



School of Engineering MSc Mechanical Engineering

Major Project
M7X01373

Interim Report

James Milling
1503259
December 2020

Table of Content

Table of Content	i
List of Figures	ii
List of Tables	ii
1.0 Introduction	1
2.0 Project Plan	1
3.0 Literature Review	2
4.0 Problem Definition	5
5.0 Reasons and Relevance of the project.....	6
5.1 Reasons	6
5.2 Relevance	6
6.0 Project Aim.....	6
7.0 Project Objectives	7
8.0 Research Question and Hypothesis	7
8.1 Research Question	7
8.2 Hypothesis.....	7
9.0 Experimentation Design	8
10.0 Experimentation Preparation	9
10.1 Pipe Sample Preparation	9
10.2 Insulation Material Preparation.....	9
10.3 Experiment Test Environment Apparatus.....	11
10.3.1 Rainwater Catch Tank	11
10.3.2 Environmental Tank	11
10.3.3 Support Arrangement	11
10.3.4 Water Distribution System.....	12
10.4 Control and Monitoring - Cyclic Heating Unit.....	12
10.4.1 PTC Heating Element.....	12
10.4.2 Microcontroller – Temperature Control	13
10.4.3 Microcontroller - Datalogger	15
10.5 Other Instruments	15
11.0 Experimentation Monitoring	16
12.0 Next Steps	16
13.0 References	17

14.0 Appendix 1 – Project Plan (Gantt Chart).....	20
15.0 Appendix 2 –Variables and Control Measures.....	21
15.1 Independent and Dependant Variables.....	21
15.2 Confounding variables	21
16.0 Appendix 3 - Observations to Week 9	23

List of Figures

Figure 4.1 Localised CUI on pipework (BoilerRock, 2017)	5
Figure 10.1 Pipe sample preparation.....	9
Figure 10.2 Insulation sample preparation, rock mineral fibre shown.....	10
Figure 10.3 Sectional view of pipe/insulation sample assembled.....	10
Figure 10.4 Samples arranged in environmental tank.....	11
Figure 10.5 Water distribution system in place within environmental tank.	12
Figure 10.6 PTC Heating element	13
Figure 10.7 PTC element and thermocouple assembly	14
Figure 10.8 Pipe sample prepared for cyclic heating.....	14
Figure 10.9 Heat cycle controller operating (Units to left of image).....	14
Figure 10.10 Datalogger in operation (Lower LCD).....	15

List of Tables

Table 15.1 Independent and dependant variables.....	21
Table 15.2 Confounding Variables and Control Measures	22
Table 15.1 Heating trend data for cyclic samples over 12-hour period	23
Table 15.2 Environmental water quality monitoring trend to week 9	23

1.0 Introduction

This interim report is produced as part of the major project and provides an update of the progress made to December 2020. The investigation focuses on the effect of water ingress into insulation materials associated with the insulation of carbon steel service pipework up to 50mm nominal diameter and the development of Corrosion Under insulation (CUI) and insulation water retention.

2.0 Project Plan

The project is scheduled in accordance with a Gantt chart project plan, a copy of the plan current to week commencing December 7th, 2020 is included within Appendix 1 for reference.

3.0 Literature Review

Corrosion Under Insulation (CUI) is a serious problem affecting process piping within refineries and other industries conveying process fluids, due to the significant of the problem both the American Petroleum Institute (API) and the National Association of Corrosion Engineers (NACE) outline causes and methods of mitigation, within API 570 Piping Inspection Code: In-service Inspection, Rating, Repair, and Alteration of Piping Systems. API 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry, and NACE Corrosion control in the refining industry. Both organisations confirm the temperature range over which CUI is likely to occur in carbon steel as between -12°C and 175°C, highlighting contributing causes as water ingress through insulation external weather cladding and cyclic temperature operation. The rate of corrosion being significant where the surface metal temperature is between 100°C and 121°C (API, 2016), (API, 2011), (NACE, 2010).

Whilst the position on general corrosion and degradation mechanism of both API and NACE align with respect to CUI, the position taken by API alters when addressing CUI specifically in API 583 Corrosion Under Insulation and Fireproofing. A lower range of between 77°C and 110°C is stated, API cite the reason being due to the process temperature being stated in many cases, rather the actual metal temperature. API point out that a critical factor in CUI is the presence of an aqueous layer on the metal surface covered by insulation, which can occur during a period of operation, either on or offline (API, 2019). The contradiction in positions of recognised authorities in asset integrity management suggest there is wider misconceptions with respect to the conditions under which CUI is likely to occur. A review of published experimental reports cite the simulated temperatures as process temperatures, not actual surface metal temperature.

Failures in pipework can be attributed to failure in a corrosion control system, Cosham, et al. describe a system combining the environment, coating condition and rapid corrosion which ultimately lead to corrosion failure, importantly the failure is not due to corrosion alone, but a failure in the corrosion control system. (Cosham, et al., 2007).

The application of suitable coating systems to process pipework as a barrier between the metal pipe and insulation is considered as an effective means of managing CUI, with Thermal Spray Aluminium (TSA) and organic coatings finding application in both process pipe and vessel protection throughout the petrochemical industries (Bahadori, 2014). A laboratory investigation comparing the corrosion resistance of a unprotected steel pipe section and a section where protected by TSA in a cyclic environment insulated with mineral wool confirms the effectiveness of TSA, the results indicating that the corrosion rate of pipe protected with TSA are reduced to 0.003 mm/year, a significant improvement over the unprotected pipe in the same environment where a corrosion rate of 1.0 mm/year was observed (Kane, et al., 2008). However, whilst there are significant gains in utilising TSA, the preparation, application and protection against damage of the coating system requires careful control to avoid localised corrosion rates of up to 0.03 mm/year.

TSA also has practical limitations with respect to pipe diameter and effective coating using manual application methods, with some systems limited to diameters above 75mm (Praxair, 2010). Pipe diameters associated with low pressure service steam distribution are typically in the range of 12mm – 50mm and are also subject to installation in restricted areas often routed around main process pipe and vessel systems. This restricted access can potentially cause set up problems for manual TSA application (Ashrafizadeh, et al., 2016), and the level of surface preparation required before application of TSA (Bock, 2015).

A case study undertaken on a failure of refinery a carbon steel process line due to CUI operating at 90°C supports the view of failure being attributed to a failure in the corrosion control system. The failure resulting due to aggressive localised corrosion where water had collected at the lowest point due to inadequate installation techniques, the remainder of the pipe system inclusive of coating and insulation system being in good order. The plant was located in a coastal area, on close examination of the corroded pipe evidence of chloride and sodium contamination was evident (Geary, 2013). An estimated corrosion rate of 0.6mm/year was suggested, correlating with figures published by NACE indicating temperatures over 80°C can result in corrosion rates of 0.75mm/y and above (NACE, 2010). The introduction of drainage openings within the outer insulation casing allowing the insulation to drain of water was shown to have a limited influence on CUI, and possible could accelerate the effect (Pojtanabuntoeng, et al., 2015).

Whilst corrosion in open systems decreases with increase in temperature, the same is not true of corrosion which takes place under corrosion, an increase in temperature correlates to an increase in corrosion, behaving in the same way corrosion would be expected within a closed system (Reichert, 1998).

Several published papers describe testing in accordance with the ASTM standard ASTM G189 – Standard Guide for Laboratory Simulation of Corrosion Under Insulation describes a laboratory test cell which simulates a cyclic environment which cycles between a wet period of 20 hours at 60°C, and a dry period of 4 hours at 150°C, which runs over a period of 72 hours. Where water is introduced as the test fluid into the area between the pipe wall and thermal insulation. However, ASTM cautions against standard laboratory test not considering actual service conditions, often presenting an inaccurate representation of the development of CUI where actual rates of corrosion are in excess of those developed in laboratory conditions (ASTM, 2013). This position is shared by Begg (2016), who proposed an alternative corrosion test which reflects field conditions with respect to geometry and wet/dry temperature cycles over a period of 60 days (Begg, 2018).

Field tests undertaken in Norway during 2010 and 2015 assessing mineral wool and cellular glass insulation with seawater used as the wetting medium Identified that the test samples subject to cyclic changes in temperature exhibited significant CUI compared to the samples which remained at ambient temperatures. Both tests being run over a three-month period with the earlier test focusing on insulated pipe subject to an operational temperature of

105°C and immersion for 30 minutes in seawater (NACE-Jubail, 2015). And the later subjecting insulated pipe to cyclic heating and cooling between ambient and 150°C, and intermittent wetting by seawater (Haraldsen, 2010). A further study suggests the rate of corrosion increased with an increase of seawater introduced to the insulation material (Eltaï, et al., 2016).

Burhani, et al. (2016) supports the position suggesting that the most influential factors in CUI are cyclic operating conditions with temperatures up to 120°C from ambient, where the most sever corrosion takes place at temperatures between 100°C and 120°C, their study also suggests that water retention within the insulation material is greater in this temperature range as it is less likely to dry completely (Burhani, et al., 2016).

Water vapour diffusion was analysed in a study of water permeable in semi-closed and closed cell insulation and the effect on corrosion rates attributed to CUI in a cyclic system in line with laboratory simulation described in ASTM G189. The study found that water permeable material which was able to dry where water could escape had low corrosion rates compared to those of semi-closed and closed cell construction (Rasmussen, 2017).

4.0 Problem Definition

Corrosion Under Insulation (CUI) occurs on steels where covered by insulation in the presences of water, it exhibits itself as a server form of localised corrosion, which if left uncorrected often results in loss of containment, unscheduled plant shutdown, and ongoing preventative maintenance costs (Winnik, 2008). The severity of corrosion is influenced by environmental and operating conditions, with the introduction of chlorides in coastal areas and cyclic operating temperatures exacerbating the problem. (HSE, 2013). Water and other contaminants such as chlorides primarily enter the insulation material due to a failure in the outer environmental barrier, caused by incorrect installation and maintenance procedures, or inadequacies in design (NACE, 2010).



Figure 4.1 Localised CUI on pipework (BoilerRock, 2017)

5.0 Reasons and Relevance of the project

5.1 Reasons

The condition of the insulation system and the associated environment barrier are of critical importance in mitigating against the onset of CUI. However, in practice this proves difficult to manage effectively due to the very nature of pipe system geometry, associated supports, valves, and other components which form part of a typical service pipe system. The potential for water ingress is high due to poor installation and maintenance practices. The extent of CUI with petrochemical refineries has been estimated to cost as much as 40 to 60% of pipework maintenance, which in turn accounts for 10% of a typical refinery maintenance budget (Fitzgerald & Winnik, 2005).

5.2 Relevance

Undetected corrosion can lead to loss of containment and the uncontrolled release of hazardous fluids, a study undertaken by ExxonMobile found that 80% of incidents in pipe systems CUI was identified as a contributory factor (Fitzgerald, et al., 2003). Such failures can result in much larger losses where the process fluid is flammable, and the pipe system forms part of a larger refining unit. One such example occurred in 2006, at an established petrochemical refinery on the US Gulf coast. A leaking 100mm diameter process line containing hydrocarbon fluids was identified as the cause of a major fire within the refining complex, destroying half of the unit in which the pipe was located, the cost of replacement was in the region of US\$50 million (Anderson, 2010).

6.0 Project Aim

The effect of rainwater ingress on thermal insulation associated with process service pipework in cyclic temperature applications where CUI is present as a degradation mechanism in manufacturing facilities in the South Wales coastal region has not been widely reported.

The intention of this research project is to contribute to the understanding of the effect of rainwater ingress and retention on thermal insulation materials in cyclic temperature applications and the effect on the development of CUI on carbon steel pipework located in manufacturing facilities in the South Wales coastal region. Carbon steel pipework is routinely specified as process service pipework in the diameter range of 12mm – 50mm and is used for the distribution of low-pressure steam and hot water for process heating and cleaning applications.

The research project investigates a range of factors to ascertain if the specification of thermal insulation materials in cyclic temperature applications where rainwater ingress is present has an influence on water retention and the development of CUI.

7.0 Project Objectives

The objectives of this research project are defined as:

1. Evaluate the effect of cyclic temperature change and the development of CUI on thermally insulated carbon steel pipework where water is introduced into the insulation material.
2. Evaluate the effect of cyclic temperature change within thermal insulation and water retention where water is introduced into the insulation material.
3. Draw conclusions and make recommendations based on the findings of the investigation.

8.0 Research Question and Hypothesis

From the project aim and objectives the following research question and hypothesis is developed

8.1 Research Question

What effect does cyclic temperature change have on the water retention of thermal insulation material and the development of CUI on thermally insulated carbon steel pipework where water is introduced into the insulation material?

8.2 Hypothesis

Cyclic temperature change will increase the water retention of thermal insulation material and development of CUI on thermally insulated carbon steel pipework where water is introduced into the insulation material.

9.0 Experimentation Design

The current social and travel restrictions in place due to the current Covid-19 pandemic have impacted on the design of the experimentation. It has not been possible to utilise the university laboratory facilities to run a laboratory experiment.

Therefore, due to the constraints a cross sectional quasi-experimental approach is applied to the study with the intention of undertaking an explanatory analysis, it is acknowledged that the sample size is limited.

As the research investigates the cause-and-effect relationship between rainwater and the development of CUI in temperature dependant conditions the dependant and independent variables are identified and considered to ensure appropriate controls are in place, detailed in Table 15.1 Appendix 2.

The confounding variables which are identified and potentially influence the research cause-and-effect relationship, and the respective control measures put in place to support validity in the findings of the analysis are set out in Table 15.2 of Appendix 2.

The duration of the experimentation, 12 weeks, aligns with studies discussed within the reviewed literature suggesting that laboratory test do not simulate service conditions and expected development of CUI in such applications.

The pipe and insulation material selected align with that commonly specified for service applications in process industries and are set out as defined below

Pipe sample

- Carbon Steel (*Tata Install Plus S235GT hot finished tube 48.3mm OD*)

Top row of samples

- Sample 1 – Cyclic - Rock Mineral Fibre Insulation (*Knauf HPS 035 AluR*)
- Sample 2 – Cyclic - Glass Wool Insulation (*Isover CLIMPIPE Section Alu2*)
- Sample 3 – Cyclic - Closed-Cell Elastomer Foam Insulation (*Union foam Eutobatex AT*)

Bottom row of samples

- Sample 4 – Ambient - Rock Mineral Fibre Insulation (*Knauf HPS 035 AluR*)
- Sample 5 – Ambient - Glass Wool Insulation (*Isover CLIMPIPE Section Alu2*)
- Sample 6 – Ambient - Closed-Cell Elastomer Foam Insulation (*Union foam Eutobatex AT*)
- Sample 7 – Ambient – Uninsulated reference pipe

The 12-week experiment simulates insulated carbon steel pipe exposed to ingress of rainwater both in ambient and temperature cyclic conditions.

The temperature and duration of the heat cycle, temperature cyclic condition, is based on a typical batch process application where a service, steam at 140°C, is required on a cyclic basis, 3 hours, for heating and cleaning purposes.

Both qualitative and quantitative methods are proposed in testing the hypothesis and observations and data is recorded accordingly.

10.0 Experimentation Preparation

10.1 Pipe Sample Preparation

The carbon steel pipe samples are sourced from the same supplied length of stock material to ensure the consistency of the material grade, the stock material being supplied with an external standard protective coating of *Tata Steel red paint*.

Each of the pipe samples are cut to a length of 60mm, half of the external protective coating as supplied is removed (0-180°) to expose the bare parent pipe material using a 120-grit abrasive flap sanding disc, ASTM G4 suggests that 120-grit abrasive will produce an acceptable finish (ASTM, 1995). The top position (0°) is marked on each end of the cut sample in addition to a sample reference using a paint marker pen.

The samples are placed in an oven at 120°C for 1 hour before the mass is recorded.



Figure 10.1 Pipe sample preparation

10.2 Insulation Material Preparation

The insulation material samples are sourced from the same supplied length of stock insulation to ensure consistency, the diameter of the insulation corresponds with manufactures specification for 48.3mm OD tube.

Each of the insulation material samples are cut to a length of 150mm. A 6mm diameter hole is formed centrally through the environmental barrier in the insulation material at the top position (0°), where the bottom is taken as the formed longitudinal split which facilitates fitting.

The samples are placed in an oven at 120°C for 1 hour before the mass is recorded.

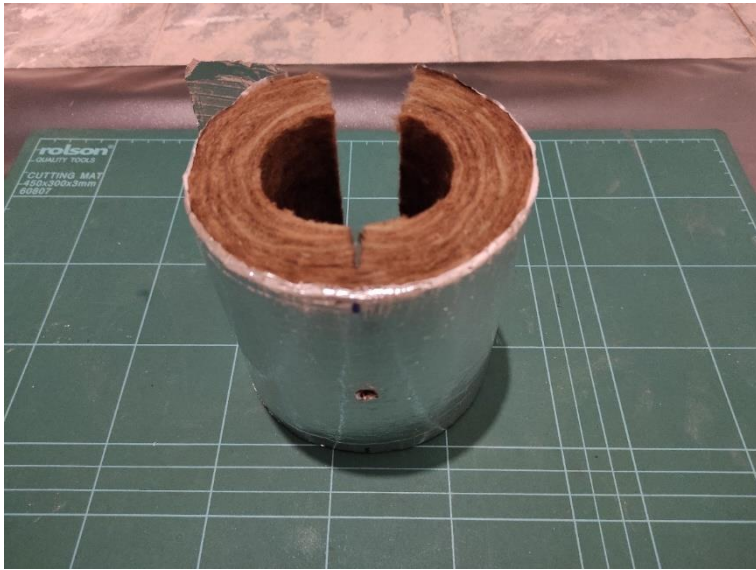


Figure 10.2 Insulation sample preparation, rock mineral fibre shown.

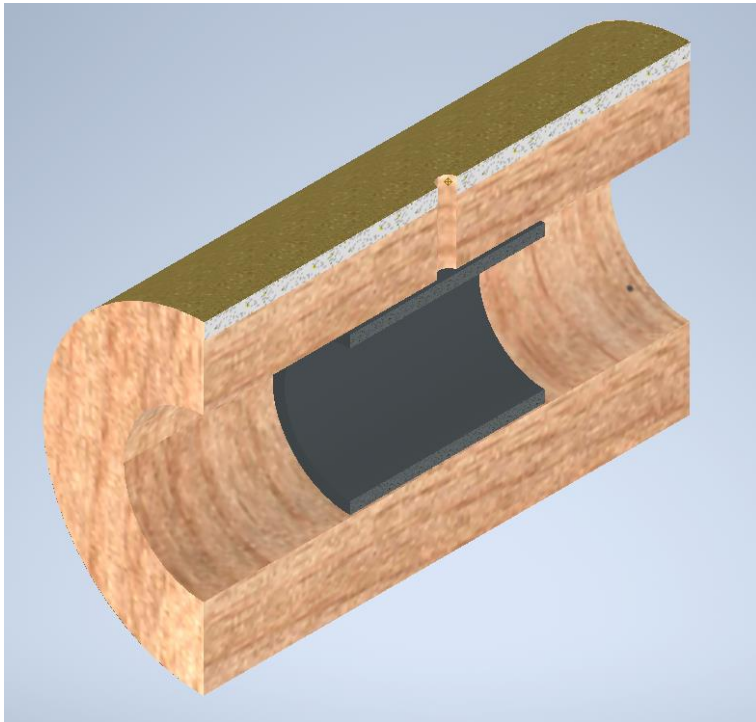


Figure 10.3 Sectional view of pipe/insulation sample assembled.

10.3 Experiment Test Environment Apparatus

The experiment is undertaken at a location 2.5km from the coastline in a northerly direction from the coastal city of Swansea. The experimental environment consists of the following apparatus.

10.3.1 Rainwater Catch Tank

The rainwater catch tank is located externally; rainwater is collected directly into the tank through a perforated cover. The capacity of the catch tank is 40 litres and is manufactured from polypropylene.

10.3.2 Environmental Tank

The environmental tank is located within an uninsulated and unheated external outbuilding which has open ventilation allowing the free circulation of external air at ambient temperature and humidity. The capacity of the catch tank is 80 litres and is manufactured from polypropylene.

10.3.3 Support Arrangement

The samples are support above the environmental tank water level by stainless steel wire. The samples being arranged in two rows, the top row is heated cyclically, the bottom row is unheated and remain at ambient conditions. The pipe sample and insulation are retained in position using a plastic retaining clip. Figure 10.4 shows samples placed in environmental tank prior to filling with water.



Figure 10.4 Samples arranged in environmental tank.

10.3.4 Water Distribution System

A small centrifugal fish tank pump (300litres/hour) is submersed below the water level of the environmental tank and distributes water through 4mm diameter PVC tubing to each of the suspended samples. The flow of water is controlled by a nylon needle valve so that each sample receives water at the rate of 3 drops/minute, a plastic funnel being partially inserted into the hole formed in the insulation material allows the drop rate to be monitored daily. The volume of each water droplet was estimated as $\approx 0.06\text{ml}$. To establish an estimation of the water volume droplet an average was taken over 3 sperate mass measurements where 30 drops were collected into a beaker from the outlet of a control needle valve. Over a 24-hour period each sample receives $\approx 260\text{ ml}$ of water which is recirculated within the environmental tank.



Figure 10.5 Water distribution system in place within environmental tank.

10.4 Control and Monitoring - Cyclic Heating Unit

The top row of pipe samples within the environmental tank are subject to a periodic heating cycle which mimics a typical service application in a process environment. The duration of each heat cycle is 3 hours, on completion of the heat cycle the pipe sample cools naturally to ambient conditions.

The cyclic heating unit consist of the following components, which operate at 12 volts and below. The Arduino microcontroller was specified as it allows the development of bespoke code scripts which meet the requirements of sample heating control and data logging within the experiment (Arduino, 2020).

10.4.1 PTC Heating Element

The internal volume of pipe sample contains air as the heat transfer fluid and is heated by a 12-volt 22w PTC (Positive Temperature Coefficient) heating element rated at 220°C . A PTC heating element is specific as it is considered safer than other electrical heating methods due to the self-regulating nature of PTC. The maximum temperature cannot be exceeded as the

resistance of the heating element increases with temperature to the point where it acts as an insulator (DBK, 2020).

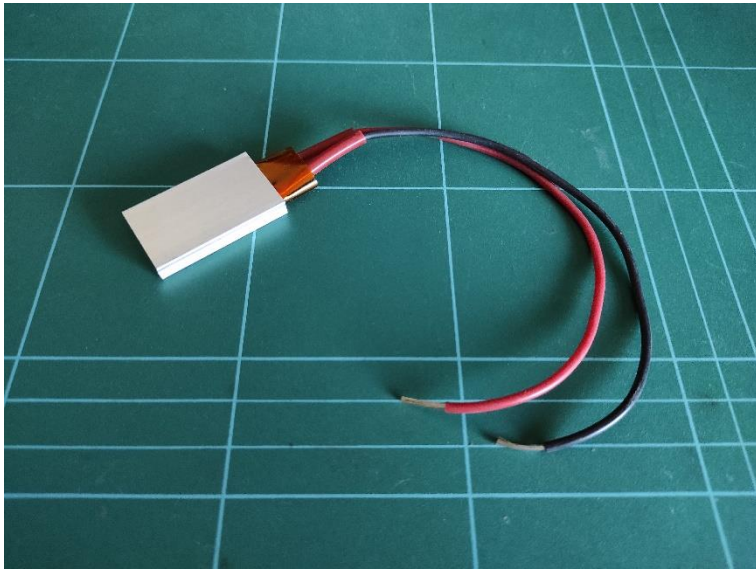


Figure 10.6 PTC Heating element

10.4.2 Microcontroller – Temperature Control

An Arduino Uno microcontroller is used to control the duration of the heating period of each pipe sample subject to cyclic heating within a 24-hour period and the setpoint temperature at 140°C. A real time clock (DS3231) provides the reference for each of the heating cycles within a 24-hour period and are defined as follows with each of the pipe samples being subject to two heating periods of three hours.

- Channel A – 0900-1200hrs (Rock Mineral Fibre Insulation)
- Channel B – 1300-1600hrs (Glass Wool Insulation)
- Channel C – 1700-2000hrs (Closed-Cell Elastomer Foam Insulation)
- Channel A – 2100-0000hrs (Rock Mineral Fibre Insulation)
- Channel B – 0100-0400hrs (Glass Wool Insulation)
- Channel C – 0500-0800hrs (Closed-Cell Elastomer Foam Insulation)

The assembled PTC heating element and thermocouple are detailed in figure 10.7, where both parts are fixed to the stainless-steel support rod. The assembled heating element is passed through the pipe with insulation fitted and the whole assembly is retained by plastic clips to maintain correct orientation as detailed in figure 10.8. The heating unit in operation is detailed in figure 10.9, the LCD screen to the right shows Channel A on a heat cycle. The units to the lower left are the thermocouple amplifiers, lower right relay unit.



Figure 10.7 PTC element and thermocouple assembly

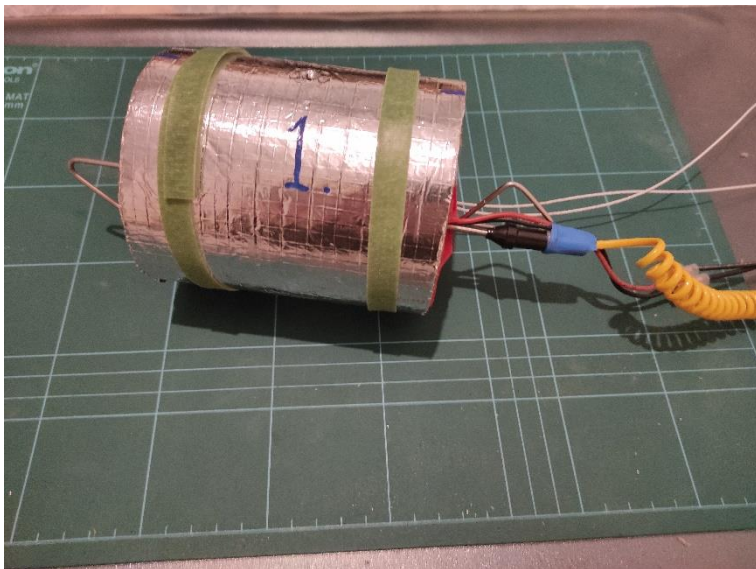


Figure 10.8 Pipe sample prepared for cyclic heating

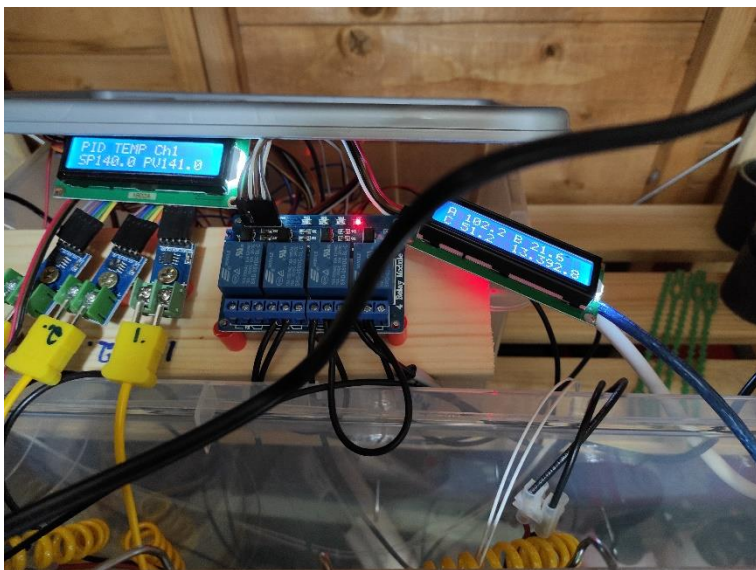


Figure 10.9 Heat cycle controller operating (Units to left of image)

10.4.3 Microcontroller - Datalogger

A simple datalogger based on an Arduino Nano microcontroller monitors and records the ambient air temperature and relative humidity within the environmental tank and the external metal surface temperature of each of the cyclically heated pipe samples in contact the thermal insulation. The datalogger is independent of the microcontroller used for the cyclic heating unit.

Figure 10.10 contains the LCD output of the datalogger (Lower LCD), the while wires to the left are the leads associated with the thermistors, the white unit in the lower left is the ambient temperature and humidity sensor.

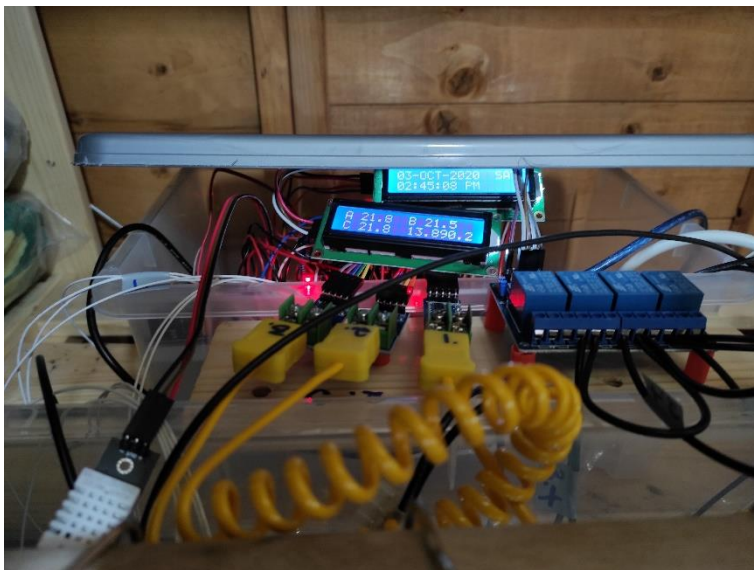


Figure 10.10 Datalogger in operation (Lower LCD)

10.5 Other Instruments

The following instruments are used to record observations undertaken during the duration of experimentation.

- Portable pH, conductivity, temperature and dissolved solids meters. Utilised for monitoring the water quality within the environmental and rainwater catch tanks on a weekly basis.
- Electronic scales – resolution 0.1g. Utilised for establishing the mass of pipe and insulation samples at the start and end of experimentation.

11.0 Experimentation Monitoring

During the 12-week period over which the corrosion experiment is conducted (5th October – 28th December) the following observations are made and recorded.

- Daily – Water drop rate from flow control valves (3 drops/minute)
- Weekly – Data download from datalogger SD card (Environment Tank)
 - Ambient air temperature
 - Ambient air relative humidity
 - Channel A – Pipe/insulation interface temperature
 - Channel B – Pipe/insulation interface temperature
 - Channel C – Pipe/insulation interface temperature
- Weekly – Environmental and rainwater catch tanks
 - pH
 - Total dissolved solids
 - Conductivity
 - Temperature
- Start/Finish
 - Mass – Pipe sample
 - Mass – Insulation sample

A sample of data recorded is provided for information in Appendix 3.

12.0 Next Steps

Develop a suitable method to analyse the pipe/insulation samples subject to the test environment experiment to establish.

- Insulation effect on corrosion where the samples are subject to ambient temperature changes only.
- Insulation effect on corrosion where the samples are subject to cyclic temperature change.
- Insulation water retention where the samples are subject to ambient temperature changes only.
- Insulation water retention where the samples are subject to cyclic temperature change.

The method is proposed to include laboratory analysis using Energy dispersive X-Ray and Scanning Electron Microscopy to establish surface morphology and elemental composition.

13.0 References

- Ain Burhani, N. R., Muhammad, M. & Rosli, N. S., 2019. Combined Experimental and Field Data Sources in a Prediction Model for Corrosion Rate under Insulation. *Sustainability*, 2nd December, 23(11), p. 6853.
- Anderson, S. A., 2010. *Out of sight, out of mind?*. [Online]
Available at: <https://www.intertek.com/articles/2010-08-corrosion-under-insulation/>
[Accessed 20th September 2020].
- API, 2011. *Damage Mechanisms Affecting fixed Equipment in the Refining Industry*. 2nd ed. Washington: API.
- API, 2016. *Piping Inspection Code: In-service Inspection, Rating, Repair, and Alteration of Piping Systems*. 4th ed. Washington: API.
- API, 2019. *Corrosion Under Insulation and Fireproofing*. 2nd ed. Washington: API.
- Arduino, 2020. *What is Arduino?*. [Online]
Available at: <https://www.arduino.cc/>
- Ashrafizadeh, H., Fisher, G. & McDonald, A., 2016. Thermal Spray Coatings for the Oil and Gas Industry. *Journal of Thermal Spray Technology*, Volume 25, pp. 1376-1440.
- ASTM, 1995. *ASTM G4 - Standard Guide for Conducting Corrosion Tests in Field Applications*. Philadelphia: ASTM.
- ASTM, 2013. *ASTM G189 - Standard Guide for Laboratory Simulation of Corrosion Under Insulation*. Philadelphia: ASTM.
- Bahadori, A., 2014. *Thermal Insulation Handbook for Oil Gas, and Petrochemical Industries*. 1st ed. Oxford: Gulf Professional Publishing.
- Baorong, H. et al., 2017. *The cost of corrosion in China*. [Online]
Available at: <https://www.nature.com/articles/s41529-017-0005-2>
[Accessed 20th September 2020].
- Begg, H., 2018. *A new Corrosion Under Insulation Test Method 1097/2018*. [Online]
Available at: <https://www.twi-global.com/what-we-do/research-and-technology/research-reports/industrial-member-reports/evaluation-of-a-new-corrosion-under-insulation-test-method-1097-2018>
[Accessed 7th October 2020].
- Bock, P., 2015. *Preventing CUI with thermal spray metal coating new use for a traditional process*, Hooksett: Advanced Polymerics Inc..
- Burhani, N. R. A., Muhammad, M., Ismail, M. C. & Mahed, M. A., 2016. An experimental analysis using Taguchi method in resolving the significant factors subject to corrosion under insulation. *APRN Journal of Engineering and Applied Sciences*, 11(20), pp. 11966-11970.
- Caines, S., Khan, F., Shirokoff, J. & Qiu, W., 2015. Experimental design to study corrosion under insulation in harsh marine environments. *Journal of Loss Prevention in the Process Industries*, Volume 33, pp. 39-51.

Cosham, A., Hopkins, P. & Macdonald, K. A., 2007. Best Practice for the assessment of defects in pipelines - Corrosion. *Engineering Failure Analysis*, 14(7), pp. 1245-1265.

DBK, 2020. *PTC Heating Technology*. [Online]
Available at: <https://www.dbk-group.co.uk/ptc-heating>

Eltai, E. et al., 2016. Investigating the corrosion under insulation (CUI) on steel pipe exposed to Arabian Gulf sea water drops. *Key Engineering Materials*, Volume 689, pp. 148-153.

Fitzgerald, B. J. & Winnik, S., 2005. *A strategy for preventing corrosion under insulation on pipeline in the petrochemical industry*. [Online]
Available at:
https://www.researchgate.net/publication/293478325_A_strategy_for_preventing_corrosion_under_insulation_on_pipeline_in_the_petrochemical_industry
[Accessed 21st September 2020].

Fitzgerald, B., Winnik, S., Lazar, P. & Kay, R., 2003. *Strategies to Prevent Corrosion Under Insulation in Petrochemical Industry Piping*. [Online]
Available at:
https://www.researchgate.net/publication/254545229_Strategies_to_Prevent_Corrosion_Under_Insulation_in_Petrochemical_Industry_Piping
[Accessed 20th September 2020].

Geary, W., 2013. *Analysis of a corrosion under insulation failure in a carbon steel refinery line*, Buxton: Health and Safety Laboratory.

Haraldsen, K., 2010. *Corrosion Under Insulation-Testing of Protective Systems at High Temperatures*. Houston, NACE.

HSE, 2013. *Corrosion under insulation of plant and pipework*. [Online]
Available at:
https://www.hse.gov.uk/foi/internalops/hid_circs/technical_general/spc_tech_gen_18.htm
[Accessed 20th September 2020].

Kane, R. D., Chauviere, M. & Chustz, K., 2008. *Evaluation Of Steel And Tsa Coating In A Corrosion Under Insulation (Cui) Environment*. Louisiana, NACE.

NACE, 2010. *Control of Corrosion Under Insulation and Fireproofing Materials - A systems Approach*, Houston: NACE International.

NACE, 2010. *Corrosion control in the refining industry*. Houston: NACE International.

NACE, 2016. *International Measures of Prevention, Application, and Economics of corrosion Technologies Study*. [Online]
Available at: <http://impact.nace.org/documents/Nace-International-Report.pdf>
[Accessed 20th September 2020].

NACE-Jubail, 2015. *Corrosion Under Insulation (CUI) and the Insulation System*. [Online]
Available at: http://www.nace-jubail.org/Meetings/CUI_2015/7-ROOKWOOL.pdf
[Accessed 12 October 2020].

Pojtanabuntoeng, T. et al., 2015. Influence of Drain Holes in Jacketing on Corrosion Under Thermal Insulation. *Corrosion the Journal of Science and Engineering*, 71(12), pp. 1511-1520.

Praxair, 2010. *Thermal Sprayed Aluminium (TSA) Corrosion Protection Systems for the Offshore Oil and Gas Industry*. [Online]

Available at: <https://www.praxairsurfacetechologies.com/-/media/corporate/praxairsurface/us/documents/brochures/thermal-sprayed-aluminum-coatings-for-oil-and-gas.pdf?la=en&rev=32d6b73fadde41a6b70e13660d40637e>

[Accessed 28th October 2020].

Rasmussen, S., 2017. *Cyclic CUI Testing of Insulation Materials*. Houston, NACE.

Reichert, D., 1998. Corrosion of carbon steel under wet insulation. *Materials Performance*, 37(5), p. 73.

U.S. Department of Energy , 2012. *Insulate Steam Distribution and Condensate Return Lines*. [Online]

Available at: https://www.energy.gov/sites/prod/files/2014/05/f16/steam2_insulate.pdf

[Accessed 20th September 2020].

Uhlig, H. H., 1949. *The Cost of Corrosion to The United States*. [Online]

Available at: <https://corrosionjournal.org/doi/10.5006/0010-9312-6.1.29>

[Accessed 20th September 2020].

Winnik, S., 2008. *Corrosion-under-insulation (CUI) guidelines*. 1st ed. Cambridge: Woodhead Publishing Material.

14.0 Appendix 1 – Project Plan (Gantt Chart)

[illegible]

15.0 Appendix 2 –Variables and Control Measures

15.1 Independent and Dependent Variables

Question	Independent Variable	Dependent Variable
Effect of cyclic temperature change and the development of CUI on thermally insulated carbon steel pipework where water is introduced into the insulation material.	Cyclic temperature change between ambient conditions and 140°C	Development of CUI
Effect of cyclic temperature change within thermal insulation and water retention where water is introduced into the insulation material.	Cyclic temperature change between ambient conditions and 140°C	Volume of water retention within insulation material

Table 15.1 Independent and dependant variables

15.2 Confounding variables

Question	Confounding Variable	Control Measure
Effect of cyclic temperature change and the development of CUI on thermally insulated carbon steel pipework where water is introduced into the insulation material.	Variation in volume of water which enters the insulation material. An increase or decrease in the volume of water entering the insulation material influences the development of CUI.	Control experimentally: Volume of water is monitored and introduced at a controlled rate, 3 drops/minute. Water enters the insulation via a 6mm diameter hole made in each of the samples at the longitudinal central point of the top dead center position. Monitored daily by manually observation and adjustment of flow control, as necessary.
	Variation in volume of water which drains naturally from the insulation material. An increase or decrease in the volume of water draining naturally from the insulation material influences the development of CUI.	Control experimentally: The insulation samples are prepared so that the cut ends have no environmental barrier in place, allowing water to drain naturally. Monitored daily by manually observation.
	Variation in upper temperature limit. Temperature in excess of 140°C would not be expected in process service pipework in cyclic temperature applications. Excess temperature will result in unexpected drying of insulation material. An	Control experimentally: Heating module controlled by PID controller. Controller set point and process variable monitored daily. Process variable temperature verified weekly against temperature measurements record by datalogger.

	increase or decrease in the volume of water entering the insulation material influences the development of CUI.	
	Variation in heating cycle time. The experiment simulates process service pipework in cyclic temperature applications where the heating service is applied for two periods of 3 hours, equally separated in a 24-hour period. Heating periods in excess of those defined will result in unexpected drying of insulation material. An increase or decrease in the volume of water within the insulation material influences the development of CUI.	Control experimentally: Heating cycle time controlled by microcontroller. Heating cycle time observed daily. The heating cycle period verified weekly against temperature measurements record by datalogger.

Table 15.2 Confounding Variables and Control Measures

16.0 Appendix 3 - Observations to Week 9

The following observations are made on the duration of the experiment up to week 9. Table 16.1 details a 12-hour period during which each of the heated samples undergoes a heating cycle. Table 16.2 sets out the water quality monitoring of the environmental tank.

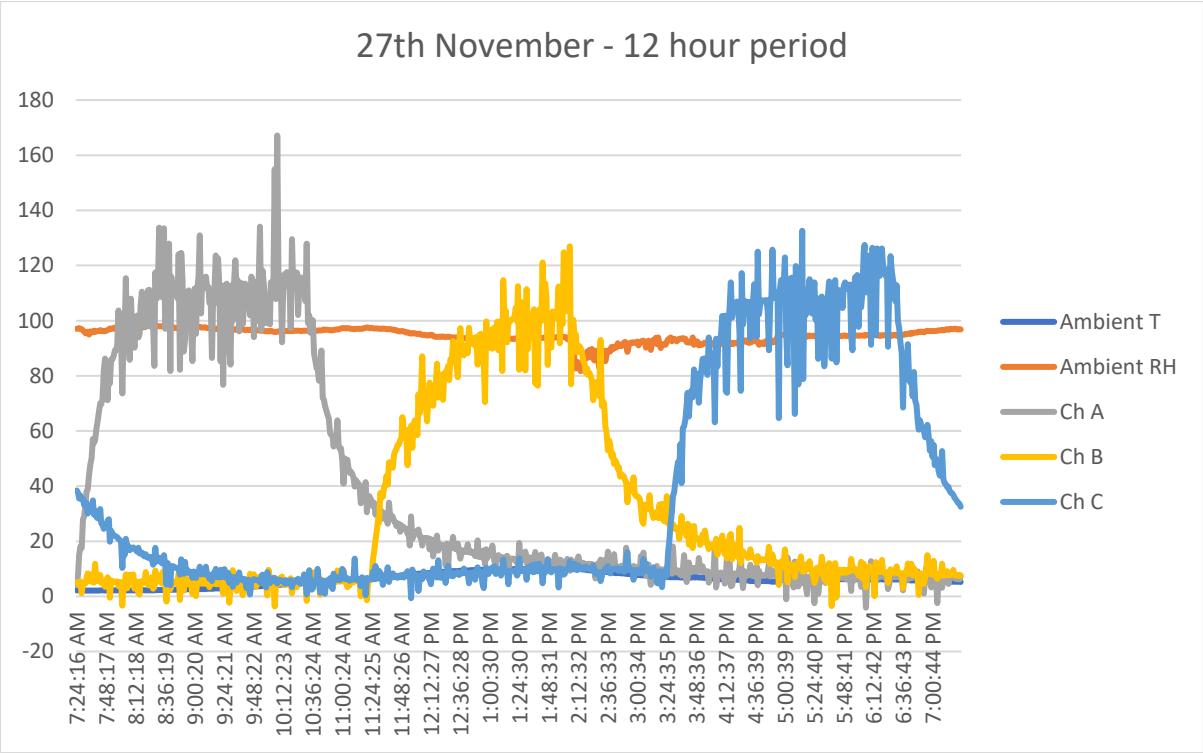


Table 15.1 Heating trend data for cyclic samples over 12-hour period

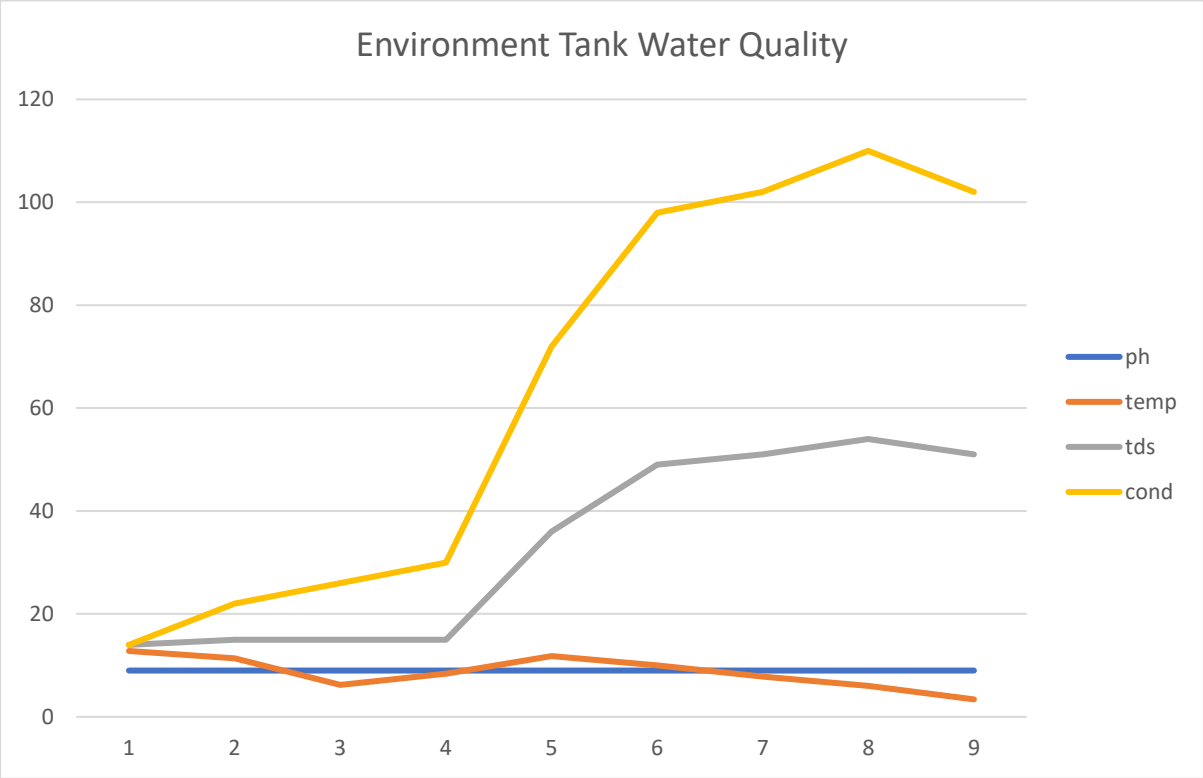


Table 15.2 Environmental water quality monitoring trend to week 9