The Enhancement of NDT Techniques through Active Thermal Infrared Thermography to Identify Corrosion under Insulation (CUI) in Downstream Piping

by

Muhamad Firdaus Bin Zaini

This dissertation is submitted to
Universiti Teknologi PETRONAS
As a partial fulfillment of the requirements for the
Bachelor of Engineering (Hons)
(Petroleum Engineering)

SEPTEMBER 2012

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CERTIFICATION OF APPROVAL

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Approved by,

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(IR Dr Mohd Shiraz Bin Aris)

UNIVERSITI TEKNOLOGI PETRONAS

engineering futures

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Prepared by,

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(Muhamad Firdaus Bin Zaini)

ABSTRACT

In the effort of sustaining the reliability of equipments, periodic maintenance and inspection is required. This is done by applying the non-destructive testing (NDT) techniques like ultrasonic, radiography, and etc. NDT act as the appropriate tool for engineers and inspectors to examine the presence and absence of any failures or defects on certain equipments without producing any disturbance to the equipments' process and operation [1]. In oil and gas industry, corrosion under insulation (CUI) is considered as the major problem arise today as it requires billion costs to inspect the corrosion involving the procedure to unwrap the insulation which will lead to 3 - 4 days operation. With the conventional NDT practice, this matter has been identified as time-consuming and costly operation. Therefore, the aim of this study was to validate the use of infrared thermography as NDT and E in locating and detecting CUI through lockin thermography testing. For this experimental study, a laboratory cell was designed to simulate the condition of CUI using the carbon steel plate (testing object) as a mock-up downstream pipe section. Factors include insulation thickness, defect's size, defect's depth, and the objective distance are the parameters affecting the accuracy of the results. For this purpose, infrared image correlation and numerical computation was used to predict the presence tendency of CUI. By numerical computation, it was demonstrated in this study that defect exhibit different temperature distribution as time elapsed. In contrast, temperature drops as the insulation becomes thick. By correlation, classification on thermal infrared colors governs the area of both defects and non-defects distinctively. It is obvious that the applicability of the present NDT and E to detect CUI depends on a heating condition and a relative difference of thermophysical property between the defect and its surrounding.

ACKNOWLEDGMENT

The author would like to extend his deepest gratitude to IR Dr Mohd Shiraz Bin Aris, who has been very kind to guide throughout the entire FYP 1 and FYP 2. The supervision and advice that were given truly help the progression of the study. The author also wishes to express his appreciation to the lab technologists Mr. Fahmi from Power Generation laboratory Block 15 and Mr. Azhar from Electrical & Electronic laboratory Block 23 for his relentless assistance rendered in providing the required electrical equipment of this project safely. Many thanks given to Phd researcher, Mr. Omar Mohamad for the sharing of his knowledge and assistance. Not to forget to the author's family and team members for the support and help either directly or indirectly. Last but not least, to Universiti Teknologi PETRONAS for providing the lab facilities to run the experiments.

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ABBREVIATIONS

2D	-	Two-dimensional
AT	-	Active Thermography
BMP	-	Bitmap Image
CUI	-	Corrosion under Insulation
CUWI	-	Corrosion under Wet Insulation
EWBL	-	Ecowool Blanket; insulation brand
IR	-	Infrared
IRT	-	Infrared Thermography
LT	-	Lockin Thermography
MDG	-	Moisture Density Gauge
NDT & E	-	Nondestructive Testing & Evaluation
NDT	-	Nondestructive Testing
OGT	-	Onshore Gas Terminal
PC	-	Personal Computer
PCSB-PMO	-	PETRONAS Carigali Sdn Bhd-Peninsular Malaysia Operation
PPT	-	Pulsed Thermograhy
PT	-	Passive Thermography
SID	-	Seamless Image Database
T_{rs}	-	Radiation Temperature
T_s	-	Surface Temperature
UT	-	Ultrasonic Testing

CHAPTER 1

INTRODUCTION

1.1 Project Background

In oil and gas industry, the use of infrared thermography (IRT) non-destructive testing (NDT) is now widely applied majorly in preventive and diagnostic inspection technique. Historically, infrared (IR) testing came about in NDT after the considerable testing by military system in early 1960's. Today, the benefits of IRT have led to a better improvement in NDT world even the applications of thermography has broadened to various kind of engineering. IRT is commonly applied in electrical and mechanical systems, structures, petrochemical, transportation and even medicine. Despite of the application, the final results depends on several external factors. The factors include understanding the task to be performed, equipment selection, operator skills, inspection technique, and documentation of findings. A thermographer needs to take into account of these factors before embarking the project which minor inaccuracy will influence the final results.

Providing the application of IRT as one of NDT in petrochemical sectors, a detailed project of active thermal thermography testing is designed to identify the major pipelines problem in downstream facilities which is corrosion. In most downstream pipelines, locating corrosion under insulation (CUI) by using current NDT such as Ultrasonic Testing (UT), Moisture Density Gauge (MDG), Radiography (X-ray) and Remote Visual Inspection (RVI) requires severe maintenance planning. This unseen corrosion became the hot issues nowadays as it is costly and time-consuming to remove the insulation and examine the corrosion. For maintaining and managing insulated pipeline satisfactorily, it is very important to detect many kinds of invisible defects under the insulation section such as pinhole, corrosion, crack and so on. Various defect diagnoses for materials have been conducted in order to detect the existence of the defects including the use of NDT and E. This technique is somehow restricted within certain areas of application. For instances, the diagnoses using X-rays, ultraviolet rays and ultrasonic waves have extensively been applied to an engineering or a biomedical application for detecting invisible defects or diseased parts. However, these rays may be harmful to living bodies or testing targets during the diagnosis process. In contrast, infrared rays are harmless to living bodies, making its applicability to be increasingly recognized for diagnose purposes in various engineering applications.

In this dissertation, we focus on the fundamental numerical computation and the infrared image correlation in order to discuss the detection mechanism of CUI with the aid of the experimental investigation using infrared thermography. The numerical computation is examined by introducing a physical model describing the detection process reasonably. The effects of changing thermophysical property between the defect and its surrounding have not been discussed on the NDT and E using the infrared thermography systematically. The heat transfer mechanism pertaining to the detection process has not theoretically been analyzed. It is necessary to simulate the detection process theoretically and empirically by applying an appropriate model based on the real phenomena. Therefore, the main target of this project is to validate the effectiveness of using IRT to detect CUI in downstream piping by using lockin thermography testing.

1.2 Problem Statement

<u>Problem Identified: Conventional NDT techniques require high cost, time-consuming and less effective.</u>

In certain NDT techniques, the operation of capturing the equipments information is a bit difficult and challenging process especially when the pipelines and vessels are located at certain height. This led to several additional procedures; for instance requires scaffolding for a man to lift to reach the specific area for the sake of data accuracy. Furthermore, different type of NDT requires different methods or procedure to be completed. Some NDT tools like P-scan involving the automatic probe that must be in contact with the surface of the vessel to gain a very accurate data. For instance, the uses of P-scan and C-scan are normally employed in Onshore Gas Terminal (OGT), Terengganu, Malaysia. Those two NDT Techniques is used by Velosi and MCI inspection team who carried out P-scan that incorporates the usage of ultrasound testing, one of Advance NDT techniques (M Khalid Ibrahim, 2011). This is done to replace the existing vessel cleaning procedure. The current vessel cleaning requires us to inspect the vessel from within by entering the manhole.

This procedure involves a lot of cost as the job is risky as the workers are exposed to hazardous materials besides the confined space hazard. Despite of high cost, the operation is highly risky due to the use of a man-lift for vessel inspection at the target location. (See Figure 1)

Figure 1: Man-lift is required to perform NDT at specific vessel location area

Another example found in a chemical plant in Kentucky. A critical raw material service is done to insulated carbon steel piping that has 1300 feet of 1 1/2" diameter. The insulated line is hanging in a pipe alley 20 feet off the ground. Historically, it is identified that the water trapped is found inside the insulation due to the damage of the insulation itself. This will eventually cause degradation to the pipes' coating, resulting in accelerated corrosion. This condition is called Corrosion under Wet Insulation (CUWI). This is the same condition to CUI as this corrosion is not readily visible since the pipe is covered by the insulation.

For the past surveillance, the site has used a MDG to survey for CUWI. MDG give good results for the inspectors, but they are cumbersome and slow to work with and require maintaining a radioactive isotope that must have specific licensing and regulatory monitoring [2]. This has required expertise by the inspector and the use of a man-lift to complete the survey, resulting in a process that took 3-4 days to complete. Time-consuming and high risk procedure is the barriers for the inspector to do the survey to capture CUWI. Hence, in this project, IRT is introduced to see the effectiveness of capturing CUI in a different distance to the target area. By using infrared length frequency, it is estimated that the temperature variation in the specific target can be captured accessibly and accurately.

1.3 Objectives

The objective of the project is to validate the use of infrared thermography (IRT) testing to identify corrosion under insulation (CUI) in downstream piping. The project is conducted in an experimental means whereby lockin thermography (LT) test is applied entirely in the experiment. For this purpose, the fundamental numerical computation and the infrared image correlation are used as the detection mechanism of CUI. Several external factors and influential parameters are considered which will be explained in scope limitation.

1.4 Scope

The scope of the project is to investigate the ability of IR camera to locate corrosion and/or defects beneath the insulation with respect to the actual condition of CUI. The LT test is entirely conducted in Mechanical Lab in Block 18, Universiti Tekonologi PETRONAS.

Two defects are predetermined on the carbon steel plate (testing object); corrosion and pinhole. The corrosion is existed initially on the testing objects meanwhile two pinholes are created by using milling machine. In the result and discussion section, the fundamental numerical computation explains the detection process reasonably meanwhile the infrared image correlation proves on CUI detection analytically. In order to specify and structure the work, the following project questions are made:

1. What are the external factors and parameters to be emphasized and give the major effects to the interpretation of the results?

2. In numerical computation, how does the heat transfer play significant role in detection process of IR rays onto the defects?

3. How to correlate the IR images taken in order to specify and detect the defect under insulation accordingly and analytically?

1.5 Scope Limitation

The scope of research is only applied to one carbon steel plate (testing object) resembling the actual layer of downstream piping section and is covered with one type of insulation – glass wool. The results data of the experimental work will be based only to two methods; numerical computation and infrared image correlation. The study only focus to downstream pipelines majorly found in petrochemical industries and not directed to other engineering field.

The researcher created two types of defect on the testing object surface focusing on corrosion and pinhole only. Factors that influence the detection factors of the infrared LT test to locate CUI are taken into account. It includes the insulation thickness, defect’s size, defect’s depth, and the objective distance, which is the distance, *l*, between the testing object and the infrared camera. In conducting the experiment, the external light sources affecting the detection process and is controlled manually by reflection correction to obtain the clear infrared images.

1.6 Project Relevancy

The project conducted will help the related maintenance company to measure the effectiveness of applying IRT as the accurate NDT tools to detect corrosion in both insulated and non-insulated along the transporting piping and/or pipelines. By proving temperature variation in pipelines, IRT helps inspection workers to do their NDT jobs in an efficient ways by means of less time-consuming, less risky, and hence reducing the company budgeting plans.

Thermograpghy allows us to scan large areas of insulated piping and/or pipelines quickly and safely whilst identifying areas where the reliability of the insulation has become subject to water exposure. Therefore, the successfulness of the project conducted will help oil and gas companies like PETRONAS Carigali Sdn Bhd, PCSB to practice and apply the use of IRT technology as the selective NDT tools.

1.7 Project Feasibility

For the whole of 8 months period of final year project (FYP) given, the project must be completed and experimentally proved the good results within the time frame. Along the project conducted, some of the probabilities and achievability had been encountered and this leads to the maturity of the project itself. Basic knowledge on IRT and CUI are mostly used and cited correctly according to American Parenthesis Appendix (APA) style. The references on defects measurement, results interpretation and methods to perform infrared LT test is basically refer to certain reliable sources from some industry papers and journals following the codes and standard practiced in the real inspection activity.

Throughout conducting the experimental work in the laboratory, researcher must fully aware of any possibilities of human errors. Errors should be accounted for as to avoid inaccuracy of data obtained. Error calculation must be done in the final result to gain the consistency of the results obtained. By completing the project, the researcher must relate to the objectives proposed and proved to be achievable by using the right methodology to encounter the problem statement identified.

1.8 Dissertation Structure

In this dissertation, the researcher will first described the project background, objective, problem statement, scope, and the project relevance and feasibility in the first chapter. The second chapter is where all the theory relating to infrared thermography and CUI is explained in details based on some papers and journals from the industry. All the methodology like the experimental set-up, the list of required materials used will be described in Chapter 3. The Gantt chart and the milestone of the project activities are stated in this chapter as well. Chapter 4 is mainly explained on the results data that is obtain from the experiment and some discussions are justified to further analyze the results. The project is summarized in conclusion part in Chapter 5 with some recommendations made on the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Infrared Thermography (IRT)

Thermography is a category of infrared imaging. The produced images from the cameras used emit infrared electromagnetic spectrum giving result information about the surface temperatures. An object will release more or less radiation depending on its existing temperature. If viewed under a thermographic camera (as shown in Figure 2), warm objects stand out well against cooler backgrounds resulting to possibly “see” an object without visible illumination.

Temperature, emission angle, and wavelength are the factors that influence the emissivity of the infrared radiation emitted by an object. As the emissivity varies, the attainment of getting accurate temperatures is very difficult. An example of this is illustrated in Figure 3. As shown, a grease pencil label on the manway cover of this drum emitting a distinctly different color. In reality, the label is the same temperature as the surrounding metal, but the apparent results are skewed due to emissivity of the different surfaces [3].

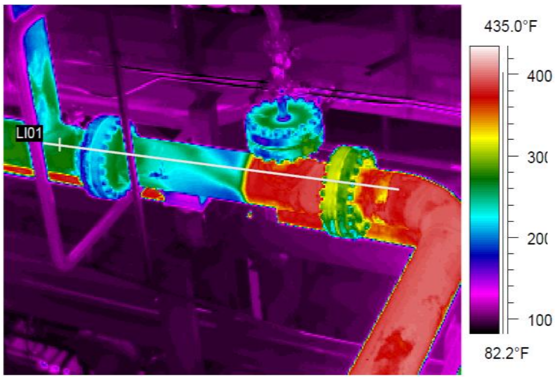


Figure 2: Thermography camera detects temperature variation in pipelines: warm region is red in color while cooler background shows purple color (McConnell P.E., 2010)

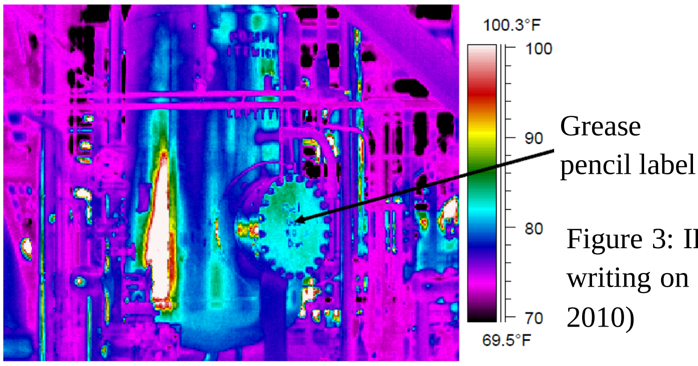


Figure 3: IR scan of a vessel with grease pencil writing on the manway cover (McConnell P.E., 2010)

2.2 Types of Thermography Testing

Thermography camera consists of large numbers of sensors which is sensitive to infrared radiation that can detect and measure small temperature differences. The temperature differences send images and displayed on a PC, normally as a color or grey-scale map. There are two basic types of thermography, namely passive and active.

2.2.1 Passive Thermography (PT)

In passive thermography, the camera is simply pointed at the target area and from the thermal image, a temperature map is constructed. Passive thermography normally uses Fluke Ti30 infrared camera as shown in Figure 4.

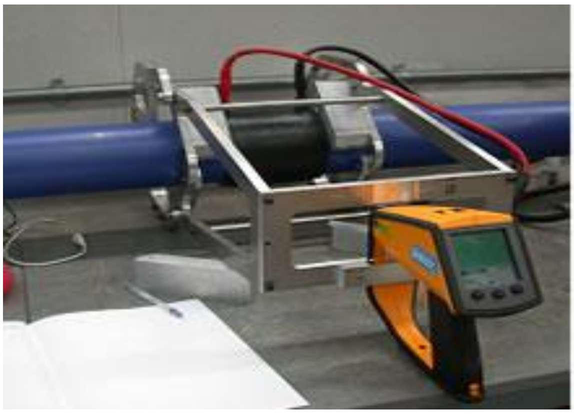


Figure 4: The Fluke Ti30 camera focused on an electro-fusion pipe joint [4]

Fluke Ti30 collect data by recording the temperature changes with time. Normally, the application of using this type of thermography is purposely to study the heat flow in joining pipilene. For example, electro-fusion welds in polyethylene pipe are captured by the Fluke Ti30 thermography camera. This operation is done to identify potential defect in the welds that occurs when one of the pipes is not fully fitted in the coupler. This scenario will led to the increment of temperature of the coupler in the under-penetrated region after welding and will decay more slowly.

2.2.2 Active Thermography (AT)

AT is defined as applying a stimulus to a target to cause the target to heat or cool in such a way as to allow characteristics of the target to be observed when viewed by thermal imagery. It is based on the evaluation of a previously excited heat flow in the tested component and its disturbance by hidden defects. The heat flow is generated with a heat pulse or through sinusoidal modulation. The heat or thermal wave can be generated in two approcahes; pulsed thermography (PT) and lockin thermography (LT).

2.2.2.1 Pulsed thermography

PT is an active thermography technique used widely in the evaluation of composite materials. Active thermography involves the process of heating the object surface rapidly by means of external heat source followed by observing how the temperature decays with time. Any defects and flaws in the material will be showed up by variations in the temperature decay rate. The NDT Validation Centre uses Thermal Wave Imaging EchoTherm™ Pulsed Thermography (PT) system for active thermography [4].

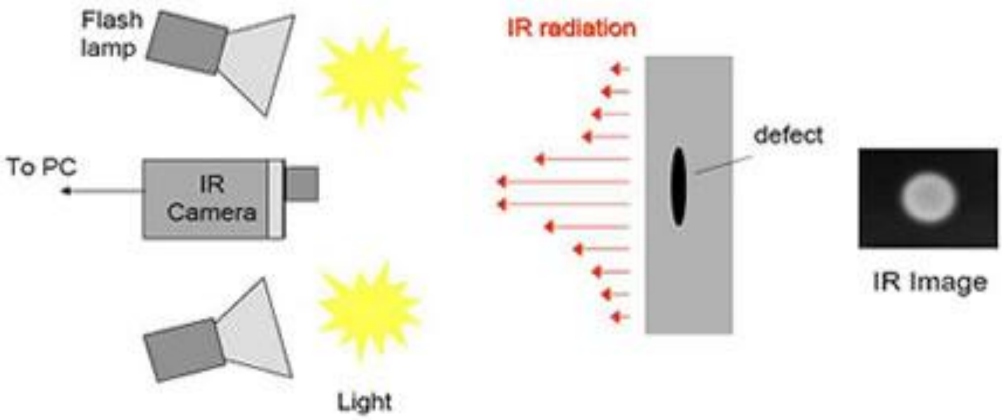


Figure 5: Principle of pulsed thermography

Figure 5 shows the principle of PT and how it carries out [4]. One or more intense light source(s) (~1kw) is the heating agent used to provide heat to the object’s surface for periods of 1-25ms. This additional heat will then react to the presence of any subsurface flaws or defetcs (example: disbonds, voids or inclusions) by altering the temperature of the object and eventually forming a temperature variation at the surface with time.

As the results of temperature difference, it is easily be detected by the infrared camera system, which captures images at a frequency rate of up to 60Hz. At the end, the software interprets the data by the following means:

- A temperature plot with respects to time is recorded at a single pixel or group of pixels.
- Time plots of temperature recorded at a single pixel or group of pixels.
- Line profiles.
- Subtle image features in the form of 3-D colour or greyscale plots.
- Reconstructed 1st and 2nd order time derivatives.

Figure 6: EchoTherm system

The system that analyzes the data obtained is called EchoTherm system as shown in Figure 6 [4]. Two units of xenon flash lamps are placed inside the hood. This system requires the lamps to be flashed and the camera takes image sequences. Once the images have been captured, the decay data are processed and displayed by the PC. Detection of impact damage to wind turbine blades is one of the widely application of this system.

2.2.2.2 Lockin Thermography (LT)

LT is based on the generation of thermal waves inside the specimen for instance by periodically depositing heat on the specimen surface while remotely recorded the resulting oscillating temperature field in the stationary regime through its thermal infrared emission with an IR camera [5].

The principle of LT is based on the application of a periodic input energy wave (i.e. thermal emitter, ultrasound, microwave, eddy current, flash lamp) to the surface of the object being examined and analyzing the resulting local temperatures on the surface of the object.

2.3 Corrosion

Oxygen and electrolyte like water, condensation, rain, dew, etc. are the essential requirements for steel to get corroded. Corrosion will occur only when there are three variables function such as the surface temperature, amount of oxygen available and the type of contaminants on the surface. In oil and gas industry, the major corrosion occurs in downstream pipelines are due to severe water rain and air exposed. Like in OGT for instance, the pipelines that touches the sea water surface connecting production from offshore to the processing facilities is the hot spot areas to do surveillance regularly. Sea water is a brine or salt water which is one of the good corrosive agents.

2.4 Corrosion Under Insulation (CUI)

The corrosion failures observed on steel and other materials under insulation, which is referred to CUI, is a great concern for the petroleum and chemical processing industries. The insulation are utilized on piping and vessels in order to maintain the temperatures of operating systems for process stabilization and for conservation of energy [6]. CUI is defined as a localized corrosion occurring at the interface of a metal surface and the insulation on that surface. This can be a particularly severe form of corrosion because of the difficulty in detection due to the corrosion occurring beneath insulation. Inspections for CUI are generally not completed regularly enough to eliminate this problem due to the cost of insulation removal and replacement and cost of labor [7].

The corrosion of steel or other materials under insulation initiates due to the presence of water. oxygen and other corrodants. Once water and oxygen are present on a metal surface, corrosion takes place via metal dissolution (anodic reaction) which is balanced by the reduction of oxygen. The rate of CUI is determined by the availability of oxygen, contaminants in water, temperature and heat transfer properties of the metal surface and wet/dry conditions of the surface.

2.5 Role of Insulation

The main contribution of insulation to CUI is to provide an annular space for the retention or accumulation of water, with access to air (oxygen). As illustrated in Figure 7, water may be introduced from external sources such as rainfall and wash downs or from condensation (Michael Lettich, 2003). The chemistry and properties of the insulation also play a role in CUI. The insulation material may wick or absorb water thus providing the required aqueous environment for electrochemical reactions to take place. Furthermore, the chemicals within the insulation such as chlorides and sulfates, may leach into the electrolyte causing an acceleration in the corrosion.

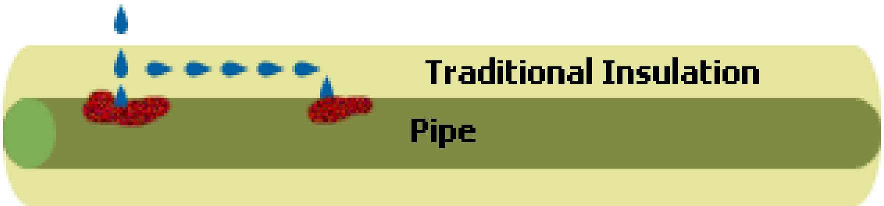


Figure 7 – Rockwool, fiberglass, or other traditional types of insulation promote corrosion, and also act as a carrier and spread the corrosion to other areas of the pipeline

2.6 Role of Temperature

Generally, the temperature of the metal surface plays an important role with regard to CUI. Increasing temperature increases the rate at which electrochemical reactions take place thus increasing the corrosion rate. Further increase in temperature will reduce the corrosion rate due to the lack of a corrosive environment as water evaporates. However, as water evaporates, the concentration of corrosive species on the metal surface increases Furthermore, high temperatures reduces the service life of protective coatings and sealants.

Figure 8 showed presents the chemical plant measurements of CUI under the influence of water temperature on the corrosion rate of steel in both a closed and an open system.

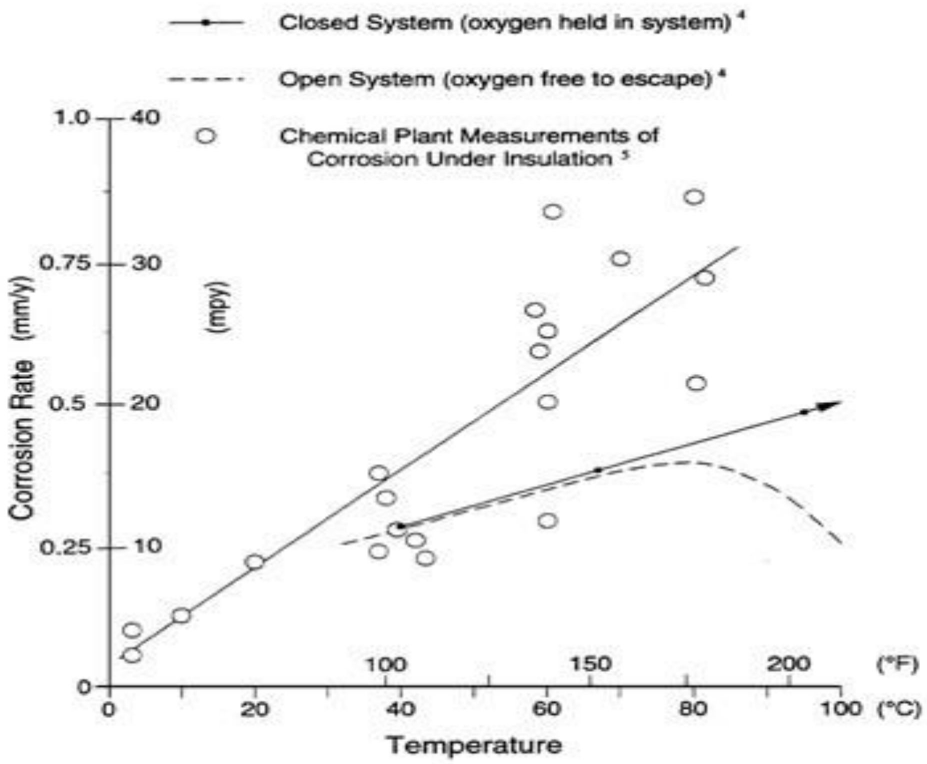


Figure 8: Relationship of corrosion rate to the water temperature distribution (Brian J. Fitzgerald, et al., 2003)

Based on the Figure 7, the trending curve of the open system (oxygen free to escape) is increasing at the beginning and starts to decrease at the end. This explains that the water decreases as the temperature increases (evaporation condition). As a result, the corrosion rate of carbon steel in aerated water begins to decrease above approximately 80°C (176°F).

However, in contrast to the open system, the corrosion rate of carbon steel in water continues to increase as the water temperature increases. This measurement proved that the corrosion rate of carbon steel corroding under insulation confirms that the rate increases with temperature. This is similar to the corrosion mechanism occurring under insulation, where the thin film of water is actually oxygen-saturated. Thus, the same oxygen cell corrosion mechanism is taking place as in a closed system. The corrosion rates taken in a field are somewhat greater than the laboratory test rates. This is because field measurements consider the external corrosion factors like the airborne or insulation-carried salts in the field.

CUI is most likely to occur in carbon steel operating in the temperature range between ambient to about 300°F (148°C). The steel temperature that is above 300°F will inhibit corrosion due to the unfavorable condition of water to remain in contact with the steel which incomplete the electrolyte element of the corrosion model.

2.7 Evaluation of CUI

CUI (as shown in Figure 9) is one of the industry's biggest challenges caused by water doorway into thermal insulation on pipe work and vessels which eventually in time leading to a rapid corrosion (Richard Norsworthy, et al., 2011). This problem is often unforeseen by naked eyes until it comes to the premature and potentially catastrophic equipment failure detection.

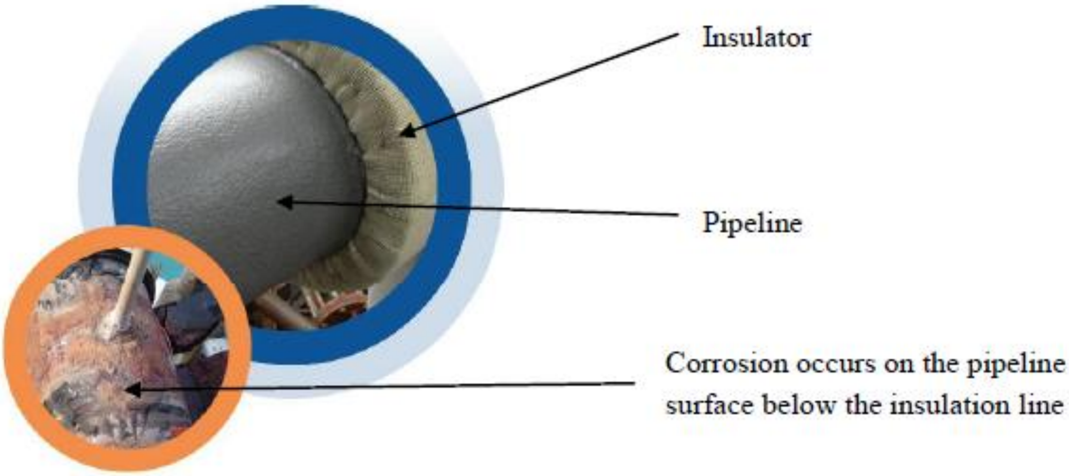


Figure 9: CUI images found in pipelines

Since CUI is readily invisible, the traditional NDT method of identifying and inspecting for CUI has been the costly and time-consuming method of removing insulation for inspection. Today, the introduction of IR as the NDT technique is continually examined and evaluated as a potential solution to efficiently identify potential CUI. Like other cameras, IR camera requires the same shooting operation but its outcomes are not as easy to analyze. Major factors like emissivity and reflectivity must be taken into consideration.

<u>Advantages</u>: By using IR, CUI can be determined in which the thermography camera does have applications in finding areas of wet insulation (see Figure 10). More specifically, IR is capable of capturing images and showing the heat transferred in an object. This is where IR has potential to find corrosion areas under wet insulation due to the loss of insulating efficiency plus with the higher temperatures.

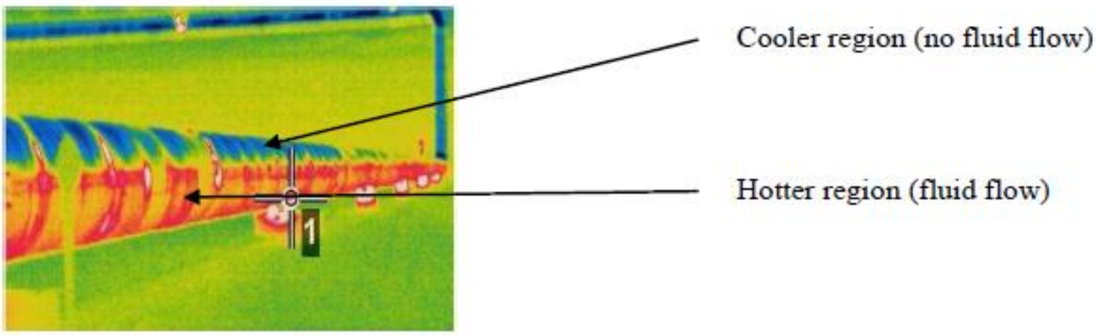


Figure 10: Different IRT color shows variation of temperature in pipeline section (Marc D McConnell, 2010)

<u>Disadvantages</u>: Different to dry insulation areas, wet insulation cause the absorbed heat to maintain longer inside the insulation. Hence, in shooting the target lines, hot areas are significantly showed compared to cooler areas. However, there are two major potential difficulties with inspection for wet insulation, namely the insulation jacket and the location.

1) Insulation jacket - Bright aluminum is a typical materials used in insulation jackets. Reflection from this material causes high amount of reflectivity that led to IR detection inaccuracies.

2) Location - location of the pipeline is another great influential of IR detection accuracy. Most insulated lines found in downstream facilities are placed closer to other insulated lines or equipment emitting the increment of reflectivity on the targeted lines. This will affect the IR accuracy as well.

CHAPTER 3

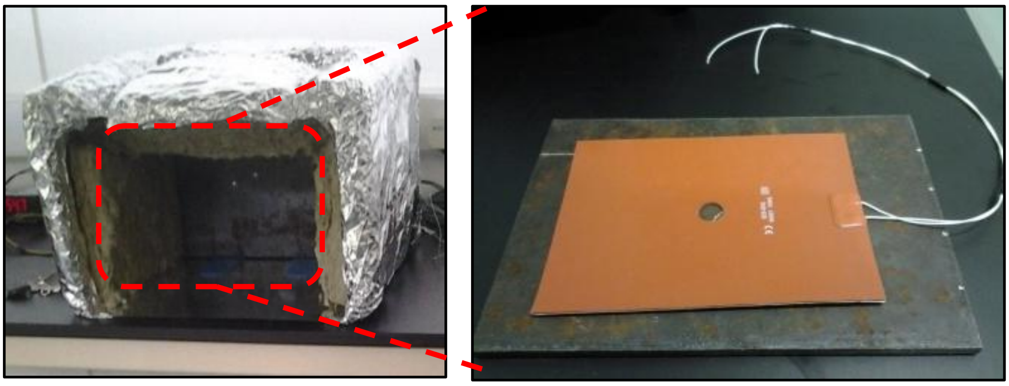
METHODOLODGY

3.1 Project Design and Implementation

The project is started by designing a CUI cell comprising of an carbon steel plate as the testing object and the process heater mat attached at the backside of the testing object. CUI cell is designed to create the real condition of pipeline section in downstream facilities where the actual condition of CUI occurs. The purpose of designing the cell is to merge the real physical properties like temperature and defects to be tested in the laboratory. Later, once the CUI cell is ready, the experimental set-up is done which includes all the required apparatus to detect CUI. The experimental set-up consider the usage of isothermal box, controller unit, IR camera, and the creation of defects which will further explain later on.

3.1.1 Test Apparatus – CUI cell

The CUI cell was designed to simulate the corrosion under insulation on the outer surface of a carbon steel plate(testing object) which were machined in a rectangular shape used as a mock-up downstream pipe section. The schematic diagram of the designed CUI test cell for laboratory simulation of CUI in a pipe section is detailed in Figure 11.



Isothermal box   Testing object embeded with heater mat

Figure 11 – CUI test cell for laboratory simulation

This cell consisted of a rectangular carbon steel plate (S35C; 28cm x 20cm) embeded with a piece of rectangular process heater mat (20cm x 15cm; 100W, 240ac) and is insulated by glass wool insulation (EWBL; R-value of 1.35 m^2K/W) forming the isothermal box. As illustrated in Figure 1.4, the boundary walls of the isothermal box is filled with adiabatic material made of glass wool to maintain the desired temperature of CUI, which the temperature set value is 120°C. The testing object, which is heated at a desirable temperature with a process heater mat attached to the backside where opposite to the defects side, is inclined at 15° towards the vertical line [8]. The full diagram of the testing object is illustrated as in Figure 12.

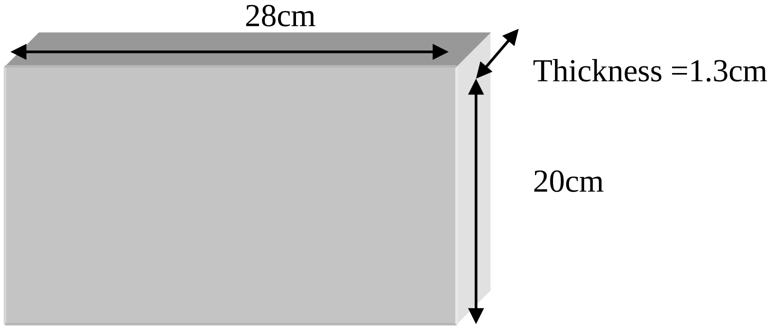


Figure 12: A piece of carbon steel plate as the testing object

3.1.2 Experimental Set-up

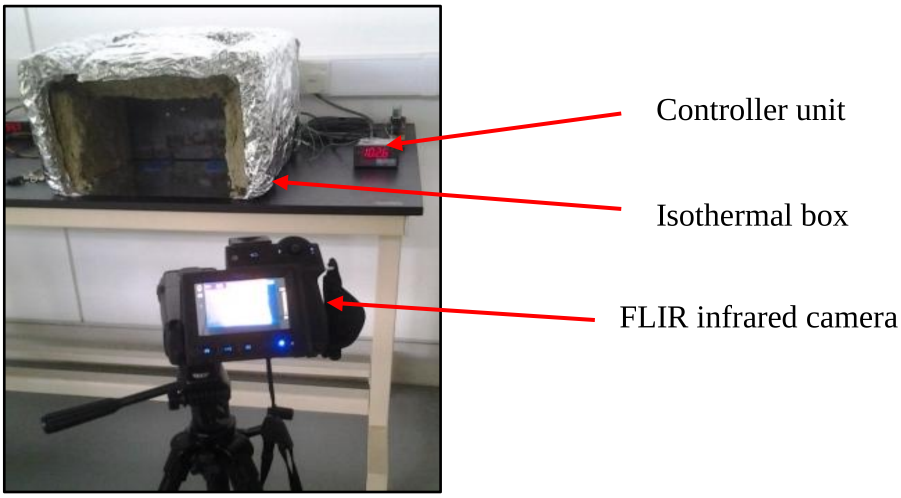


Figure 13 – Schematic illustration of the experimental apparatus for LT testing

Figure 1 shows a schematic illustration of the experimental apparatus for the fundamental NDT using the infrared LT testing. The infrared camera which can generate a two-dimensional thermograph representing radiation temperature, T_{rs}, on a color monitor of the infrared camera. In general, the detecting resolution for a picture element depends on an objective distance, which is the distance, *l*, between the testing object and the infrared camera. In this experimental work, the *l* value of 700 mm with 20° angle towards the perpendicular direction (90°). These two parameters are set to be constant in the entire experimental work. Note that the emissivity, ε is set in the infrared camera to be 0.97. Reflection correlation was made to control the limit of emissivity that can affect the correlation and to increase thermal image accuracy.

The controller unit consists of temperature display box, relay, thermocouple, and the heater connection. The controller is design in on and off mode where the temperature limitation is set to be 120°C as described previously. When the temperature reaches the set value and exceed by 1°C, the relay will be automatically turn off the heater connection making temperature to drops and maintain below the set value. To measure the temperature of the testing object surface, T_s, K-type thermocouple is attached to the surface of the testing object by using epoxy [9]. When using quantitative infrared thermography, T_{rs} should be calibrated to adjust to T_s because T_{rs} will not always be consistent with T_s when $\boldsymbol{\varepsilon} < 1$ as mentioned earlier.

3.1.3 Defects Design

As this study suggests incorporating the temperature distribution factor into the correlation to further characterize the heat circulation in the insulation and analyze the defect's area. For this purpose, a total of 4 spotted areas on testing object (3 with defect and 1 without defect) and 4 measurements of insulation thickness were used to assess the correlation. Table 1 gives the details of the defects.

TABLE 1: Details of Defects Created in CUI cell

No of defect	Defect Types	Defect Dimension
Defect1	Pinhole1	1.2cm *(d)* x 0.3cm *(H)*
Defect2	Pinhole2	1.2cm *(d)* x 0.5cm *(H)*
Defect3	Corrosion	$20cm^2$ grid

As shown in Figure 14, defect 1 and 2 are created in the laboratory using milling machine. The defect is made in circular form whereby the diameter, *d* for each defect is the same but with different depth, *H* into the testing object. Meanwhile, defect 3 is the corrosion type initially present on the testing object and is measured in grid (1 grid box: 1cm x 1cm) to be $20cm^2$.

Corrosion area = 20 cm square grid

l (plate) = 1.3cm

l (hole1) = 0.3cm

l (hole2) = 0.5cm

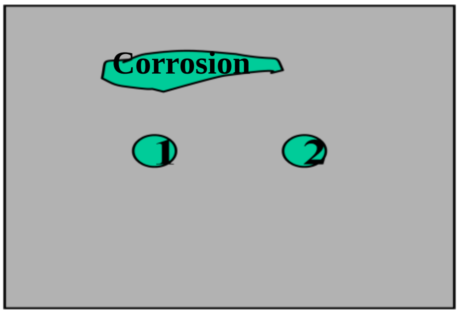


Figure 14: Illustration of testing object and its detail view

3.2 Project Testing and Evaluation

To achieve the objectives stated, there are several parameters to be considered as this parameters contribute to the interpretation of the thermal images in the result and discussion section. By relating the parameters identified to the thermal image effects, we can further determine what parameters brings significant effects to the results and this lead to the interpretation of the thermography test itself.

The project is first evaluated by plotting the temperature distribution with the time interval. The temperature distribution is recorded in the time of interval of 1 minute. The total time taken is up to 8 minutes only and the purpose of this testing is to see the difference in temperature between the three defect created and the area of non defect of the testing object without the insulation. Table 2 illustrates the project testing described.

TABLE 2 – Temperature distribution versus time interval table

Time (min)	Surface Area Temperature (°C)				Max temperature on camera (°C)
	Defect 1	Defect 2	Defect 3	No defect	
1					
2					
3					
4					
5					
6					
7					
8					

Once the data has been recorded, the graph of temperature versus time interval is plot to see the relationship of time effects to the temperature distribution in different testing object surface condition. The result is then analyzed by looking at the curve trend as the time elapsed. For this result, the interpretation and comparison of temperature recoded determines the type of defects present on the testing object. The justification on the curve trend will be discussed details in the next chapter.

One more testing is to relate the temperature distribution with the insulation thickness. The insulation thickness is varied and the relationship of the insulation thickness and the temperature distribution by infrared camera is recorded. Table 3 shows the relation of the variation thickness of insulation made to see its effect to the temperature of the testing object.

TABLE 3 – Temperature distribution versus insulation thickness table

Insulation thickness (cm)	Surface Area Temperature (°C)		
	Defect 1	Defect 2	Defect 3
0.5			
1.0			
1.5			
2.0			

The LT testing requires the thermographer to be fully understood on how to use the IR camera effectively. This is to ensure that the results obtained are logic and follow the theory stated. Hence, it is easier for thermographer to analyze the IR image accordingly and precisely with subject to the image taken. In this project evaluation, the researcher uses two approaches in which numerical computation method and the thermal image correlation method. These two methods is used to further analyze the data obtained and justify them according to the outcomes of the two plots constructed earlier.

In the case of the result to plot the graph is not as expected, the LT test is run again until the trend of temperature recoded shows proportional increment or decrement. The researcher will then do the best fit line for the plotting of graph at the end of the trials. Once the data obtain is reliable, then the researcher proceed to the next step which is the evaluation section by applying the two methods mentioned. At this stage, analysis on the IR image taken and further interpretation on the heat distribution on the testing object is done. In this case, if the analysis concept is not the same as the curve trend concept, it means the analysis is not accepted and probably a significant error in obtaining the results. To overcome this problem, double checking on data analysis must be done or perhaps must redo the LT testing In contradict to it, the project can be concluded and the results is said to be valid.

3.3 Required Hardware and Software

To conduct the LT test mentioned earlier, several tools (hardware & software) are required in order to set up the experiment. Table 4 below provides the details of the required hardware and software needed together with the function of each tools.

TABLE 4: List of required hardware and software

Hardware	Function	Details/Remarks
Carbon steel plate (testing object)	To use as the specimen of the real downstream piping	Quantity : 1 unit Dimension : 20cm x 28cm (square) Thickness : 1.3 cm Type : Carbon
Glass wool	Use as the insulator for the testing object	Thickness : 5cm, 10cm, 15cm, 20cm Dimension : 20cm x 28cm (square) R-value :1.35 m^2K/W.
Thermal Imaging IR Camera	Primary tools to detect CUI by penetrating infrared rays	Unit : 1 Provided by the university
Isothermal box	An adiabatic box that is equipped with glass wool insulation to prevent temperature loss.	Unit : 1 Characteristics : Body made up of zinc sheets and is square shaped box
Controller	Control the desired temperature on the testing object	Unit : 2 Provided in the laboratory
Thermocouple (K-type)	Used to detect the desired CUI temperature beneath the insulation	Unit: 1 Provided in the laboratory
Computer	Attached to infrared camera for data images captured to be analyzed	Unit : 1 Provided in the laboratory
Process Heater mat	Used to provide heat sources to the testing object	Unit : 1 Purchased from RS Components Sdn Bhd Dimension : 20cm x 15cm Details : 100W, 240Vac
Software	**Function**	**Details/Remarks**
Microsoft Excel, Office	Used for data collection and analysis	Provided in the laboratory

3.4 Project Activities

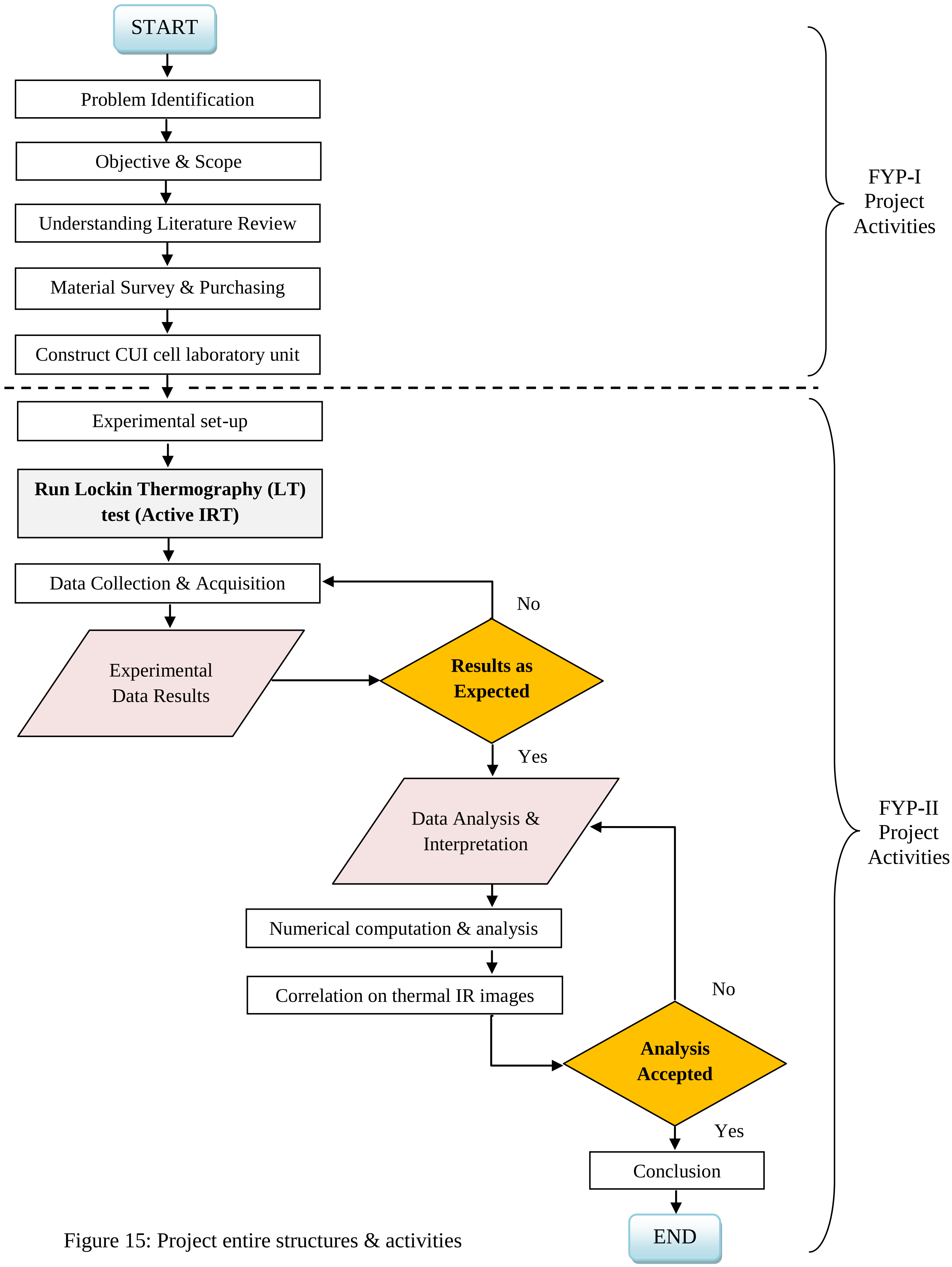


Figure 15: Project entire structures & activities

3.5 Key Milestone

Milestone is made to observe the progress updates of activities to be exactly run smoothly within the time range of project.

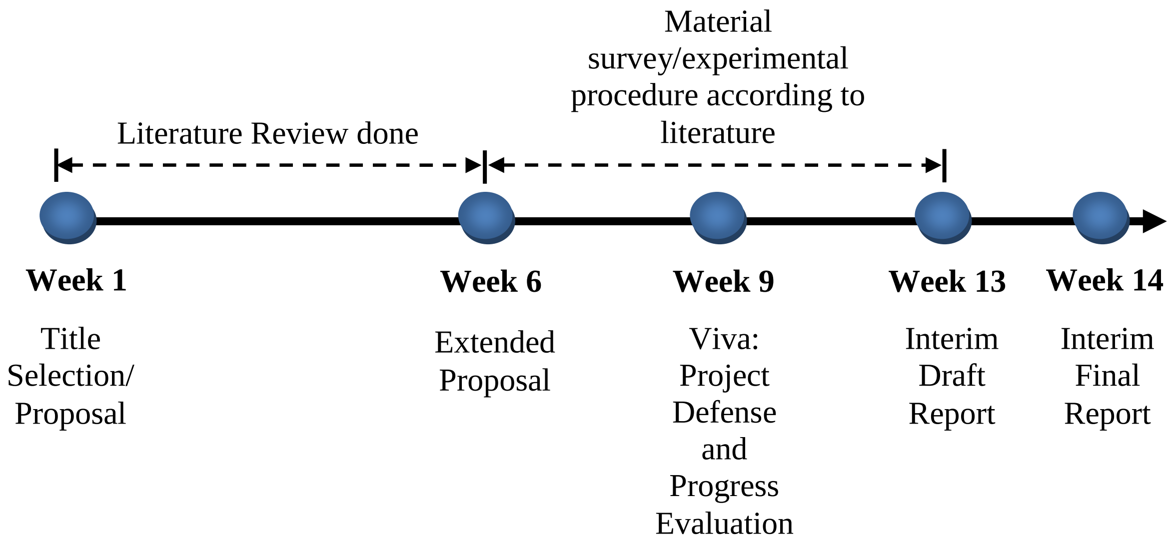


Figure 16: Key milestone for FYP-I

Figure 16 is the milestones for Final Year Project I. All of the key milestones have been completed. For next semester, we will continue the project in Final year Project II as shown in Figure 17. The project should be completed by week 10 with results prior to the pre – SEDEX and dissertation report as well as the technical papers.

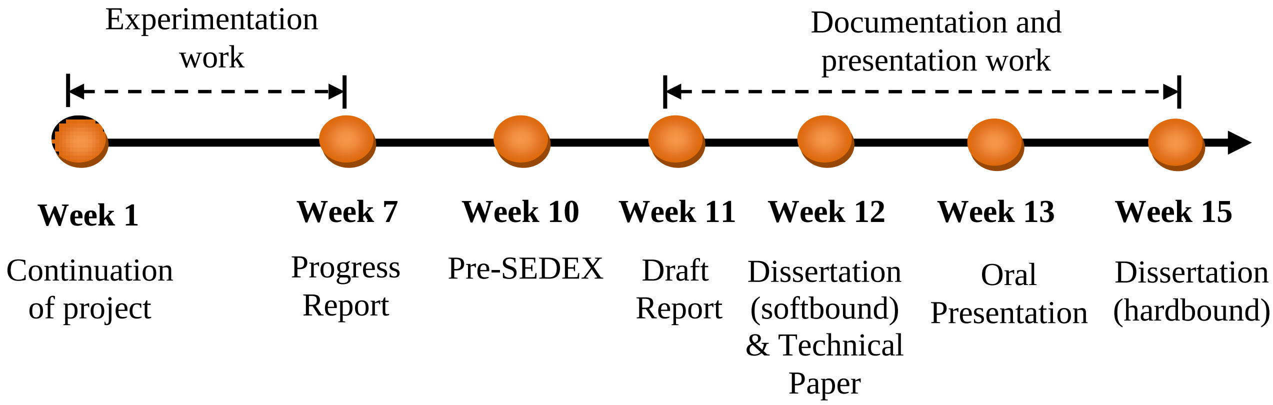


Figure 17: Key milestone for FYP-II

3.6 Gantt Chart

FINAL YEAR PROJECT I (FYP-I)																
No.	Details of work	WEEK														
		01	02	03	04	05	06	07		08	09	10	11	12	13	14
1	**Project selection**								MID-SEMESTER BREAK							
2	**Preliminary research and work**															
3	**Submission of extended proposal**															
4	**Proposal defense**															
5	**Project work** - familiarization on - laboratory booking - material survey (ex.: pipe, insulator, IRT camera)															
6	**Commencements of experimental work** - experimental set-up & procedure															
7	**Submission of interim draft report**															
8	**Submission of interim report**															

Figure 18: Gantt chart for FYP-I

FINAL YEAR PROJECT II (FYP-II)																	
No.	Details of work	WEEK															
		01	02	03	04	05	06	07		08	09	10	11	12	13	14	15
1	**Continuation of experimental work** - pulse phase thermography test - passive thermography test - improve on experiment, reducing Errors								MID-SEMESTER BREAK								
2	**Submission of progress report**																
3	**Data analysis** - comparison of experimental results to the actual site results - ensure results to achieve project Objective																
4	**Pre-SEDEX**																
5	**Submission of draft report**																
6	**Submission of dissertation**																
7	**Submission of technical paper**																
8	**Oral presentation**																
9	**Submission of final dissertation**																

Figure 19: Gantt chart for FYP-II

CHAPTER 4

RESULTS & DISCUSSION

4.1 Data Acquisition & Analysis

Several analyses that can be done once we have recorded the thermal images captured on the testing object. A detailed approach must be done to acquire and analyse the data accurately. Figure 20 shows the sequence on how the data or the thermal images captured by infrared camera is being transferred for analyse purpose. The data images must go through certain files before it can be read by the computer for further analysis.

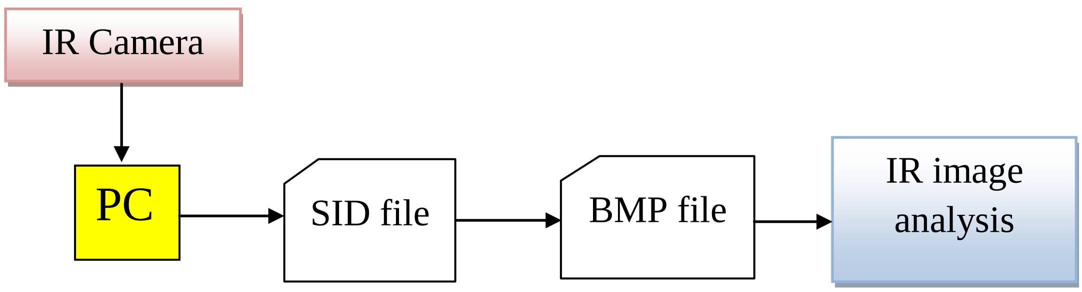


Figure 20: Data acquisition and analysis

The thermal images captured will shows the temperature distribution of the testing objects as well as locating the defects. In this experiment, the data or the images captured are taken in a set of 2 pictures; one under IR rays, and the other one under normal vision. Once the data has been recorded, it is then conveyed and transform into the file format before it can be read by the computer for analysing.

4.2 Experimental Results

Based from experimental results, two plots were made to investigate of temperature distribution with time and the insulation thickness. The results of temperature distribution were tabulated accordingly and plotted in a graph. In collecting the temperature data, several factors are to be considered and few assumptions were made. This is to ensure that the data obtained are as per expected and theoretically right. The assumptions below were made and applied in the entire experimental work:

1) The effect of ambient temperature to the heat loss is negligible.
2) Reflection correlation is made to avoid the distraction in temperature distribution and to obtain clearer IR images.
3) The emissivity is set to be constant with value of 0.97.
4) Distribution of glass wool structure and its density are neglected.
5) The radiation temperature, T_{rs} is the same as the testing object surface temperature, T_s due to the emissivity close to 1.

Table 5 shows the experimental result obtained by relating temperature distribution of the testing object surface, T_s with the time for the non-insulated testing object.

TABLE 5: Temperature distribution versus time interval result

Time (min)	Surface Area Temperature (°C)				Max temperature on camera (°C)
	Defect 1	Defect 2	Defect 3	No defect	
1	34.3	32.5	48.5	45.5	49.0
2	50.1	44.2	73.3	70.5	80.0
3	55.8	50.1	85.5	81.9	92.0
4	72.2	66.1	96.2	92.7	105
5	65.4	55.0	97.3	94.2	106
6	75.8	56.3	97.8	94.6	107
7	92.9	88.2	101	97.0	109
8	106	104	103	100	111

(*See Appendix A for the view of IR image taken*)

Meanwhile, table 6 shows the result obtained by relating temperature distribution of the insulated area, T_{ins} with the various thickness of insulation used.

TABLE 6: Temperature distribution versus insulation thickness result

Insulation thickness (cm)	Surface Area Temperature (°C)		
	Defect 1	Defect 2	Defect 3
0.5	66.7	58.0	55.2
1.0	62.5	55.4	43.7
1.5	53.1	48.8	40.0
2.0	50.9	42.8	35.5

4.2.1 Effect of Time with Temperature

In Figure 21, the temperature distribution versus time is plotted for the total time of 8 minutes. The temperature is recorded in every 1 minute interval to see the trend of heat distribution on the testing object. Note that the temperature recoded is the radiation temperature, T_{rs} whereby we assume earlier that T_{rs} is equal to the surface temperature being heated, T_s due to the constant emissivity.

The effect of temperature on different defects shows different temperature distribution. Overall, the temperature for the four spotted areas increasing as the testing object is heated in increasing time. This is becasue as the heat is distributed to the testing object, the heat capcity, Q circulated on the testing object also increase making the increment of temperature by 1°C. This obeys heat capacity equation as Q is directly proportional to $\Delta\theta$ as expressed:

$$Q = m \times c \times \Delta\theta \text{...............Equation (1)}$$

Where;

Q	= heat supplied, kJ	
m	= mass, kg	
c	= specific heat capcity, kJ/kg ^{o}C	
$\Delta\theta$	= change in temperature, °C	

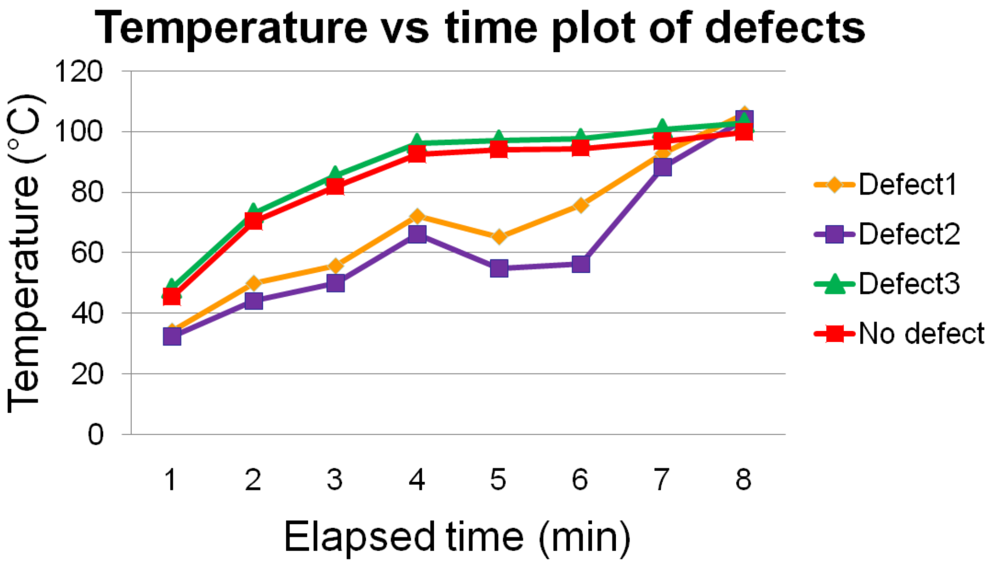


Figure 21: Temperature versus time plot of each defects recorded for infrared LT testing

In Equation 1, with the constant mass of testing object and the specific heat capcity value of the carbon steel, *c*, temperature plays an important role in determining the amount of heat that the testingobject can absorb through time. Taking into account the defects areas, the temperature abosorbed by the testing object at the defect areas may be slightly different with the non-defect areas. This is due to the mass loss of the testing object causing the distraction in the process of haet absorbtion as it affect the mass parameter value in Equation 1.

As shown in Figure 21, defect 1 and 2 (pinholes) recorded among the lowest temperature distribution as compared to defect 3 (corrosion) and non-defect areas. As described previously, mass loss of the testing object causing the temperature to drops. In addition, the heat that transfer from the heater mat is first travelled in the hole of the pinhole and eventually the heat traps. This results the temperature of the plate surface to record among the lowest temperature increment shown in Figure 21. This theory only applies to both pinholes defect. Corrosion is detected to permit slightly higher temperature than the non-defect area. This is because in this case, corrosion produces shining surface and it involves minor or very less amount of mass loss of the testing object. When the infrared camera captured this image, the shining surface will then obstruct the emissivity causing the temperature to be recorded higher than expected.

4.2.2 Effect of Insulation Thickness with Temperature

For the purpose of the project, another parameter to be considered is the insulation thickness, d_{ins} .Insulation thickness plays an important role in affecting the temperature distribution. Insulation covering the testing object is said to be the limitation factors for the infrared images to capture and detect the defect right on the spot. Figure 22 explains the results of temperature using different insulation thickness.

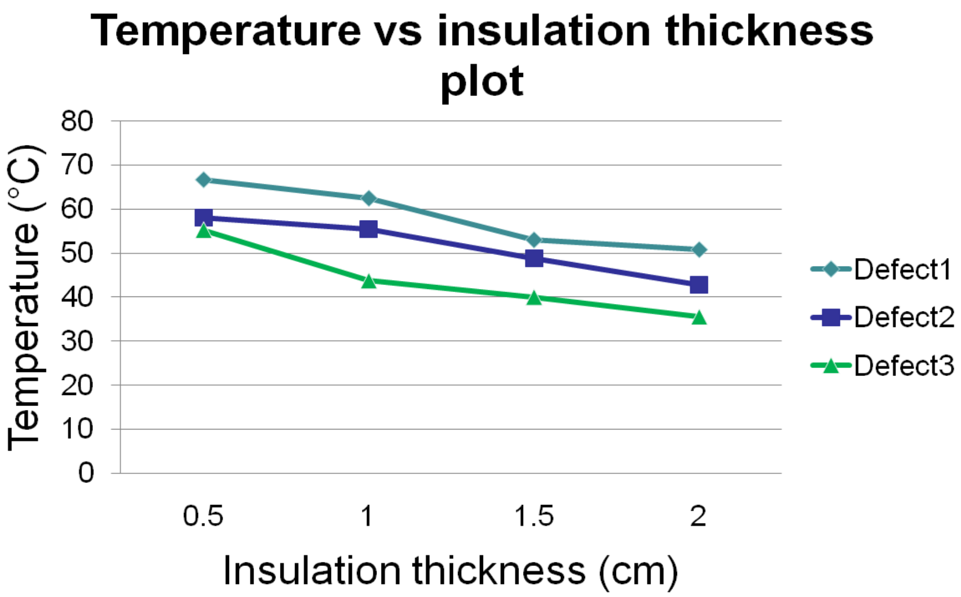


Figure 22: Temperature versus insulation thickness plot of each defects recorded for infrared LT testing

Based on Figure 22, it clearly shows that by placing the insulation on the surface of the testing object, the temperature distribution is distracted. Heat can transfer in medium. When heat is applied onto the tesing object, the heat is then circulated to the insulation section once the testing object has reached its own maximum heat capacity. As heat travel to insulation, it takes time for heat to spread out into the void spaces of the insulation section. This is the reason why the T_{rs} is decreasing as the insulation becomes thick. The thicker the insulation used, more temperature drops will be recorded. As of this phenomena happens, it give difficulties for thermogrpaher to detect the defect spot visibly by naked eyes.

4.3 Numerical Computation & Results

The numerical computation is performed to simulate the detection mechanism and the limit of the present NDT and E using the infrared thermography. The purpose of conducting the numerical computation is to track the heat distribution on the testing object and understand the temperature variation that pass through the defect. In this section, two-dimensional (2D) concept model is described and illustrated based on the CUI cell testing object and the understanding of heat transfer mechanism is theoretically explained.

4.3.1 Two-dimensional (2D) Concept Model

Figure 23 illustrates the two-dimensional concept model for the numerical computation along with the heating condition (*See Appendix B for the view of IR image taken*). The concept model indicates the unsteady heating from the backside surface of the testing object. This is merely to allow a parametric study of how detection mechanism to detect the defect area under the insulation section [10]. Note that the defect is illustrated only one as to resemble the concept model of the CUI cell.

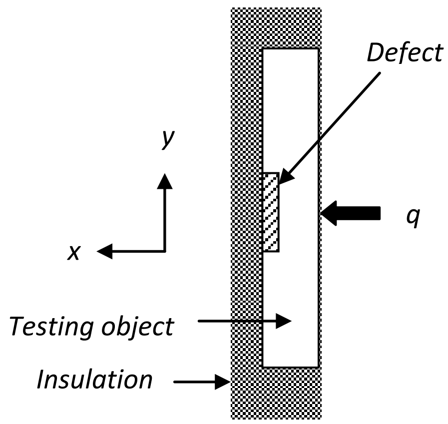


Figure 23: Two-dimensional concept model for numerical computation by unsteady heating from the surface.

4.3.2 Heat Transfer Analysis

As we can treat the concept model as a heat conduction problem when using the present NDT and E technique, the governing equation is applied in the following form:

Equation (2): Unsteady two-dimensional heat conduction [11]:

$$\rho C_P \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left[\lambda \frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda \frac{\partial T}{\partial y}\right]$$

It is adequate for discussing the two-dimensional model when the symmetrical defects are only prepared for fundamental investigation. For the external heat sources, the heat balance equation is applied as in the following form:

Equation (3): Heat balance equation [12]:

$$-\lambda \frac{\partial T}{\partial x} = h(T_s - T_a) + \varepsilon\sigma[(T_S)^4 - (T_a)^4]$$

Assuming that the heat transfer coefficient, h, is the laminar natural convection along a vertical testing object heated uniformly. The ambient temperature, T_a is set to be consistent together with the emissivity, ε. In this project, the heat is transferred to the testing object uniformly as the heater mat is placed at the center of the testing object. Taking the view of IR image taken in Figure 24 below shows the red color is the heated region is clearly seen. It shows that the thermal wave captured by IR camera shows the computation of Equation 2 and 3 are valid for the unsteady 2D heat conduction.

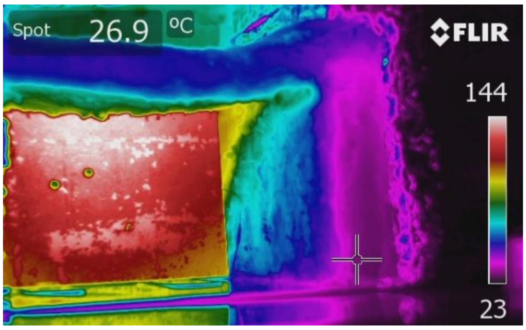


Figure 24: Heat conduction throughout the testing object

4.4 Correlation Results

The infrared image correlation is done to interpret in details the section of the testing object that consider the movement and progression of water for CUI. The correlation is made by comparing between the reference image and the captured image at certain time.

4.4.1 Thermal Zone Classification

Figure 25 shows the correlation made whereby the comparison of reference image (without insulation) and the captured image (with insulation at certain time) is done. It can be analyze that the color of the infrared image classify the temperature of the testing object section thus justifying the condition of the specific areas of the testing object.

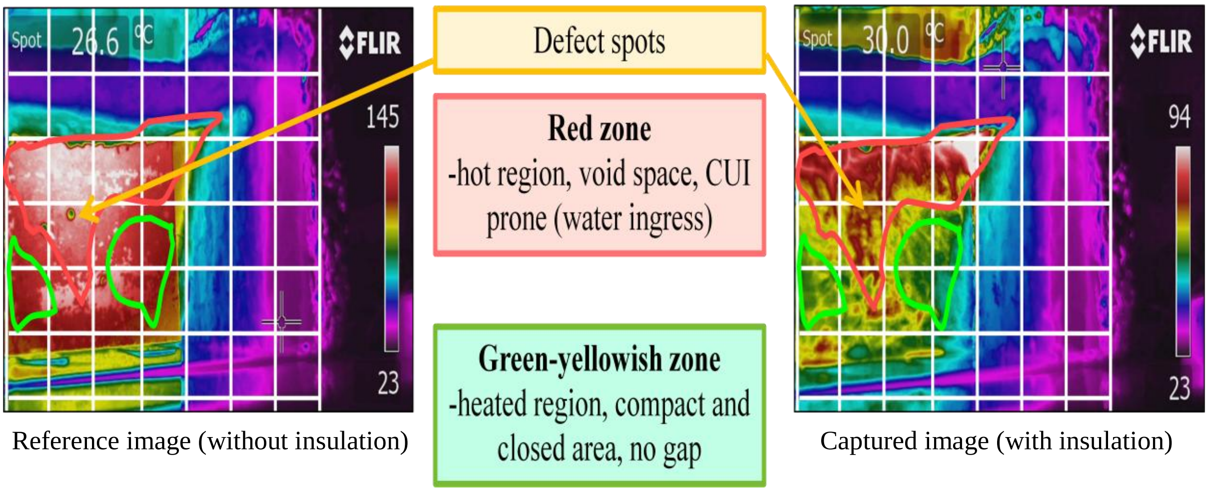


Figure 25: Infrared image correlation to spot the areas of CUI prone

Theoretically, the temperature increases as the presence of defects detected. In relation to the correlation made, different colors of infrared image indicate different thermal distribution involved. Initially, the maximum temperature recorded for reference image is 145°C which is then reduce to 94°C for the captured image. This is due to the existence of insulation where the thermophysical property of the testing object has been changing. To start doing the correlation, the colors of the infrared images were recorded and classified.

Red colored zone is identified to be the hot region meanwhile the green to yellowish colored zone is identified to be the cooler/normal heated region. As to distinguish these two zones, further interpretation on IR color is made by correlating the captured image to the defects area and relates them theoretically.

4.4.2 Detection of Defects

From the IR color, it can be interpreted that the red color is the zones with higher temperature traps. In this region, the insulation pocket is made in which there void spaces of the insulation that contacting the testing object. This is the reason of water ingression occurrence that leads to CUI. As water enters into the insulation through these spaces, it accumulates on the pipe surface and eventually corroding the pipe. Meanwhile, the cooler region is determined by the green-yellowish color. In this region, the insulation is designed to be compacted and well-arranged as to avoid from the heat trap. It is obviously from Figure 25 that two pinholes are located nearby the hot region where the water enters and accumulates in the void spaces of the insulation. This interpretation is yet to be provably accepted by noticing the cooler region that occurs on the testing object with no defect spotted. Table 7 summarizes the detection of defects by classifying the color of IR images.

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TABLE 7: Detection of defects by IR color variation

IR color	Zone	Temperature	Reason	CUI prone
Red	Very hot region	Very High	Void spaces present	Yes
Yellow	Hot region	High	Little void spaces	Possible
Green	Moderate heated	Moderate	Compact area, no gap	No
Velvet, blue, light blue	Cooler region	Moderate	Insulation area	-

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

As a conclusion, it has certified that the applicability of the infrared thermography for NDT and E as follows throughout a series of experimental investigation, numerical computation and correlation analysis. Few of the highlighted outcomes based on the project are:

1. The infrared thermography for NDT and E is useful in detecting defects and provably applicable to locate CUI by infrared image correlation. The heat zone classification is vital in governing the location of CUI and its potential to accelerate to other areas.
2. As time elapsed, the temperature increases. Corrosion gives the highest temperature distribution as compared to the area of non-defect. The two pinholes are among the lowest heat circulation recorded.
3. From the numerical computation, it is explained that the heat transfer theory is essential in determining the heat distribution and circulation to the entire testing object.
4. The thicker the insulation thickness, the temperature gradient is decreasing. This is due to heat circulation to insulator causing distraction on defect's thermal visibility.

Therefore, to validate the use of IRT technology in NDT methods especially in oil and gas industry, LT testing provide adequate outcomes required to prove the effectiveness of the IR thermogrpahy to locate CUI. Although the use of other NDT techniques is practicable in the current oil and gas industry, it is still considered as the non-effective NDT as the methods requires engineers and inspectors to plan a full budget for the inspection activities and inefficient as it takes about few days to complete the inspection. From this project, hopefully the results obtained from the experiment will provide evidence on the effectiveness of using IRT in NDT techniques to replace other conventional NDT for the benefits of the company and NDT technology.

5.2 Recommendation

Few improvements on the experimental procedure need to take into account as it will lead to the accuracy of the results obtained. The experiment is good if it is conducted twice as the researcher can detect the errors and flaws while conducting the experiment. Expertise in thermography is one of the best options for researcher to discuss and interpret the thermal images in an expert ways.

This technique really helps the plant engineer to predict any potential failure, thereby planning the shut down well before. Therefore, it is expected that low cost of IR thermo-vision instruments will be available in near future, making its usage more user- friendly and expanding the application elsewhere.

In short, with the on-line condition monitoring technology becoming an inevitable part of maintenance strategy in today’s scenario, non-contact type temperature monitoring methods have become more popular. Infrared Thermography (IRT) is such a non-contact type technique which provides a fast, reliable and accurate temperature profile of any material surface.

REFERENCES

1. Marwan, Danny Keck. 2003. ‘Nondestructive Testing Technologies for the Oil Industry.” SPE 81563. Bahrain.

2. Hatfield, David A. 2004. ‘Using IR Surveys to Locate Corrosion under Wet Insulation.” InfraMation Proceedings.

3. McConnell P.E. 2010. “Applications of Thermography In Diagnosing Corrosion And Material Issues In Today's Refinery.” NACE International, Publications Division, 1440 South Creek Drive, Houston, Texas 77084. FIGURE 1 – IR Scan of a Vessel with Grease Pencil Writing on the Manway Cover.

4. 2012, TWI Ltd. “The NDT Validation Center”. http://www.ndt-validation.com/technologies.

5. X. Maldague, F.Galmiche, A.Zaidi. 2002. “Advanced in pulsed phase thermography”. Infrared Physics & Technology; Elsevier Science B.V publication; Department of Electrical and Computing Engineering, Universite Laval, Quebec City (Quebec), Canada, Canada G1K 7P4.

6. Dharma Abavarathna, William G. Ashbaugh, Russell D. Kanev; Measurement Of Corrosion Under Insulation And Effectiveness Of Protective Coatings; CLIInternational, Inc. 14503 Bammel-North Houston Suite 300 Houston, Texas 77014-1149.

7. Michael LettichCorrosion Under Insulation (Cui) - A Nanotechnology Solution; Industrial Nanotech, Inc.; 801 Laurel Oak Dr. Ste. 702, Naples, FL 34108, USA.

8. Shepard SM, Favro LD, Thomas RK.Thermal wave NDT of ceramic coatings, SPIE Proc 1995;2473:190.

9. Burleigh DD. Thermographic NDT of graphite epoxy filament-wound structures. Thermosense XI. SPIE Proc 1989;1094:175.

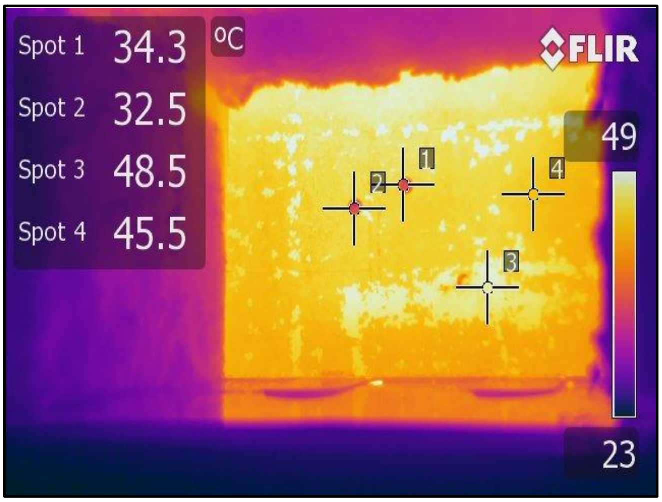
10. Ogura K, Sakagami TA.New ispection technique for the damage inspection of CFRP using thermal image. Proceedings of Joint ASME-JSME Advances in Electronics Packaging, 1992, p.909.

11. Terumi Inagaki, Toshimitsu Ishii, Toshikatsu Iwamoto; 1999; “On the NDT and E for the diagnosis of defects using infrared thermography”; Elsevier Science Ltd. publication; Department of Mechanical Engineering,; Ibaraki Universite Laval, 12-1 Nakanarusawa 4 Chome. Hitachi, Ibaraki, 316, Japan.

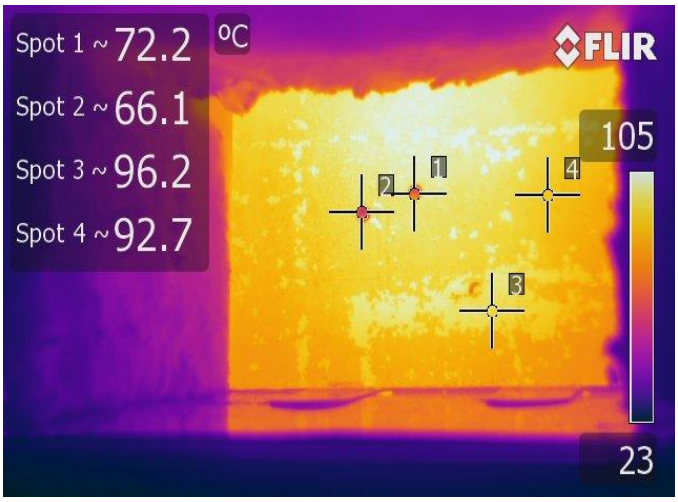
12. Pantakar SV. Numerical heat transfer and fluid flow. Hemisphere Publishing Corporation, 1980.

APPENDICES

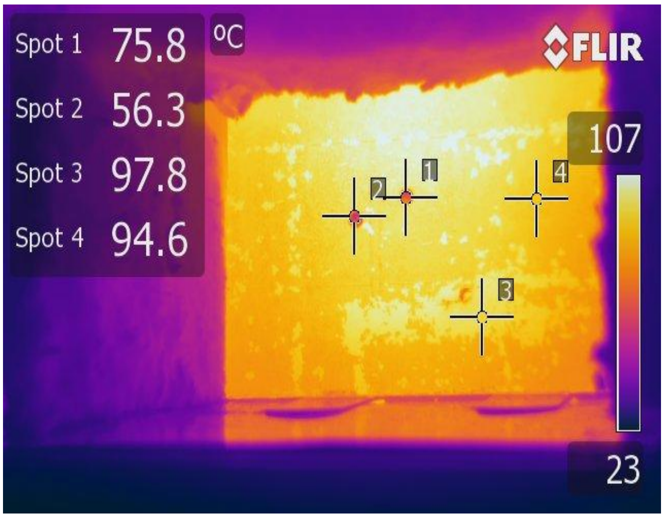
Appendix A



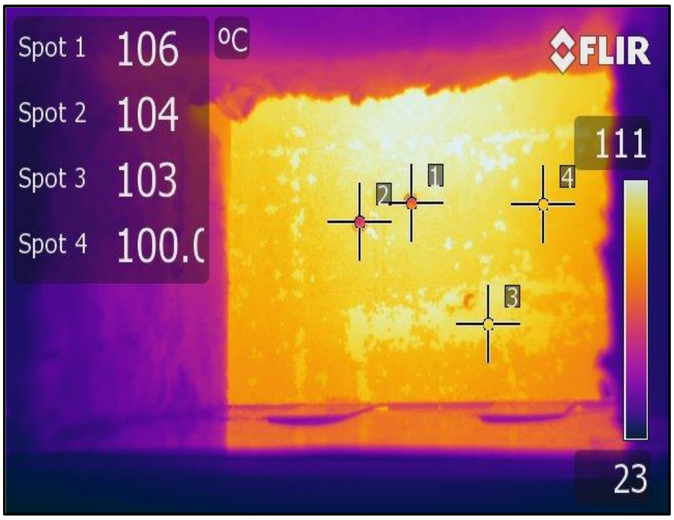
(a) 1 *min* after heating



(b) 4 *min* after heating



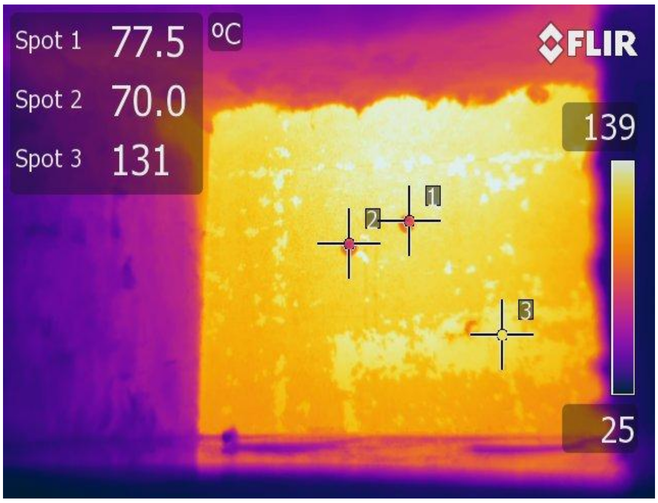
(c) 6 *min* after heating



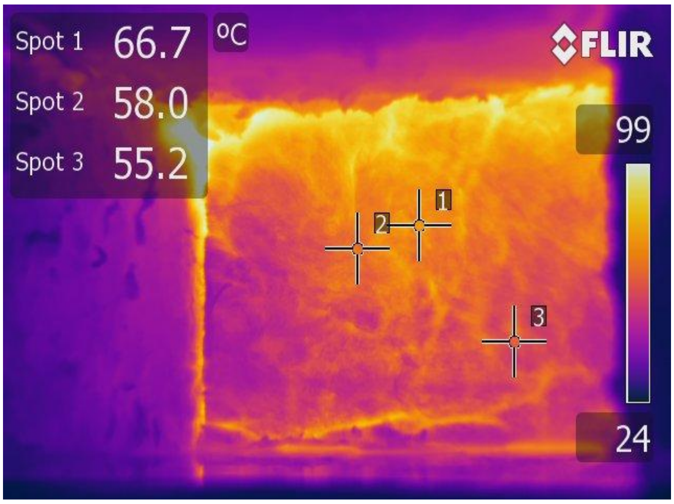
(d) 8 *min* after heating

Appendix A: Transient thermograph of carbon steel testing object with 4 spotted areas;
(a) 1min after heating; (b) 4min after heating; (c) 6min after heating; (d) 8min after heating

Appendix B



Testing object without insulation



Testing object with insulation

Appendix B: Temperature drawdown on the thermograph of carbon steel testing object with 3 spotted areas; (a) testing object without insulation; (b) testing object with insulation

--- END OF DISSERTATION ---