and utilizing the current technology, major incidents due to corrosion under insulation can be more readily prevented in the future.

Work Cited

1. NACE International. *SP 0198-2010 Standard Recommended Practice The Control of Corrosion Under Thermal Insulation and Fireproofing Materials—A Systems Approach*. **2010,** (2010).
2. Fitzgerald, B. J. & Winnik, S. A Strategy for Preventing Corrosion Under Insulation on Pipeline in the Petrochemical Industry. *J. Prot. Coatings Linings* 52–57 (2005).
3. Liss, M. Preventing Corrosion Under Insulation. (1988).
4. G. S. Frankel. *Corrosion: Fundamentals, Testing, and Protection*. *ASM Handbook* **13A,** (2003).
5. Board, U. S. C. S. and H. I. *Investigation report E.I. DuPont De Nemours & Co., Inc. Final Report Methyl Chlordie* (2010).
6. McGaughy, L. Geismar plant had history of noncompliance, leaks before fatal explosion. *The Times-Picayune* (2013). Available at: http://www.nola.com/environment/index.ssf/2013/06/geismar_plant_explosion_leaks.html . (Accessed: 3rd December 2017)
7. Sampaio, R. & Leite, A. Lessons ‘ Re -Learned ’ from Corrosion Under Insulation. (2009).
8. Wood, M. H., Vetere Arellano, A. L. & Van Wijk, L. *Corrosion - Related Accidents in Petroleum Refineries*. *JRC Scientific and Policy Reports* (2013). doi:10.2788/379
9. American Petroleum Institute. API RP 581: Risk-Based Inspection Technology. *API Recommended Practice 581* (2008).
10. The U.S. Chemical Safety Board. Williams Olefins Plant Explosion and Fire - Investigations. *Investigations* (2016). Available at: http://www.csb.gov/williams-olefins-plant-explosion-and-fire-/. (Accessed: 3rd December 2017)
11. Kemsley, J. Chemical Safety Board releases draft report on DuPont accidents. *The Safety Zone by c&en* (2011).
12. Chigusa, N. *et al.* Stress Corrosion Cracking Incidents and Repair Technologies on PWR Dissimilar Weld Metal Joints in Japan. 147–156 (2010).
13. James Higgins. Corrosion Under Insulation Detection Methods and Inspection. *NACE Section Meeting* (2013).

14. Mcfarland, S. Practical experience of corrosion under insulation-detection and mitigation.
15. Twomey, M. Inspection Techniques for Detecting Corrosion Under Insulation. *Inspectioneering Journal* (1996). Available at: https://inspectioneering.com/journal/1996-11-01/116/inspection-techniques-for-dete. (Accessed: 3rd December 2017)
16. Burhani, N. R. A., Muhammad, M. & Ismail, M. C. Available Prediction Methods for Corrosion under Insulation (CUI): A Review. *MATEC Web Conf. 13* **13,** 5005 (2014).
17. Charlton, J. S. *Radioisotope Techniques for Problem-Solving in Industrial Process Plants*. (Springer Netherlands, 1986). doi:10.1007/978-94-009-4073-4
18. Cheng, W. Pulsed Eddy Current Testing of Carbon Steel Pipes' Wall-thinning Through Insulation and Cladding. *J. Nondestruct. Eval.* **31,** 215–224 (2012).
19. Tremblay, C. CUI: The 7 Inspection Methods You Must Know About. *Eddies and Currents* (2017). Available at: https://www.eddyfi.com/ndt/surface-inspection/corrosion-under-insulation-7-inspection-methods-you-must-know-about/. (Accessed: 3rd December 2017)
20. Tai, C., Rose, J. H. & Moulder, J. C. Thickness and conductivity of metallic layers from pulsed eddy- current measurements. *Rev. Sci. Instrum.* **67,** 3965–3972 (1996).
21. Olympus. Thickness Gage Tutorial. *Olympus* (2017). Available at: https://www.olympus-ims.com/en/ndt-theory/thickness-gage/. (Accessed: 3rd December 2017)
22. Jones, R. E. Use of Microwaves for the Detection of Corrosion Under Insulation: The Effect of Bends. (2012).
23. Berthold, J. W. & Roman, G. W. Fiber Optic Acoustic Emission Distributed Crack Sensor for Large Structures. *J. Struct. Control* **7,** 119–129 (2000).
24. Machijima, Y., Azemoto, M. & Tada, T. Corrosion Detection By Fiber Optic Ae Sensor. *J. Acoust. Emiss.* **27,** 3–10 (2009).