Preliminary investigation of corrosion surfaces under coating on a plate using IR thermal imaging camera

by

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Dissertation submitted is partial fulfillment of the requirements for the

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the:

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MECHANICAL ENGINEERING

Approved by,

____

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2013

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.

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(Erhan Nikman Bin Rizal Nikma)

ABSTRACT

A novel integration of infrared IR thermography is proposed for nondestructive detection of steel corrosion by taking advantage of the difference in thermal characteristics of corroded and non-corroded steel. The objective of this research is to study the potential of infrared thermography as early identification method and as complement to Non-Destructive Testing (NDT) to identify corrosion under paint. Steel were fabricated and coated with primer paint. Active infrared thermography is applied to those plates to detect the corrosion which are not visible via normal visual inspection. The experiments are assisted by heat stimulation device and an infrared camera. The difference in temperature between the corroded and non corroded area was found to be high enough to get a clear image of the defect. The positive results gives verification that there is a potential for infrared thermography to be used to detect pipe thinning and corrosion under paint.

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION

1.1 Background of Studies

Service failures of a component and structures have been increasingly experienced in many industries and quite often it all happens without warning. Some may be trivial and some may cause a phenomenal disaster. Metal has the tendency to rust so corrosion is like cancer to metal and the damage can be greatly exaggerated by the circumstances. Although many corroded components leading to accidents have not gone public for liability reasons or due to the fact it just disappeared in the catastrophic event, other have turn heads and made headlines around the world. Take for example one of the biggest oil spill in nearly 30 years of North Slope petroleum production. BP's failure to monitors its field pipeline and leak detection system resulted in a thick layer of black crude oil covering an area larger than a football field. (Roberge, 2005) The March 2nd, 2006 incident was due to a corroded transit pipeline and cost BP three year probation and a staggering $20 million in criminal penalties for the 201,000 gallon Prudhoe Bay oil spill. (Anderson, 2010)

From this we can see how important it is to detect and help maintain a structure and its component from corrosion. Prevention is better than cure is the saying thus having test carried out to prevent a disaster is much better than having to pay for damages and also caused destruction to nature. One of the tests that could be carried out to help detect corrosion under a surface would be by using thermal imaging cameras. Thermal imaging cameras are used to detect heat flows from and or through an object. It involves measurement or mapping of the surface temperature. Thermal imaging cameras are of great significance in preventative maintenance and also technical diagnostics. It helps locate and detect anomalies such as corrosion under a paint coating possible. The best part of using a thermal imaging camera is it test out materials and components without causing damage to the body parts and can expose any corroded area before it gets any worse. Thermal imaging inspection is non destructive equipment or known as NDE. It uses infrared spectral band of the electromagnetic radiation.

Thermal imaging camera is now much easier to get in the market compared to years back. Although these equipments are marketed as easy to use, they are not readily applicable under plant conditions. As written in the book practical Non-Destructive Testing it is very important that proper non destructive test or NDT equipment is selected to suit test requirements as well as the condition (Raj, Jayakumar & Thavasimuthu, 2002). Having a correct and detailed procedure is important to getting a good and clear result.

1.2 Problem Statement

Thermal images are artificially colored to help interpretation to be much easier. The quality of the image is influenced by non-uniformity in emissivity caused by surface roughness and the state of cleanliness of the surface. Not being at the correct distance between the camera and object may cause the image of corroded area not seen clearly in the digital image. A procedure is needed to run the test in order to obtain results that are optimum.

1.3 Objective

The objectives of this project are:

-To design and fabricate a rig that consists of test equipment and thermal imaging camera.

-A standard test for equipment failure detention is to be developed and data obtain is to be analyze.

1.4 Scope of Work

The scope of the research is to find the most suitable distance in order to have the clearest image differentiating a corroded region on a plate metal. Besides that, a standard test procedure is laid out step by step so failure detection rate is high when a thermal imaging camera is used to detect corrosion. Data of the experiment obtained will be analyzed.

1.5 Relevancy of the Project

This project's main aim is to make the best use of thermal imaging camera as a NDT in the industry. If the objectives are achieved in this research, thermal imaging camera can be used in the manufacturing plant or industries that deal with various process equipment that a prone to corrosion. After detection, the next steps to stop corrosion can be taken and could save cost of replacing equipment.

CHAPTER 2

LITERATURE REVIEW

2.1 Non-Destructive Testing

Non-destructive testing (NDT) relates to the examination of materials for flaws without harming the object being tested. As an industrial test method, NDT provides a cost effective means of testing while protecting the object's usability for its designed purpose. The ability to inspect castings, weldments, wall thicknesses and roll shells in an accurate and comprehensive manner is critical; and even more important when the machine has been in use for several years, possibly with changes made to the original framework, and operating conditions that are now placing more stress on the equipment than original design allowed. NDT uses several methods, including: visual inspection, ultrasonic, dye penetrant, magnetic particle, acoustic emission, electromagnetic and radiography. Common tools used include: trained expert's eyes, caliper micrometers, ultrasonic wall thickness gauges, and portable grinders in addition to the specific tools used for more complex testing methods.

According to (Raj, Jayakumar, & Thavasimuthu, 2007)
"Non-destructive testing (NDT) are the term used to represent the techniques that are based on the application of physical principle employed for the purpose of determining the characteristics of materials or components or systems and for detecting and assessing the inhomogeneitis and harmful defects without impairing the usefulness of such materials or components or systems" (p.1)

And, according to Hellier, (2001)
"A general definition of NDT is an examination, test, or evaluation performed on any type of test object without changing or altering that object in any way, in order to determine the absence or presence of the conditions or discontinuities that may have an effect on the usefulness or serviceability of that object.

2.2 Advantages and Disadvantages of NDT

Table 1 below are the advantages and disadvantages of focused NDT; Ultrasonic Testing, Radiography Testing, and Infrared Thermography (Raj, et.al, 2007, p.g. 77 and 110; Bond, L.J., 2001; Shen, G. & Li, T., 2007).

Table 1. Types of NDT

NDT Method	Advantages	Disadvantages
Ultrasonic Testing	• Testing can done in one side of the material • Can gives accurate thickness and distance measurement • Immediate results • Part preparation required is minimum	• Require a clean and low roughness surface • High-skilled operated is needed to operate and analyze the inspection data • Defects that parallel with sound beam can be undetectable • Point-to-point inspection consumed much time for long piping inspection
Radiography Testing	• Able to detect surface and subsurface defects • Multi-layered structure inspection	• Safe distance from radiation source is needed during inspection work • High-skilled operator is required

	capability • Can inspect wide range of materials	• High thickness area takes much time • Radiation beam to non-volumetric defects orientation is important
Infrared Thermography	1. Non-contact NDT 2. Fast and harmless operation 3. Able to inspect large portion of inspection at shorter time compared to Ultrasonic Testing 4. Simple and easy equipment setup 5. Image interpretation is relatively easy to understand 6. Straightforward post-inspection data processing	• Emissivity of the surface may affect the interpretation • External heat need to be introduced for better heat distribution • Time factor is important for Active Infrared Thermography (transient heat transfer)

2.3 Infrared Thermal Imaging in Industrial Application

Thermal imaging is an NDT technology that is evolving rapidly. The equipment can be obtained easily in the current market either by online or at selected supplier. In this day, routine inspection is very much important to help maintain a component so less money is spent in buying a new one. The IR thermal imaging is widely used in the aviation, shipping and pipe inspection industries. Some of the worst cases of corrosion like the Guadalajara sewer explosion, the oil spill caused by the corroding tanker Erika could have been completely avoided if the appropriate maintenance measures were taken early on (Malmcom, A. 2013). The application of IR imaging is growing rapidly in industry as well as in research and development (Vollmer & Mollmann, 2010)

2.3.1 Basic Mechanism and concept

IR thermal imaging camera most basic concept is that it operates by applying heat to the area of the surface that is being tested and then obtaining a thermal image of the sample surface as heat dissipates into the part. The properties of infrared radiations are the same to electromagnetic radiations such as visible light excluding that the transmission and absorption behavior is different from that of visible light (Raj, Jayakumar & Thavasimuthu, 2002). The region beyond red is called the infrared region. From the electromagnetic spectrum, it shows the temperature increases from the violet region of the spectrum to the red region and beyond as shown in **Figure 1**. When an object is irradiated by infrared radiation, it gets heated and heat flows on the surface or through the thickness of the object from the warmer to the cooler region. This result in temperature variation and is related to the pattern of heat flow. The transfer of heat energy continues from the warmer to the cooler region, till equilibrium is reached. This energy is detected and monitored by infrared cameras (Prasad & Nair, 2008).

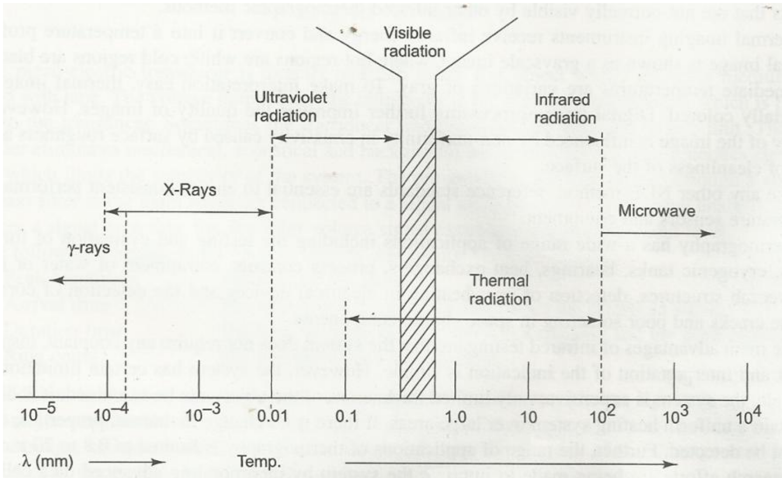

Figure 1. Electromagnetic Spectrum

2.3.2 Advantages of IR Thermal Imaging Compared to Other NDE

Thermal imaging measurement might be useful in locating hot spots, such as a bearing that is wearing out and starting to heat up due to an increase in friction. In its more advanced form, the use of thermal imaging systems allow thermal information to be very rapidly collected over a wide area and in a non-contact mode. Steven M. Shepard, Ph.D., President of Ferndale, Michigan-based Thermal Wave Imaging explains, "If you just look at a part with an infrared camera, you get an interesting picture, but that picture doesn’t necessarily tell you much about what’s inside. If you go to the next step, which is using a heat source to heat it up, you begin to get an inkling of what’s inside, but again it’s difficult to control, difficult to interpret and nearly impossible to replicate. The next step is to be more precise about how you heat the part and how you analyze the data. And at that point, you start to get pretty serious about learning what’s inside." (Escobar, 2001). Thermal imaging can also save money as it only uses single equipment without the need of other extra tools. It is also safer as its non contact mapping in such manner that the test does not harm the material in any way.

2.4 Steel coating for offshore application

Petronas Technical Standard PTS 30.48.00.31-P recommended that surface preparation is to be done by blast cleaning for new construction painting. Blast cleaning can be carried out through ISO 8504-2: 1992. The minimum grade of blasting shall be Sa 2.5 for successful coating application (Petronas Technical Standard, 1999).

Offshore platform, tanks and pipelines are usually coated with two or three coating system. Suitable with the aerated environment, both systems provide corrosion protection sometimes with enhanced fire protection purpose. Coated steel substrate for testing of fire protection was primer-coated with epoxy-zinc phosphate (Amir, Ahmad & Megat-Yusoff, 2011). Epoxy zinc phosphate is a zinc rich primer that is commonly used in offshore application as it acts as a sacrificial anode to provide corrosion resistance (Offshore structures, 2009). Intermediate coat usually a higher build epoxy is used for other performance such as fire resistant, abrasion resistant, wear and weathering (Ault, n.d.)

Thermal spray system has been introduced for higher performance coating system though its utilization is limited to certain areas of the structure. They are to be applied on hot risers for submerged, splash zone and atmospheric service (Thomasan, Olsen, Haugen & Fischer, 2004). This is also recommended in NORSOK standard (M-501: Surface preparation and protective coating) (Norsok Standard, 2012).

2.5 Corrosion under insulation

Although the extent and resultant cost of corrosion under insulation (CUI) are not known exactly, J. F. Delahunt in "Corrosion Control Under Thermal Insulation and Fireproofing"[1] shows the seriousness of the problem by presenting case histories. These cover deep pitting, as well as general corrosion, that have occurred on galvanized steel tanks under 12-year-old polyurethane foam.

Delahunt advises that metal loss can be the least of the problem. For example, an eight-inch carbon steel pipeline carrying heavy fuel oil was insulated with calcium silicate block and protected with a metal weather jacket. The pipe corroded, resulting in a leak. The oil was ignited and a large fire ensued, causing hundreds of thousands of dollars in damage to process equipment.

2.5.1 Types of Corrosion under Insulation

By understanding the types of corrosion that can occur under insulation, the proper materials and construction can be employed to prevent them. Intruding water is the key problem in CUI. Special care must be taken during design not to promote corrosion by permitting water to enter a system either directly or indirectly by capillary action. Moisture may be external or may be present in insulation.

Corrosion may attack the jacketing, the insulation hardware, or the underlying piping or equipment. Depending on other factors, chloride, and galvanic, acidic or alkaline corrosion may occur.

Galvanic corrosion generally results from wet insulation with an electrolyte or salt present that allows a current flow between dissimilar metals (i.e., the insulated metal surface and the outer jacket or accessories). The extent and severity of the attack on the less noble metal depends not only on the difference in potential of the two metals, but also on their relative areas. The complete galvanic series and the voltage potential for each metal or alloy appear in handbooks and other standard references. The mechanism of galvanic corrosion is detailed by G. Butler and H. C. Ison in "Corrosion and Its Prevention in Waters."

Alkaline or acidic corrosion results when an alkali or acid and moisture, are present in certain fibrous or granular insulations. For hot service above 250^{o} F, most of the water is driven off. This water vapor may condense at the edge of the insulation, and dissolve the alkaline or acidic chemicals there, resulting in corrosion of the aluminum or steel jacketing.

Some alkaline waters with aluminum produce etching and pitting. Pitting can be severe, especially when chloride ions are present. Insulating cement may also contain alkaline chemicals and water (while the cement is still drying). Below 250° F, alkaline water may cause corrosion if the substrate or insulated surface is stainless steel, copper, brass or aluminum. Steel would normally not be affected in the time needed for the cement to dry. Fresh, potable water is recommended when mixing insulating cement.

Delahunt reported on leaching tests performed on polyurethane foam insulation containing fire retardant chemicals (i.e., brominated or chlorinated compounds). Distilled water was used, and aggressive acidic solutions were formed. The same was found true for phenolic foams. The pHs of the solutions were often two to three. Laboratory corrosion rates have been shown to be 15-20 mils/yr. Of the two foams, the phenolics are by far the more corrosive.

Chloride corrosion can be caused by the combination of insulation containing leachable chlorides with the 300 series austenitic-stainless-steel surfaces, when moisture is present and temperatures are above 140^o F. Concentration of the chloride ion usually results from the evaporation of rain water, or of water used to fight fires, or of process water. Stress-corrosion cracking of insulating jackets often results from airborne salts in coastal regions.

The probability of failure and the speed of crack propagation are governed by the temperature of the stainless steel and the chloride concentration at the metal surface. Solutions containing less than 1 ppm are normally considered safe. Below 176°> F, levels of 100 ppm are not particularly dangerous if continuous surface-wetting occurs; but at higher temperatures, lower levels can result in failure.

In practice, it should be assumed that evaporation of the solution will inevitably occur. Because local concentration of chlorides takes place at the metal surface, the bulk concentration may be of little importance. Above 390° F, external stress-corrosion cracking is normally not experienced. The stress required to cause cracking of stainless steel may result either from fabrication or operation (or shutdown).

Water entering the insulation and diffusing inward will eventually reach a region of dryout at the hot pipe or equipment wall. Next to this dryout region is a zone in which the pores of the insulation are filled with a saturated salt solution-this includes any chlorides present. When a shutdown or process change occurs and the metal-wall temperature falls, the zone of saturated salt solution moves into the metal wall. Upon reheating, the wall will temporarily be in contact with the saturated solution (e.g., chlorides), and stress-corrosion cracking may begin.

CHAPTER 3

METHODOLOGY

3.1 Research methodology

This project is an experiment and design based project. The first will be the experiment where by experiment is carried out with to detect corrosion hidden under paint. Then, Active Infrared Thermography will be applied to the steel plate to qualitatively detect corrosion under paint at the surface of steel pipe using Active Infrared Thermography method.

The second part is designing of the rig and fabricating it. The rig will have to be compatible to hold the specimen and the Active Infrared Thermography camera. Thus experiment needs to be carried out to see the best distance and positioning of the specimen and camera so that future experiment can be carried our easily using the rig. Methodology flow chart is as shown in **Figure 2** below.

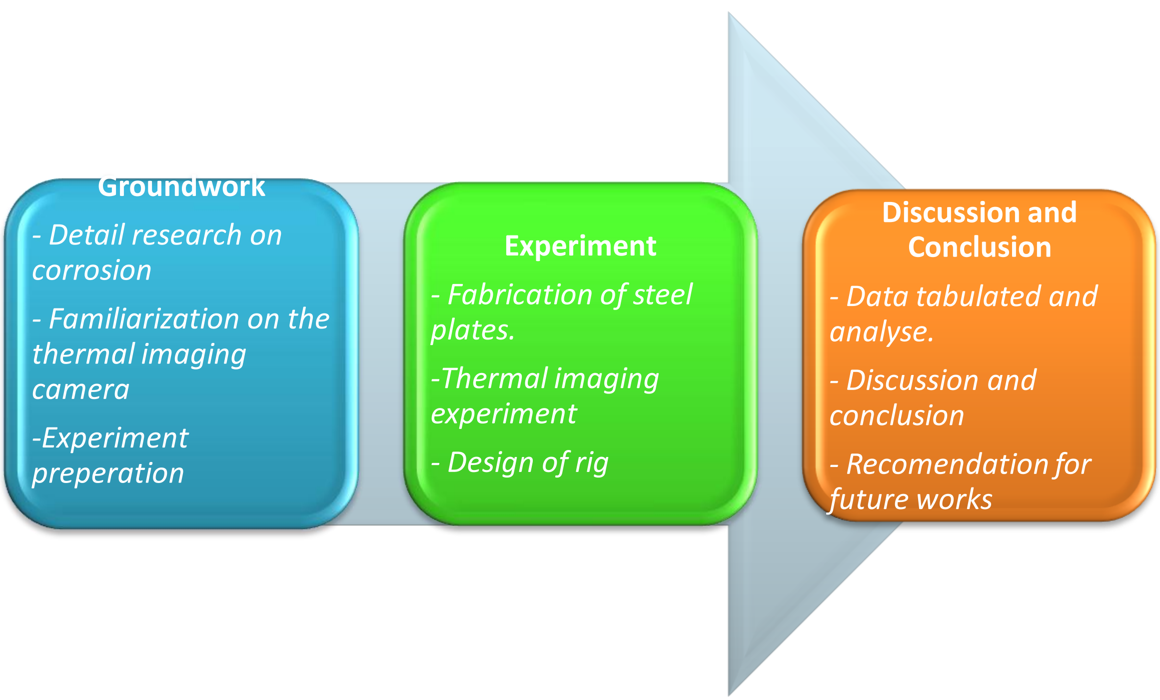

Figure 2. Process flow of project

3.2 Project Activities

3.2.1 Material Preparation

Materials for experiment of corroded steel and fabrication of the rig were prepared. Mild steel SS304 with different sizes was used to simulate steel with corrosion. The steel like in **Figure 3** has no corrosion on it and in order to simulate the corroded area under insulation, each steel was dipped into salt water separately so that a small area would corrode, leaving the rest of the other area free from corrosion. Sea water consists of 3.2% of salt in every liter. (Sharqawy, Lienhard & Zubair, 2009). Thus in order to increase the corrosion rate of the steel, salt water was used with a higher amount of salt mixed in normal H2O. 4.0% of salt was mixed into 1 Liter of water. Corroded section is grinded with sand paper using an air pressured grinder. A small area is left corroded so that test can be carried out on a specific area to collect data. Steel is than coated with paint so the corroded area is not visible to the naked eye.

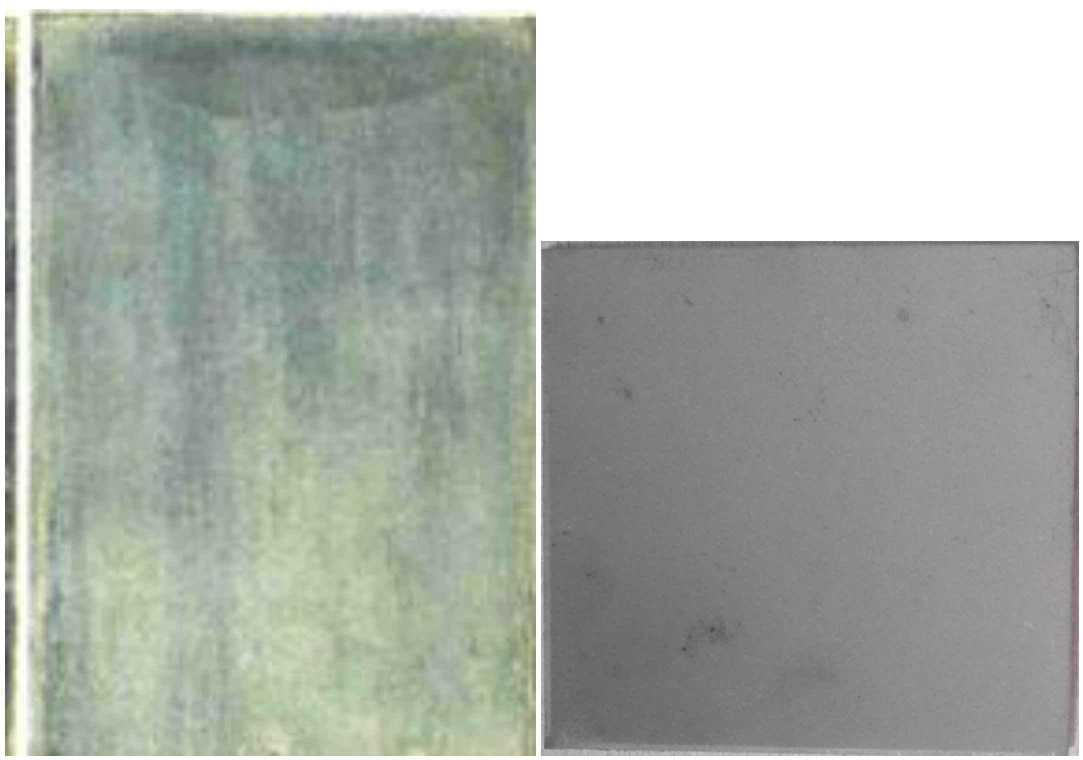

Figure 3. Steel before corrosion

3.2.1.1 Procedure

Procedure for modification of steel plate:

1. 40grams of salt was dissolved in 1 Litre of H2O.
2. Steel plates was then placed into the salt water and left until it corrodes. Refer **Figure 4, Figure 5** and **Figure 6.**
3. Corroded plates are then modified using air pressured grinder to leave only a small area corroded. **Refer Figure 7 and Figure 8**.
4. The whole area of the three different plates is painted with red oxide primer paint, black oxide primer paint and normal white paint. **Refer Figure 9, Figure 10** and **Figure 11**
5. Surface of the plates are made sure to be uniform as shown in Figure

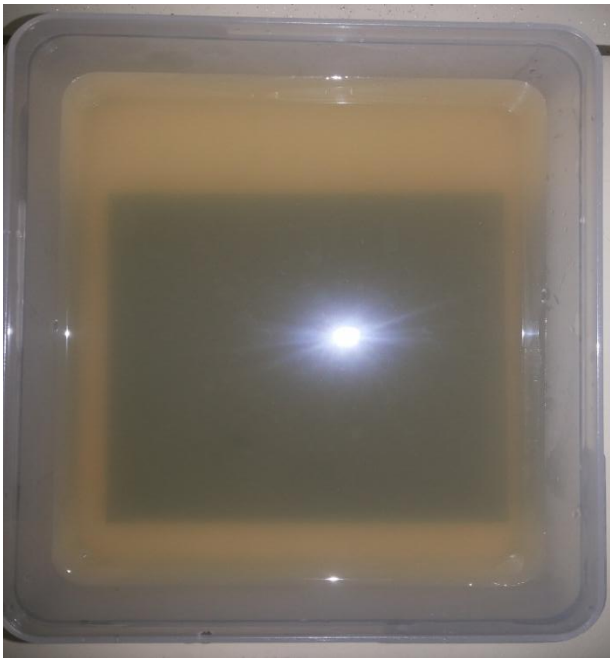

Figure 4. Steel in seawater

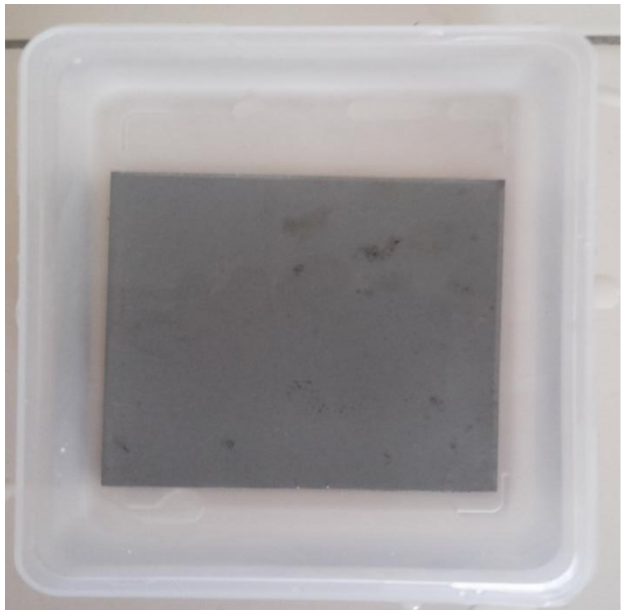

Figure 5. Steel in salt water

Figure 6. Steel after corrosion process has occur

Figure 7. Steel after grinded

Figure 8. Steel after grinded

Figure 9. Steel painted with red oxide primer paint

Figure 10. Steel painted with black oxide primer paint

Figure 11. Steel painted with white paint

3.2.2. Thermal NDE test setup

The thermal NDE test will be done using two different heat source methods that will provide the heat to the test region. An IR camera is connected to a computer and digitizes the temperature across the test region. The image acquired from the test region is in form of 2-D temperature image frames, with each frame obtained by averaging a number of images of temperature. A basic schematic of the test setup is shown in Figure 12. During experimentation, besides the detection of corroded area under insulation, the distance is also tested to determine the maximum and minimum distance that is optimum in order to design the rig that would hold the IR camera and specimen later on.

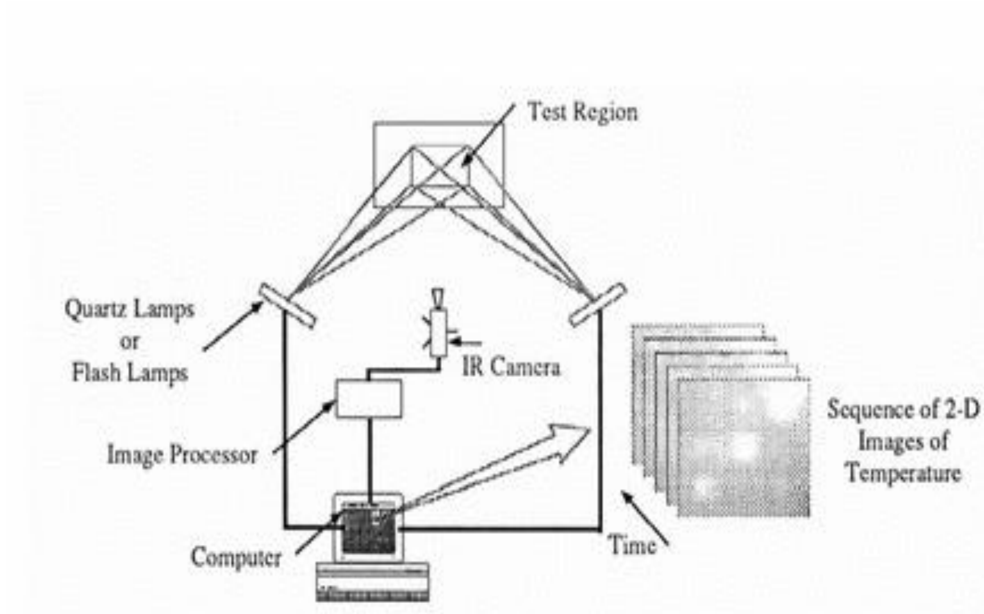

Figure 12. Schematic of the thermal NDE test setup

3.2.3 Recommendation from previous research and experiment

From the research done by Mohd Aliff Muniff on 2012 and followed suit by Mohd Nazrin on 2013, it was recommended that the experiment to be carried out in a room with minimal lighting or sunlight. These so that the reflection effect could be minimize. Further steps were taken to minimize the surrounding reflection by placing the specimens in a box while the thermal images were taken. Experiment was carried out in a room with stable room temperature.

3.2.4 Experiment 1: Conducting experiment – Heat mat

3.2.4.1 List of equipments and materials

Experiment was setup according to **Figure 13** by using the list of material below:

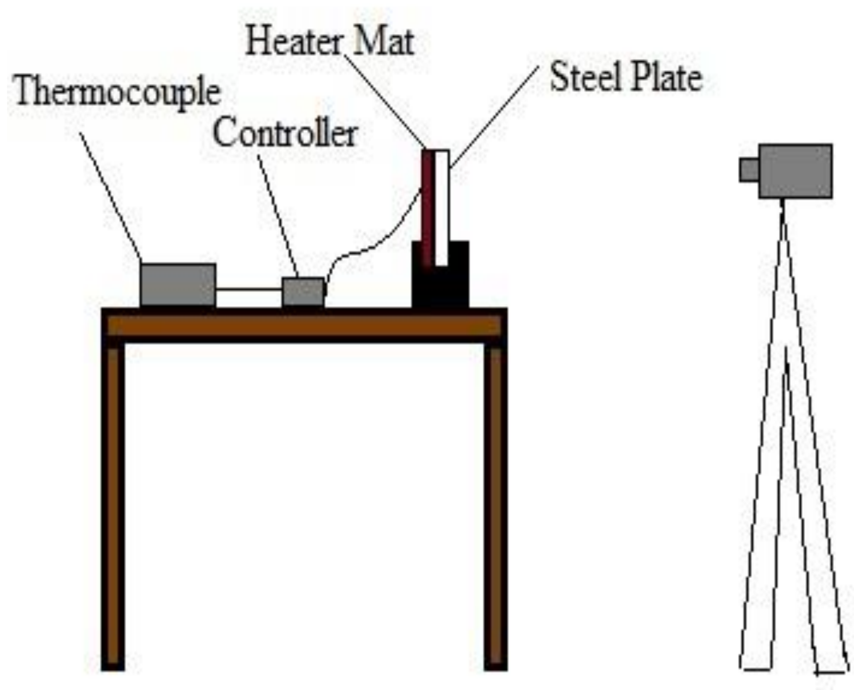

Figure 13. Setup for Experiment 1 with heat mat

3.2.4.2 Experiment procedure

The procedure of the experiment is as follows:

1. One heater is attached at the front of the steel plate with the coated surface facing the heater mat (Refer **Figure 13**).

2. Glass wool is placed at the side and back of the plates to insulate the heat and minimizing heat loss to the surrounding.

3. The infrared camera then is placed at 1m distance from the steel plate.

4. Thermocouple is placed on steel surface.

5. Heater mat then is turned on and the steel plate will be heated. At the same time, infrared camera will record the front part of the steel plate.

6. Infrared image is taken for every 20 seconds and data taken is tabulated in **Table 4.**

7. The thermal images are recorded for further analysis.

8. Data obtained are analysed in FLIR® software and tabulated in **Chapter 4.1.**

Figure 14. Equipment setup for Experiment 1

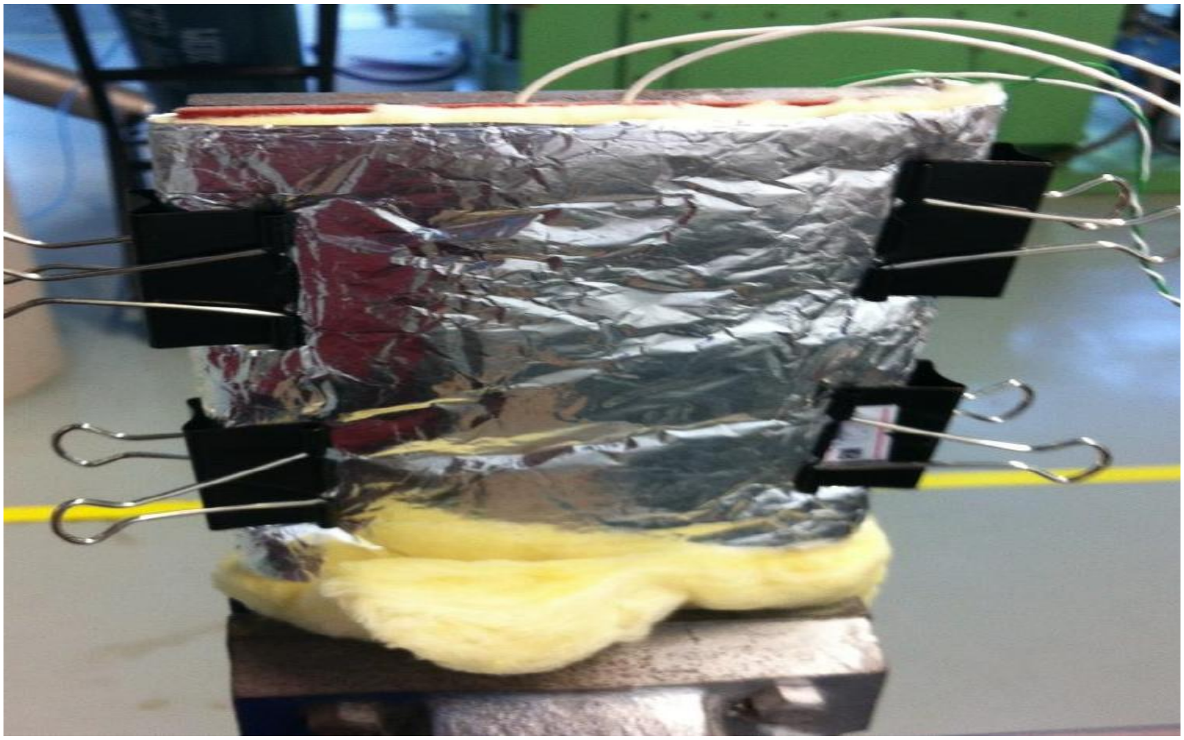

Figure 15. Heater mat with insulation

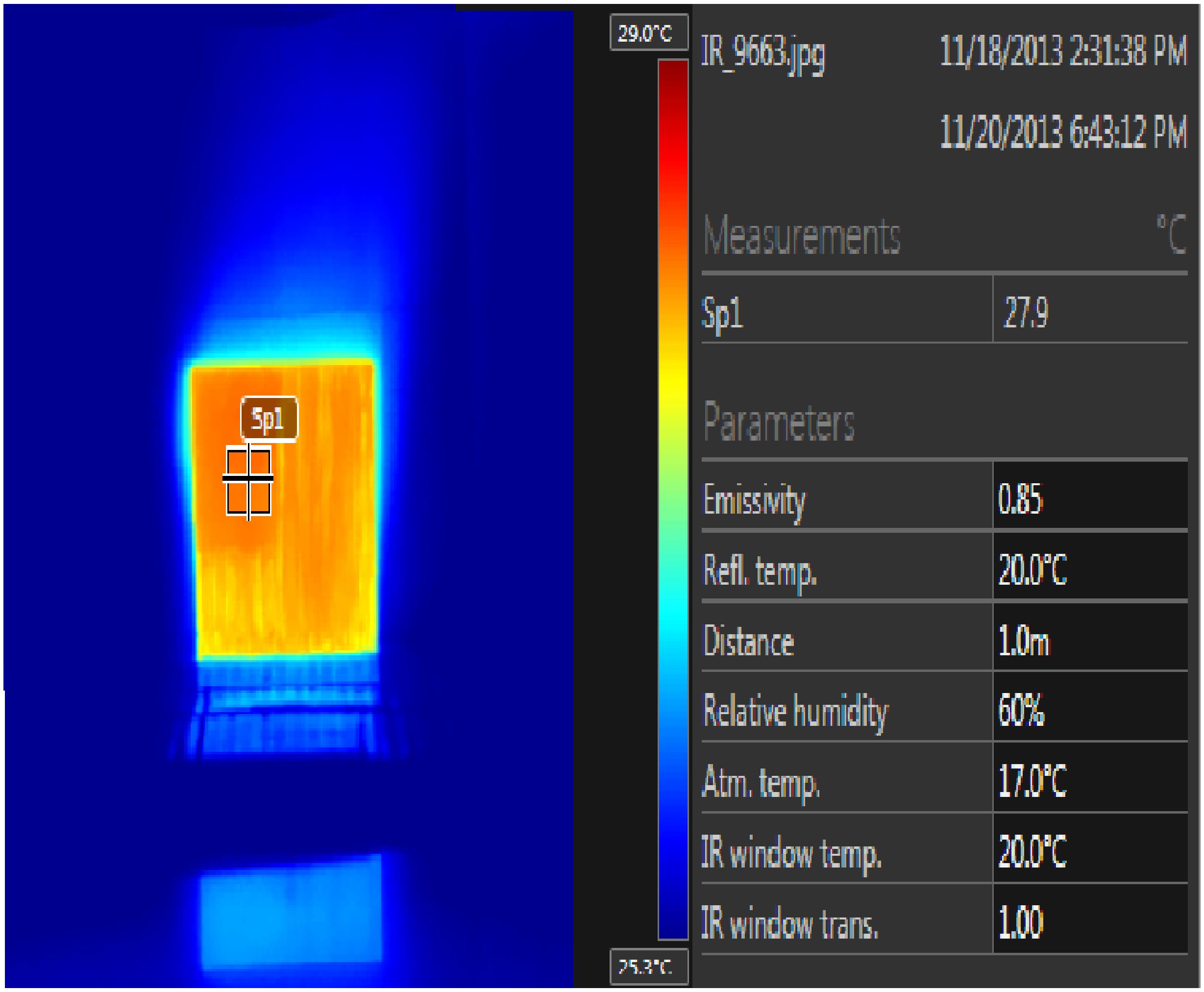

Figure 16. Image under thermal camera for experiment 1

3.2.5 Experiment 2: Conducting experiment – Spot Light

3.2.5.1 List of equipments and materials

Experiment was setup according to **Figure 17** by using the list of material below:

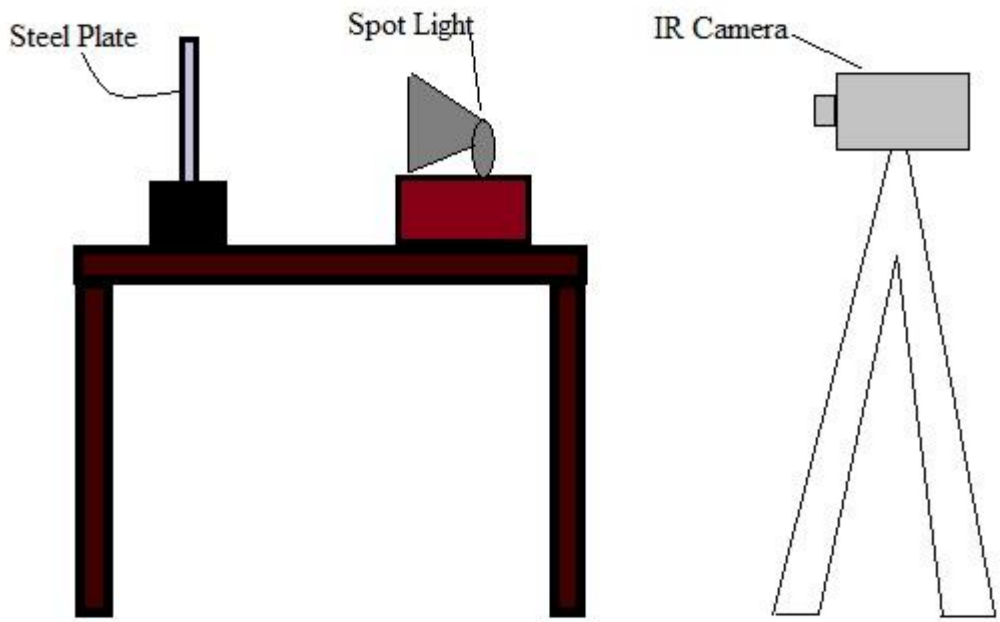

Figure 17. Setup for Experiment 2 with spotlight

3.2.5.2 Experiment procedure

The procedure of the experiment is as follows:

1. A 200W spot light is placed at the front of the steel plate with the coated surface facing the heater mat (Refer **Figure 17**).
2. Spot light is placed 10cm from the steel.
3. The infrared camera then is placed at 1m distance from the steel plate.
4. The spot light is turned on for 45seconds.
5. The then spotlight was put aside immediately and the images of the plate are taken by using infrared camera.
6. Infrared image is taken for every 20 seconds and data taken is tabulated in **Table 5.**
7. The thermal images are recorded for further analysis.
8. Data obtained are analysed in FLIR® software and tabulated in **Chapter 4.2.**

Figure 18. Real time experiment setup

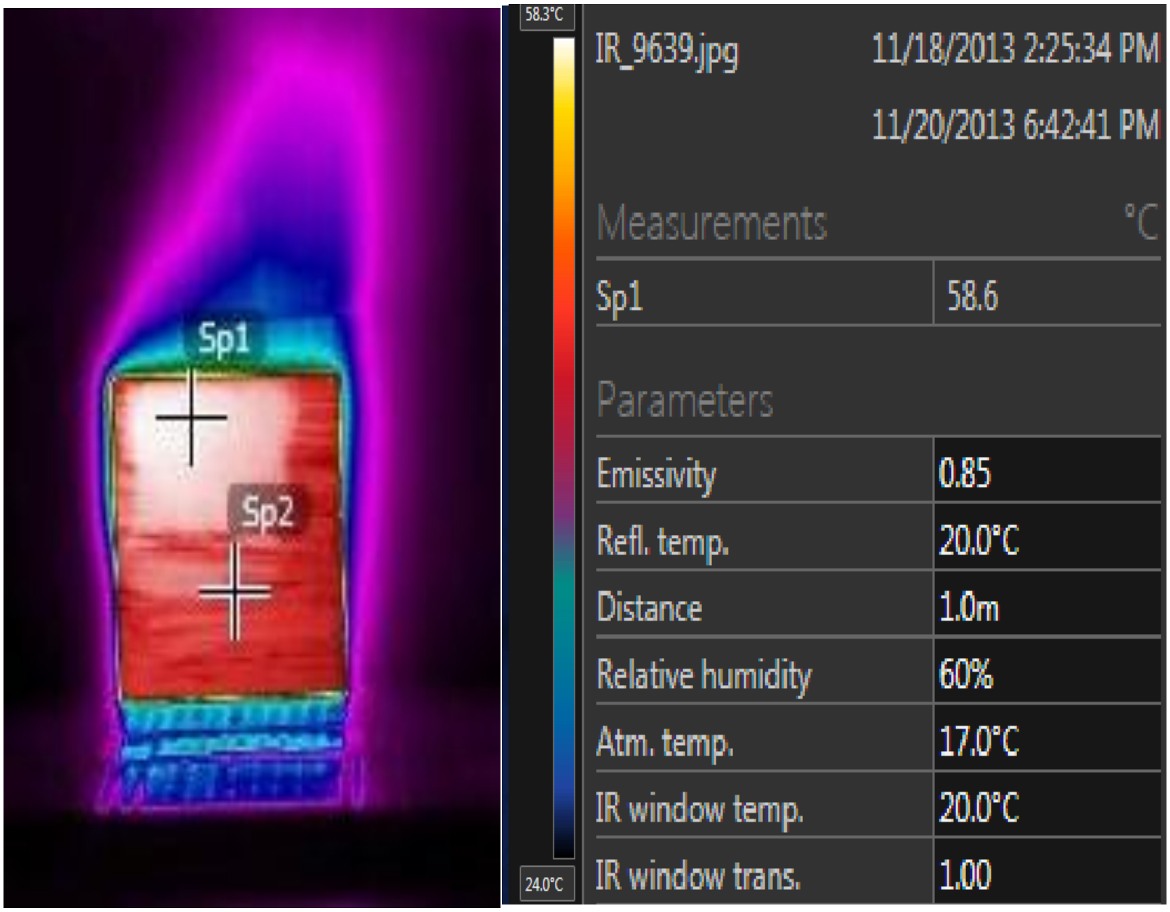

Figure 19. Image under thermal camera for Experiment 2

3.2.6 Design of rig

3.2.6.1 Design development

Design was first developed and they fall into two stages;

i) Conceptual and
ii) Detailed design.

3.2.6.2 Conceptual Design

Conceptual design was developed to give a rough idea of the design concept. A simple plan drawing was drafted to show the existing design including any previous improvements. This design was drafted based on the experiment setup and determined the rough setup needed to design.

3.2.6.3 Detailed design

Detailed design was developed to provide accurate design guideline. Accurate dimension is determined in order to ease the design stage. This detail design with measurement is required in order to fabricate the part without any problem. Each part was measured and designed accordingly. Design of the rig was done using Solid Works 2013 engineering drawing software. **Figure 20** shows the dimension of each part of the design. **Figure 21** and **Figure 22** shows the three dimension (3D) design of the rig. The remaining design layout are provided in Appendix I.

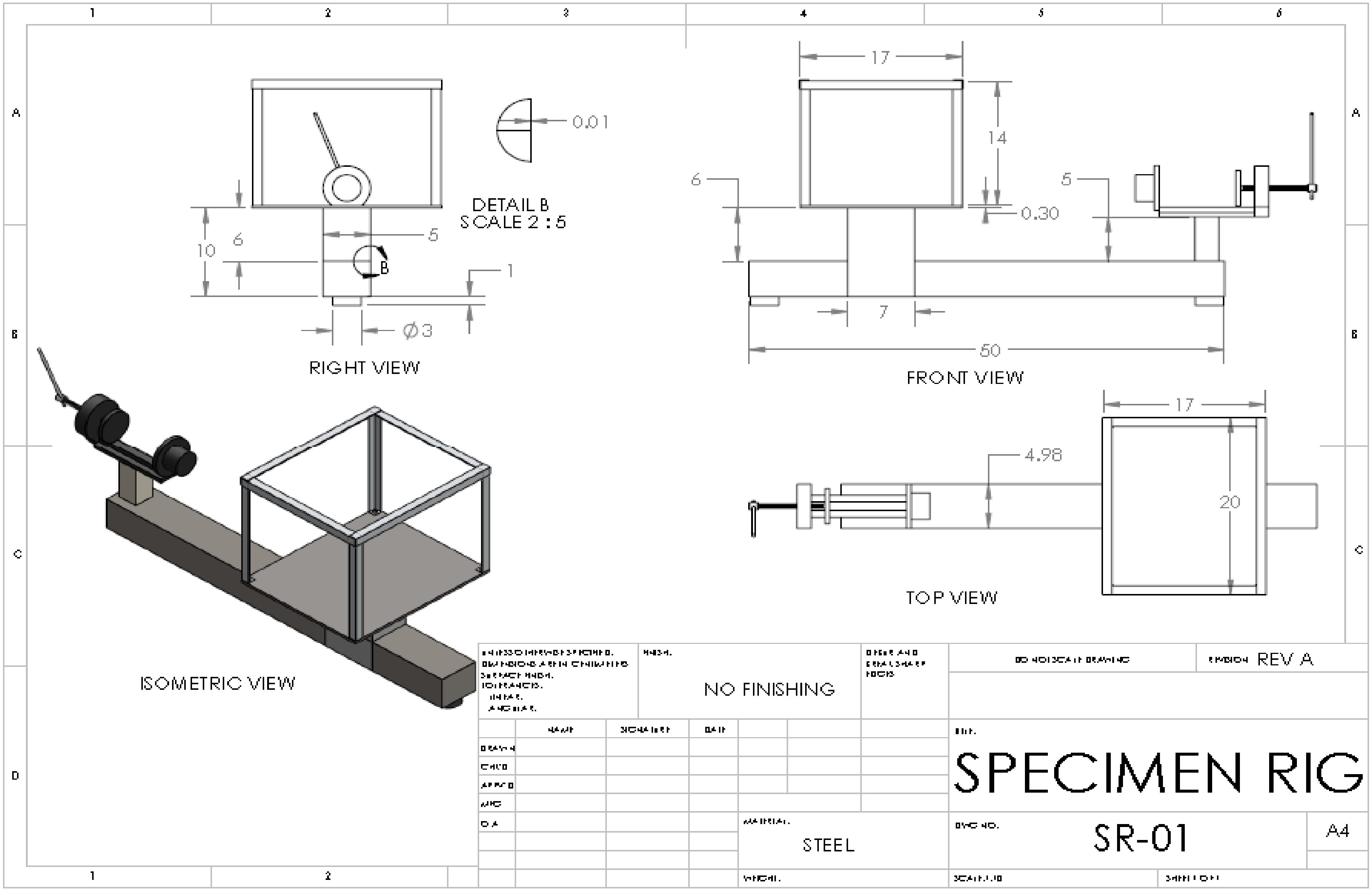

Figure 20 Dimension for each part of the design

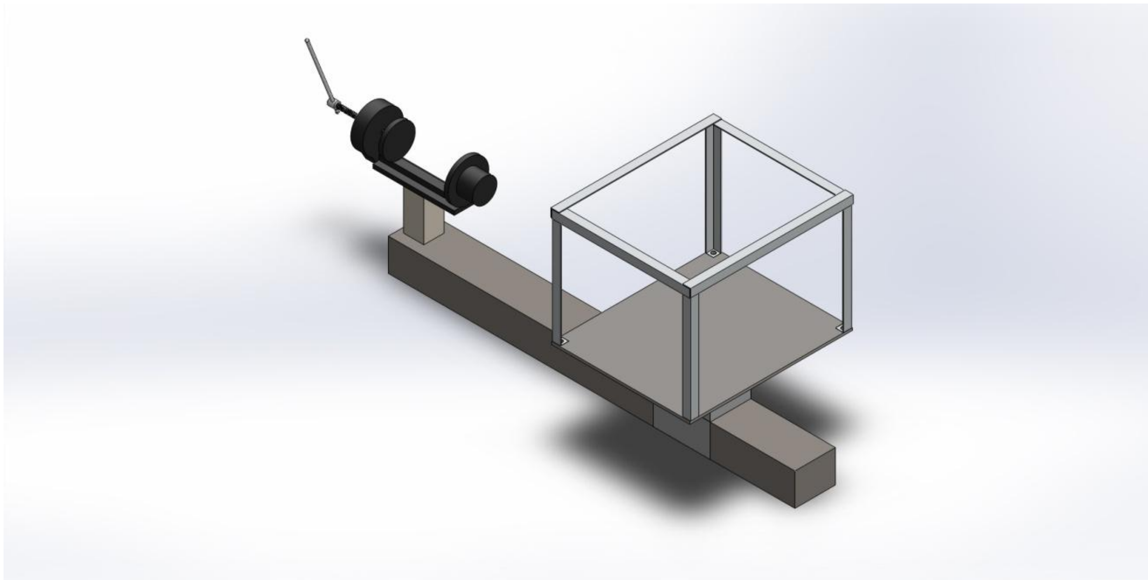

Figure 21. Design of rig from top view

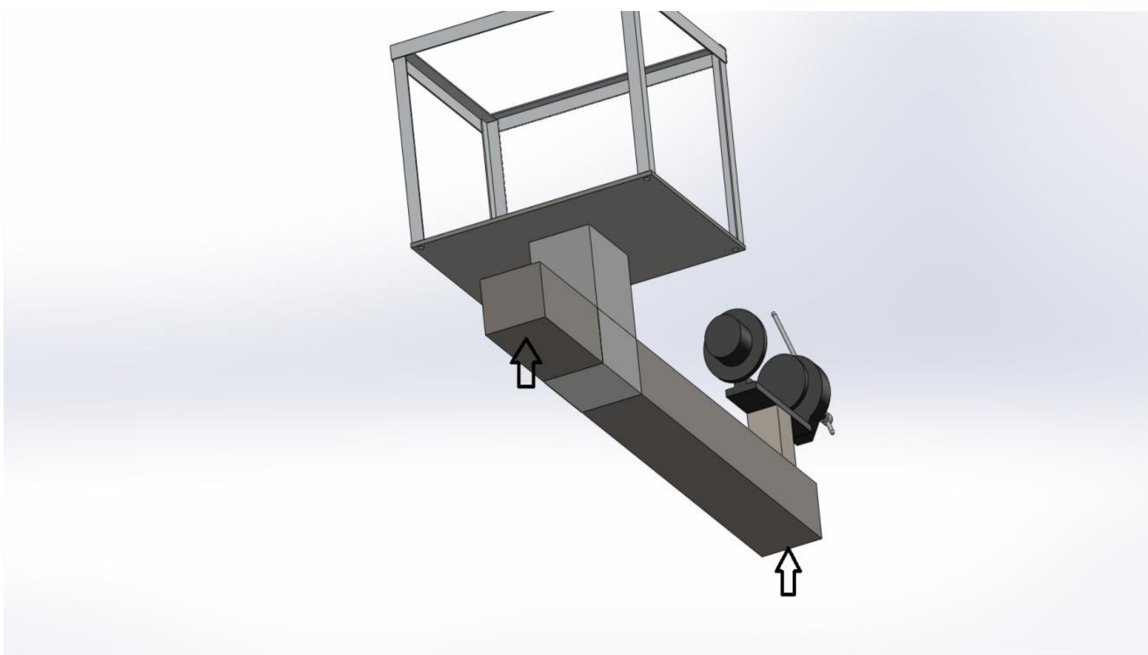

Figure 22. Design of rig from bottom view

3.2.6.4 Fabrication of components

Fabrication of test rig components was done with the design able to hold the test equipment and the thermal imaging camera. **Figure 23**, **Figure 24** and **Figure 25** show the parts before assembly.

Figure 23. Clamp and rail for the camera to move along.

Figure 24. Cover to help secure the camera on the platform.

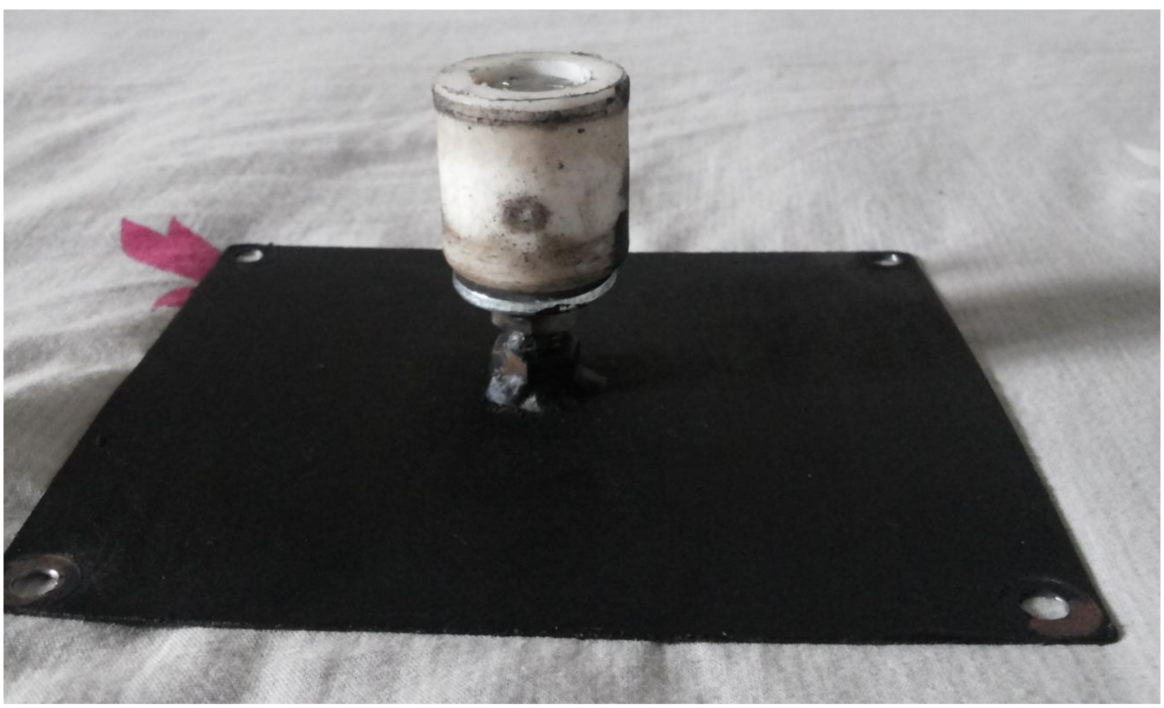

Figure 25. Platform of the camera with roller to enable the platform to move along the railing.

3.2.6.5 Assembly of components

Next stage is the assembly of the components that had been fabricated.

Figure 26. Side view of rig after assembly

Figure 27. Top view of rig.

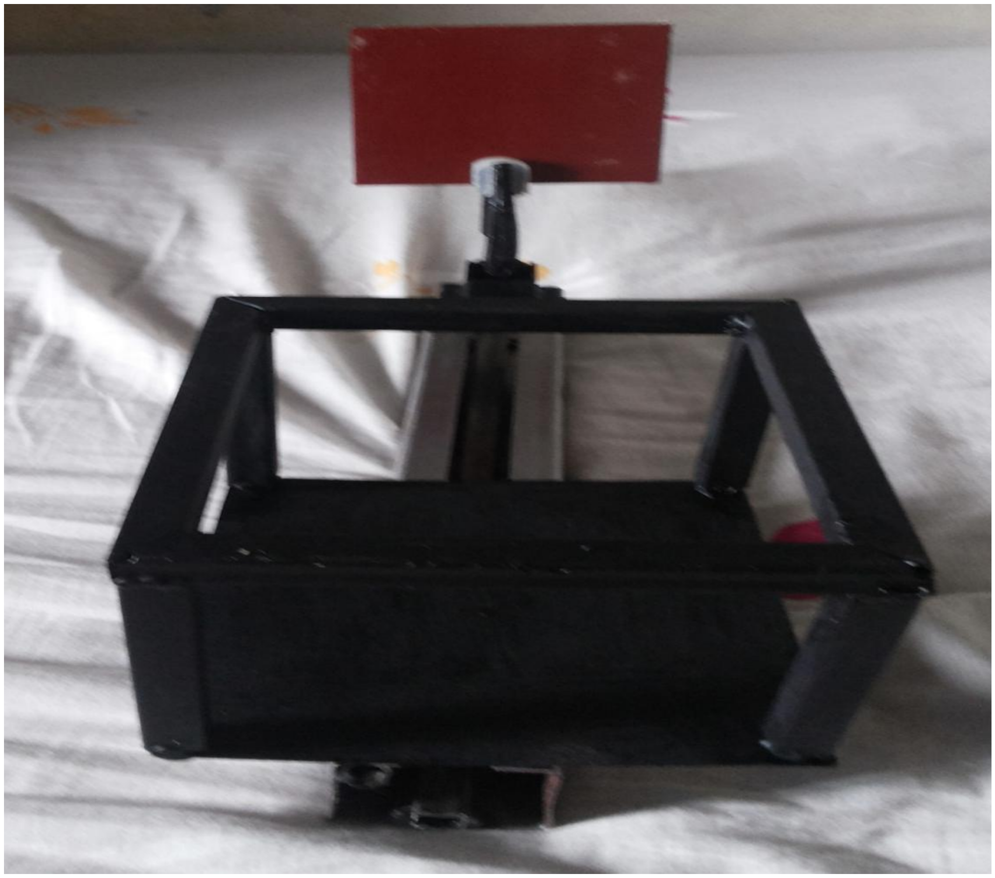

Figure 28. Front view of rig

Figure 29. Steel is clamped to the rig.

3.3 Gantt chart

Table 2. Gantt Chart

Activities	**Final Year Project 1 (FYP1)**														**Final Year Project 2 (FYP2)**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Data Gathering			■	■	■																							
Detailed studies						■	■	■																				
Experiment preparation and material fabrication								■	■	■	■	■																
Experiment 1													■	■	■	■												
Experiment 2																	■	■	■	■								
Design																					■	■						
Fabrication																							■	■	■	■	■	
Final Data Analysis																											■	■

3.4 Key Mileston

Table 3. Key Milestone

Activities	Final Year Project 1 (FYP1)														Final Year Project 2 (FYP2)													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Material Fabrication											●																	
Completion of Experiment 1																	●											
Completion of Experiment 2																				●								
Design																						●						
Rig Fabrication																											●	
Completion of Final Data Analysis																												●

CHAPTER 4

RESULT AND DISCUSSION

4.1 Data tabulation

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4.1.1 Experiment 1: Heat Mat

- Distance : 1.0m
- Reflective Temperature : 20.0 ^{o}C
- Atmospheric Temperature : 17.0 ^{o}C
- Emissivity : 0.85

Table 4. Data Tabulation Experiment 1

Time (seconds)	Temperature (Non-Corrode)	Temperature (Corroded)	Temperature Difference
0.0	27.3	27.9	0.6
20	28.4	29.0	0.6
40	29.2	29.6	0.4
60	30.8	31.3	0.5
80	32.4	33.0	0.6
100	34.4	34.9	0.5
120	35.0	35.6	0.6
140	36.8	37.3	0.5
160	38.7	39.3	0.6
180	41.0	41.5	0.5

All the images taken during experiment for the experiment are provided in the **Appendix II**.

4.1.2 Experiment 2: Spotlight

- Distance : 1.0m
- Reflective Temperature : 20.0 ^{o}C
- Atmospheric Temperature : 17.0 ^{o}C
- Emissivity : 0.85

Table 5. Data Tabulation for Experiment 2

Time (seconds)	Temperature (Non-Corrode)	Temperature (Corroded)	Temperature Difference
0.0	58.5	56.7	1.8
20	57.2	55.6	1.6
40	55.9	54.2	1.7
60	54.2	52.9	1.3
80	53.1	52.0	1.1
100	51.5	50.4	1.1
120	50.0	48.2	1.8
140	48.6	47.9	0.7
160	47.1	46.3	0.8
180	46.1	45.4	0.7

All the images taken during experiment for the experiment are provided in the **Appendix III**.

4.3 Data analysis

The value of Temperature Difference, ΔT can be obtained by using the formula in **Equation 1.**

$$\Delta T = | T_c - T_n | \text{ ------------------------------------- Equation 1}$$

Where,

ΔT = Temperature Difference (ºC)

Tn = Temperature at normal thickness (ºC)

Tc = Temperature at corroded area (ºC)

Figure 30 shows a Temperature at normal thickness, T_n VS Temperature at corroded area, T_c for steel plate in Experiment 1 heater mat as the heat source.

While **Figure 32** shows a Temperature at normal thickness, T_n VS Temperature at corroded area, T_c for steel plate in Experiment 2 using spot light as the heat source.

Figure 31 and **Figure 33** shows Temperature Difference, ΔT between Temperature at corroded area (Tc) and Temperature at normal thickness (Tn) for both experiments.

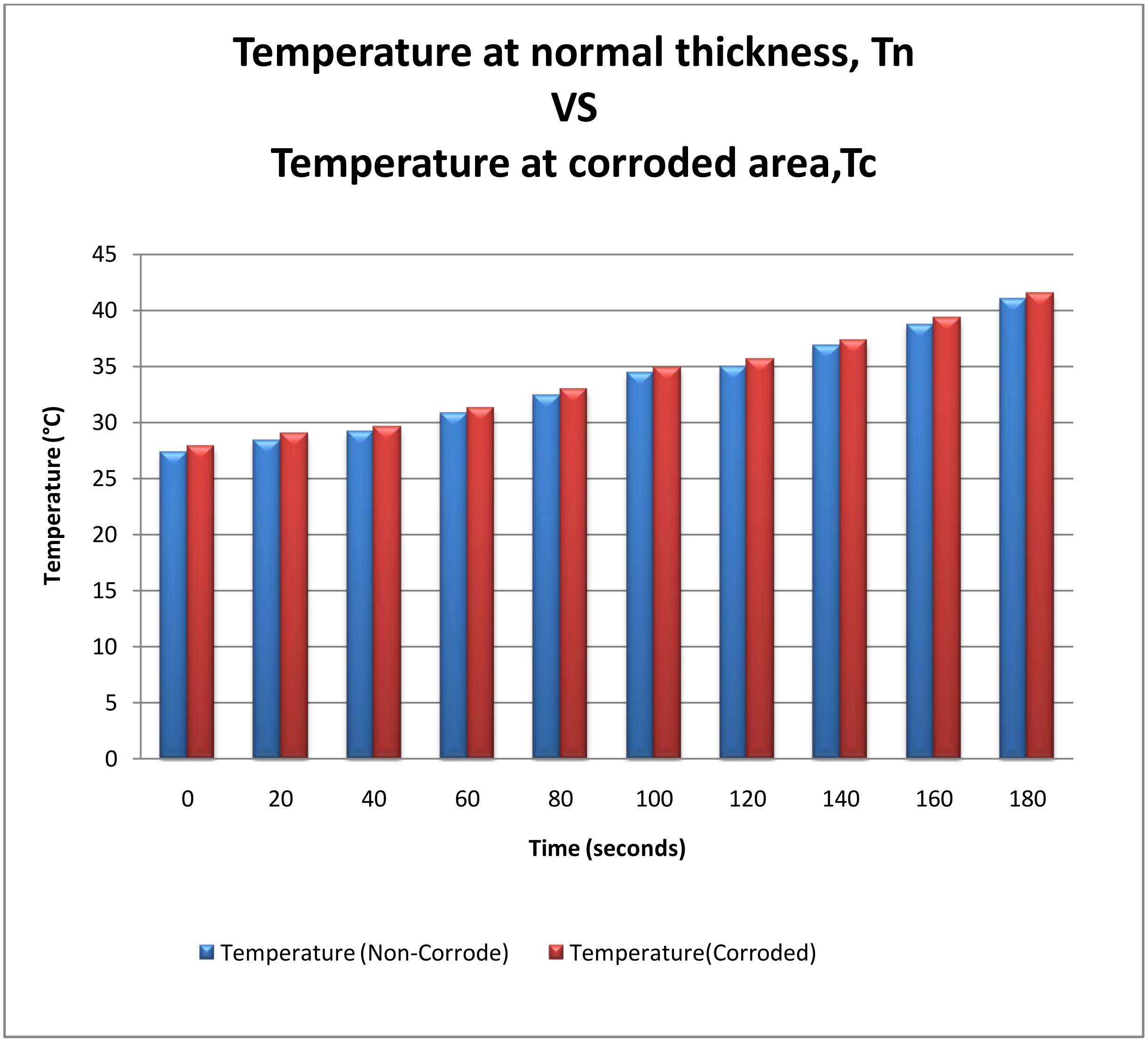


Figure 30. Temperature at normal thickness, (Tn) VS Temperature at corroded area (Tc) for Experiment 1 steel plate

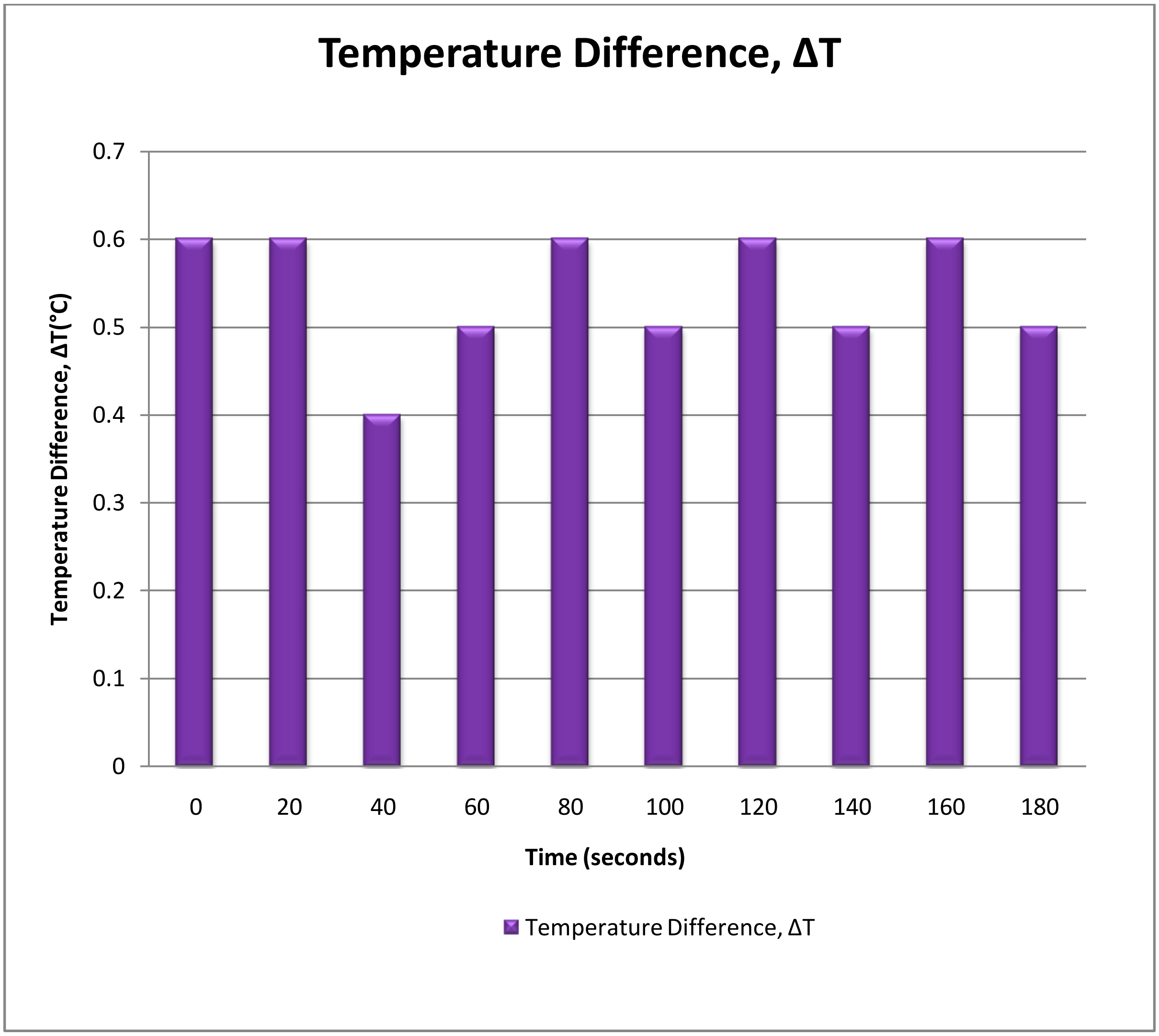


Figure 31. Temperature Difference (ΔT) between Temperature at normal thickness, (Tn) and Temperature at corroded area (Tc) for Experiment 1 steel plate

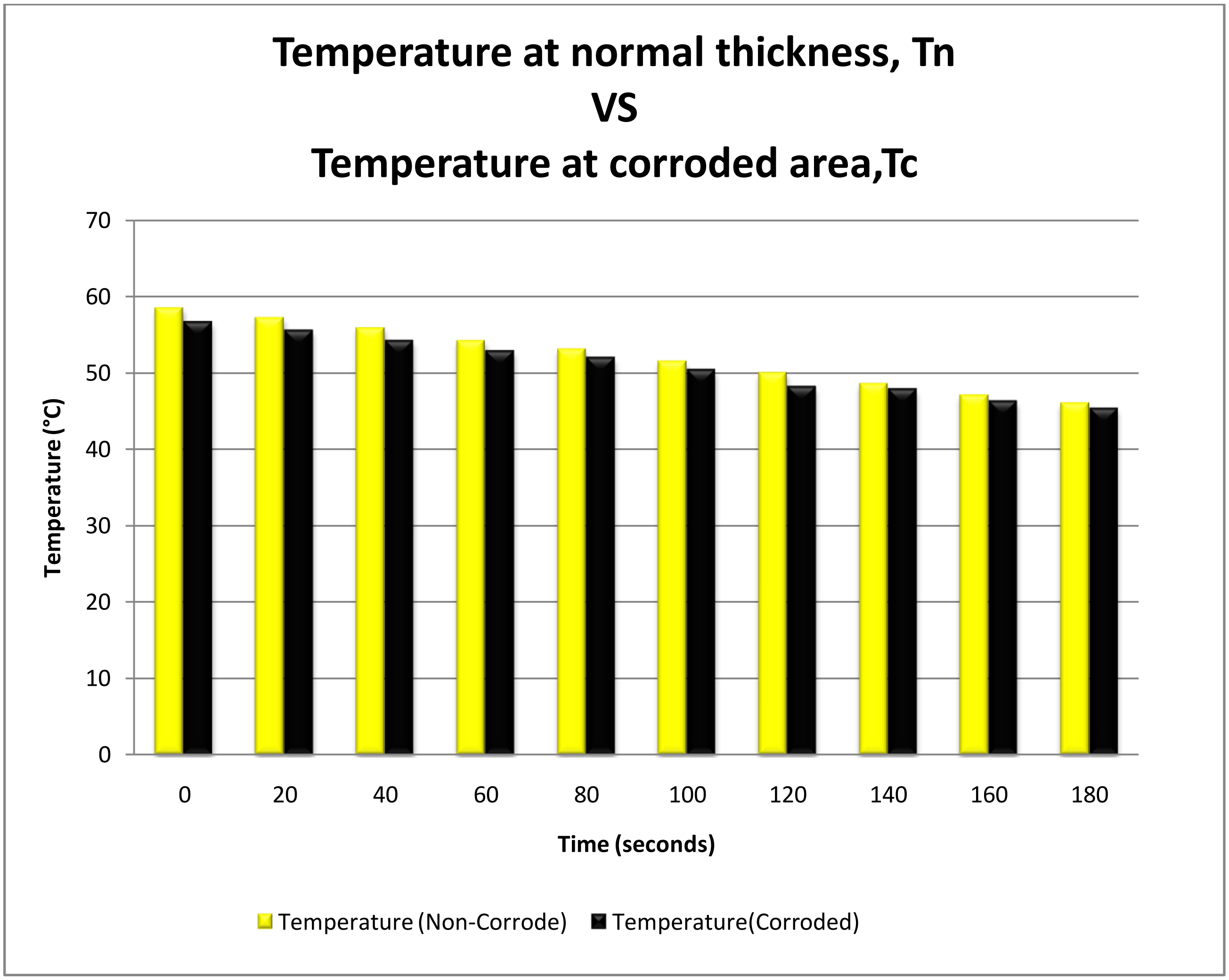


Figure 32. Temperature at normal thickness, (Tn) VS Temperature at corroded area (Tc) for Experiment 2 steel plate

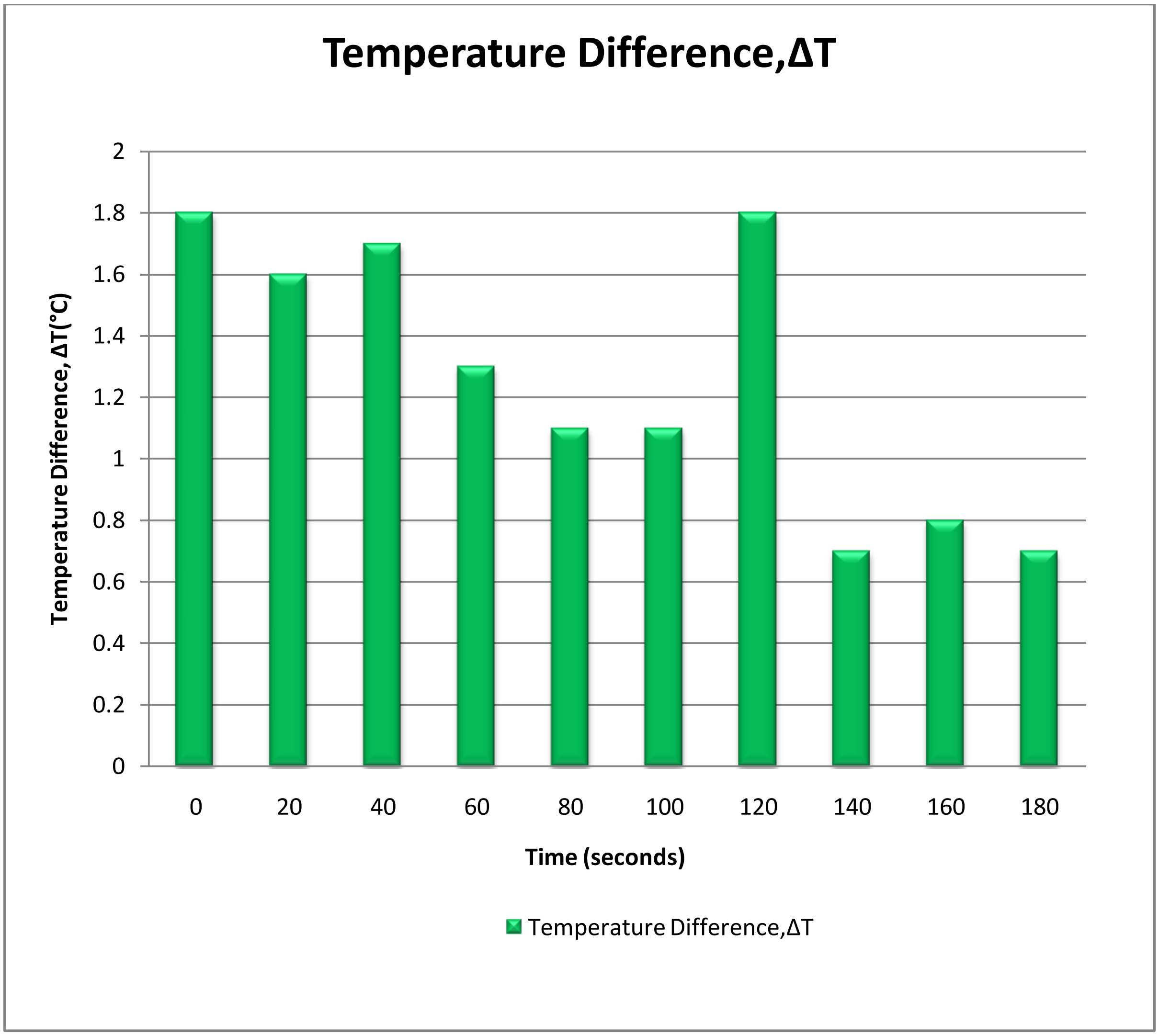


Figure 33. Temperature Difference (ΔT) between Temperature at normal thickness, (Tn) and Temperature at corroded area (Tc) for Experiment 2 steel plate.

4.4 Discussion

4.4.1. Infrared Thermography Experiment I

From the images obtained from the qualitative experiment, it shows a clear image difference between the corroded and non corroded part of the steel. This difference is impossible to be seen with the normal human vision. The slight difference in temperature at the corroded part is also recorded. The corroded area, Tc, has a higher temperature (31.3^{o}c) compared to the non corroded area, Tn, (30.8^{o}c).

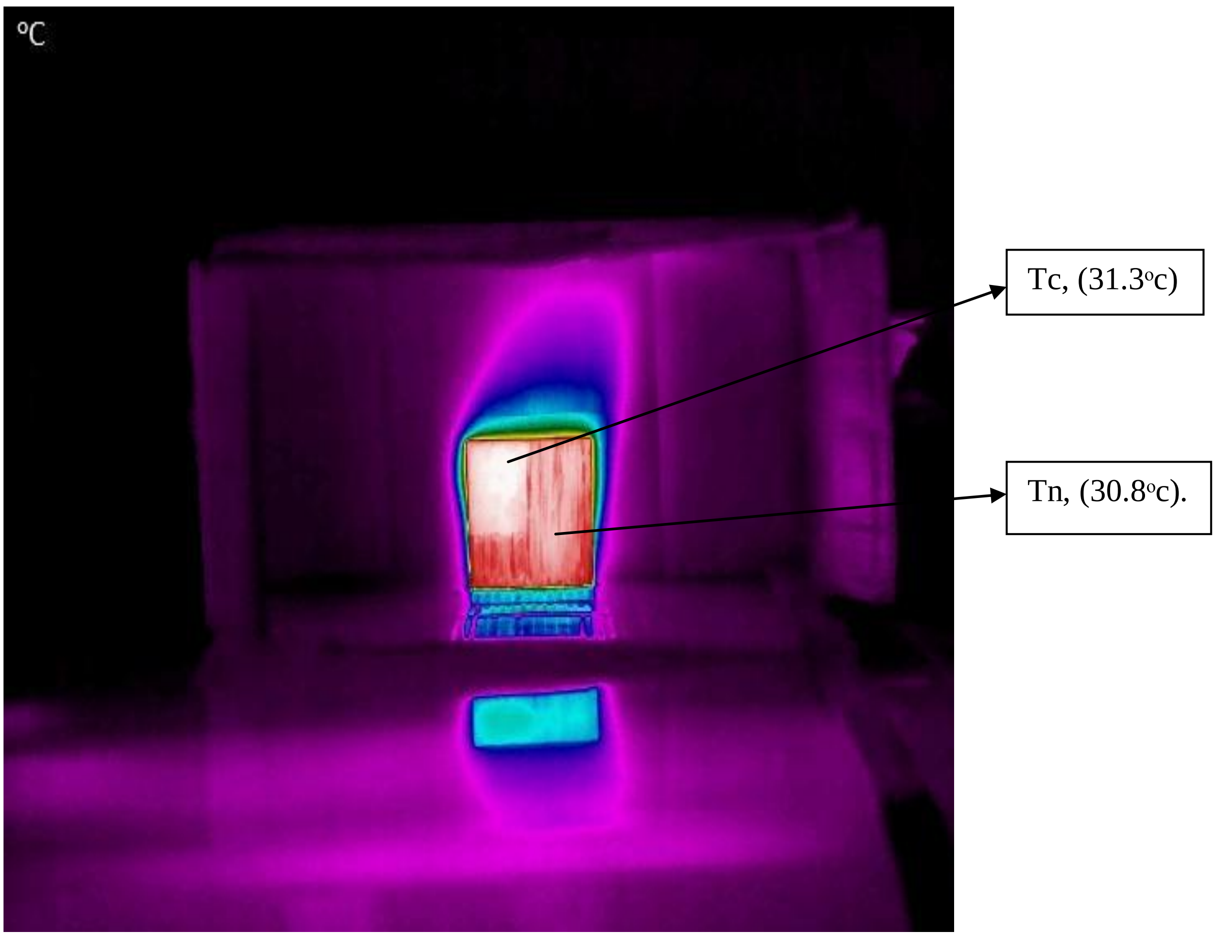


Figure 34. Infrared image of steel at 60 seconds of heating.

The detection is due to the uneven area of the corroded part of the steel. This discontinuity of the heat around the corroded area causes disturbance to the heat flux. It is then detected through thermal maps emitted through the surface and is captured by the camera. It proves the hypothesis that uneven area of the surface will emit different temperature signals.

Referring to **Figure 34**, the temperature difference is noticeable and detectable to observe the temperature change between the two surface conditions. This result supports the hypothesis that thermal imaging camera is able to differentiate the different heat of a surface with uneven or different texture. The results also contribute to the confidence of potential of Active Infrared Thermography as early NDT identification method to detect corrosion under paint in steel surface.

Figure 35 and **Figure 36** shows the image of the steel before and after coating to indicate the corroded area under coating can’t be seen with normal vision.

Figure 35. Steel used in Experiment 1 before coating.

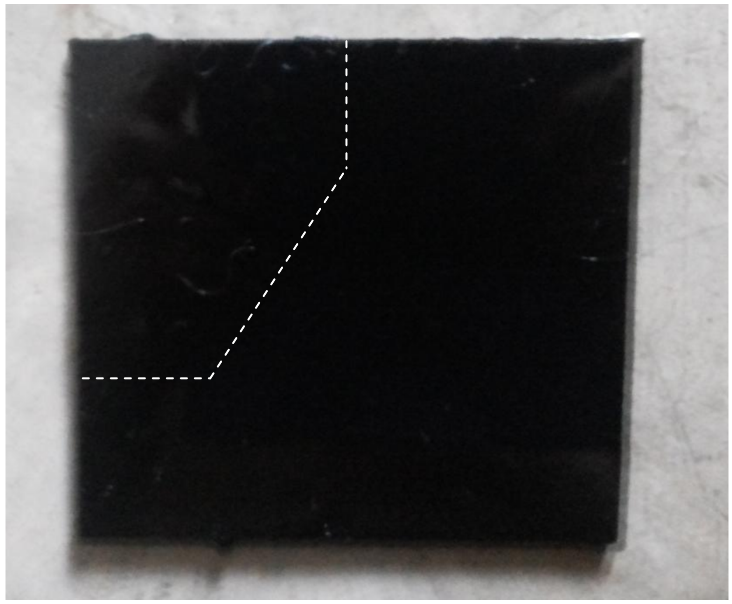


Figure 36. Location of corrosion in (white line) hidden under coating.

Transient Heat Transfer

The experiment depends on how well the heat is distributed along the steel. And at a certain point the whole of the steel will eventually have a very small difference of heat. Transient conduction occurs when the temperature within an object changes as a function of time. (Abbott,Smith &Van Ness,2005). For the Experiment 1, images from 0.0seconds to 180seconds, the defects on the steel can still be detected. But as time progress, and heat start to increase, the image of the defects get harder to detect using the thermal imaging camera. By this point the image are in steady state condition of heat transfer and causes the data analysis beyond 180 seconds to be inaccurate. **Figure 37**, **Figure 38, Figure 39** and **Figure 40** are images taken of the steel at zero seconds, 60 seconds, 120 seconds and 180 seconds to show the changes in thermal image. In **Figure 41**, the corroded area can't be seen clearly anymore.

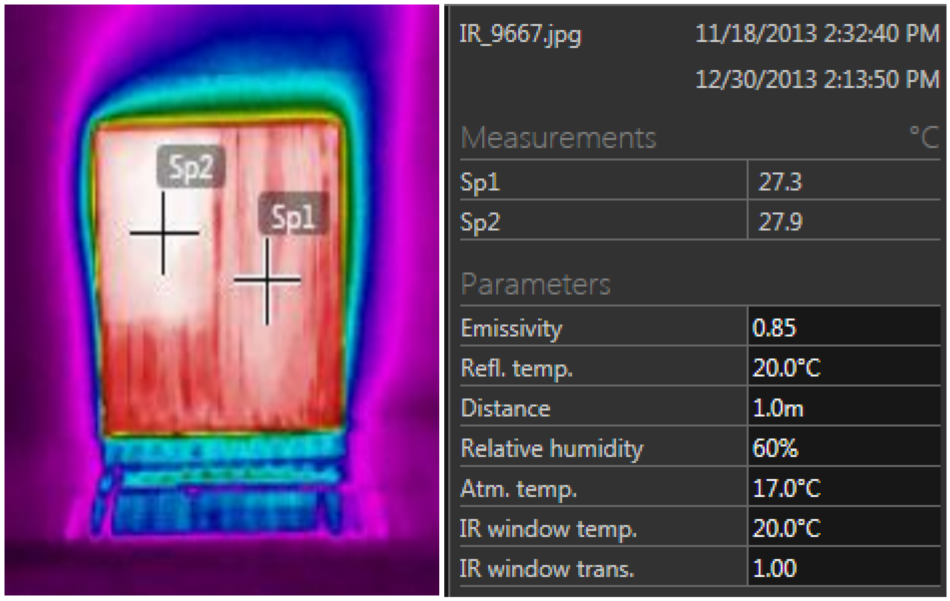


Figure 37. Thermal image at 0 seconds.

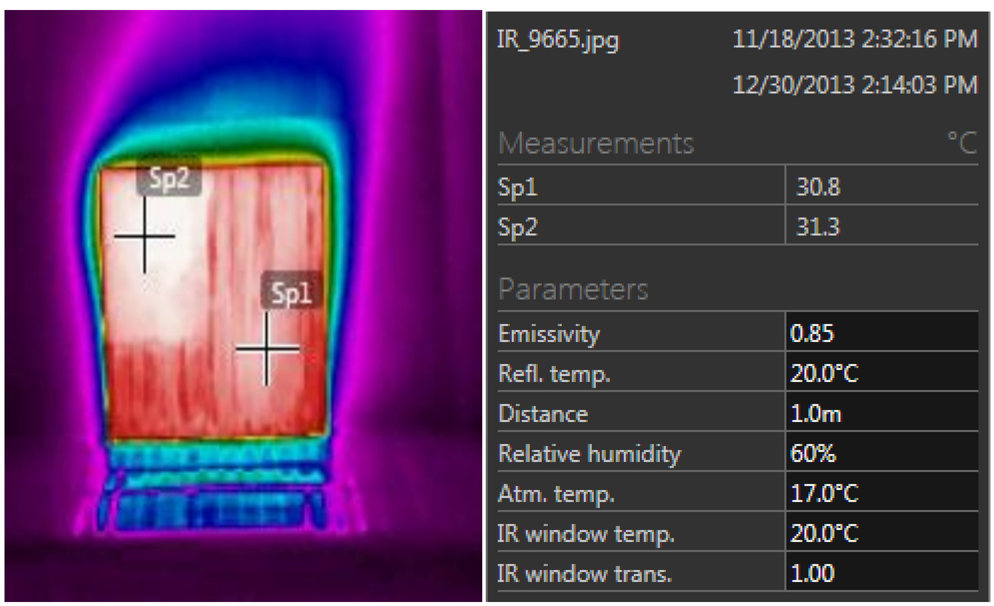


Figure 38. Thermal image at 60 seconds.

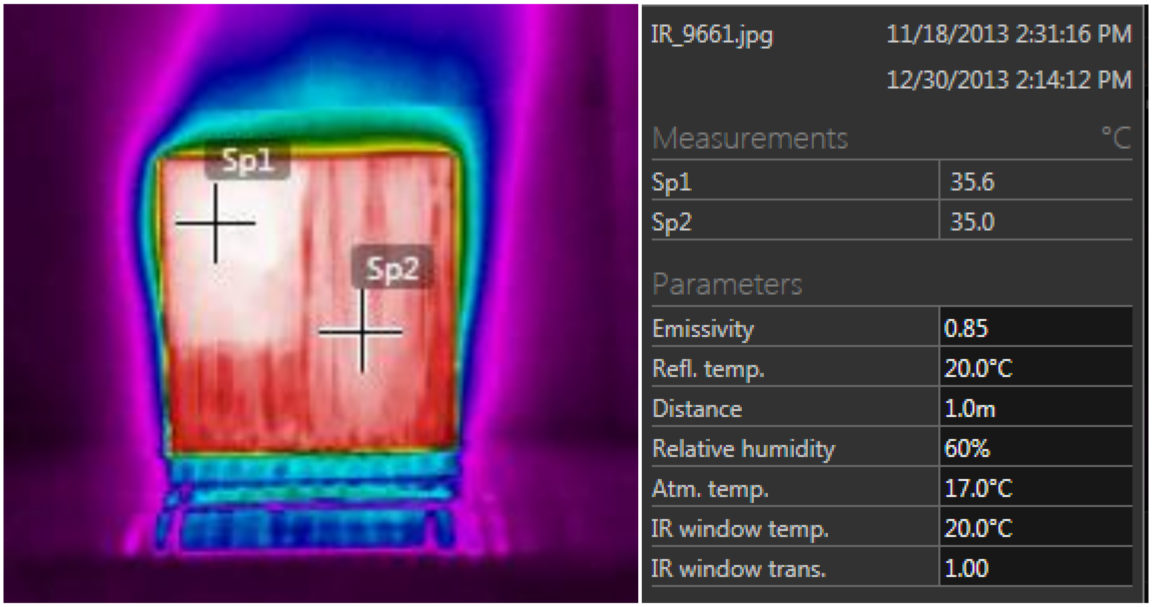


Figure 39. Thermal image at 120 seconds.

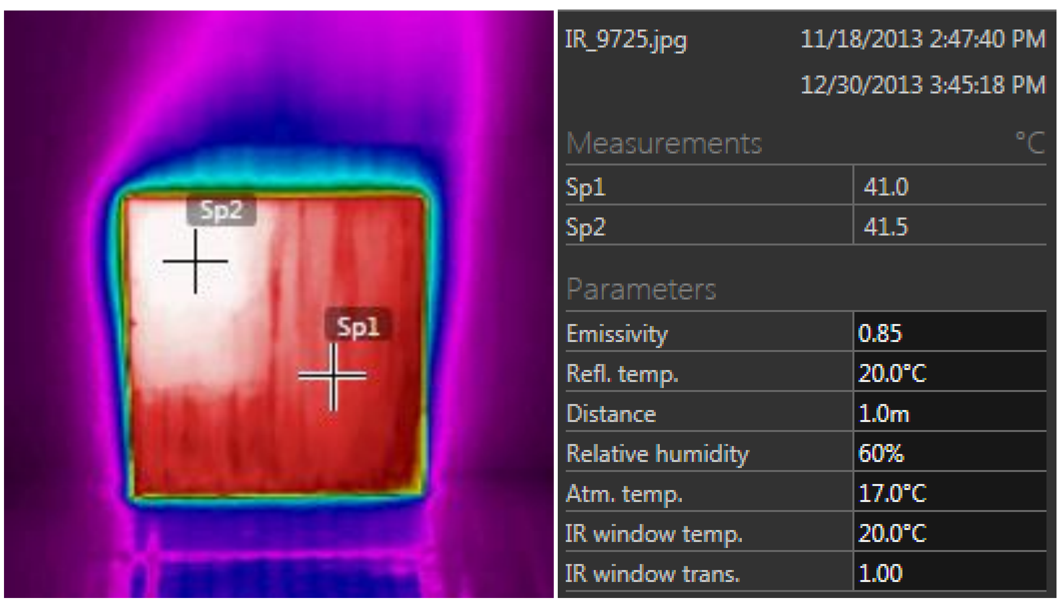


Figure 40. Thermal image at 180 seconds.

Figure 41. Steel image after 180 seconds. (at 200 seconds)

4.4.2. Infrared Thermography Experiment II

Experiment 2, the steel was heated using a spot light. In this experiment, the steel expose to the light will heat up. It was left for around 1 minute before images was captured. The heat from the light is transferred onto the steel. The process is from electric energy, to light, and then heat. Images captured also show a clear indication of the corroded and non corroded area on the steel surface. **Figure42** show the different heat measurement of the steel for the corroded, Tc and non corroded part,Tn.

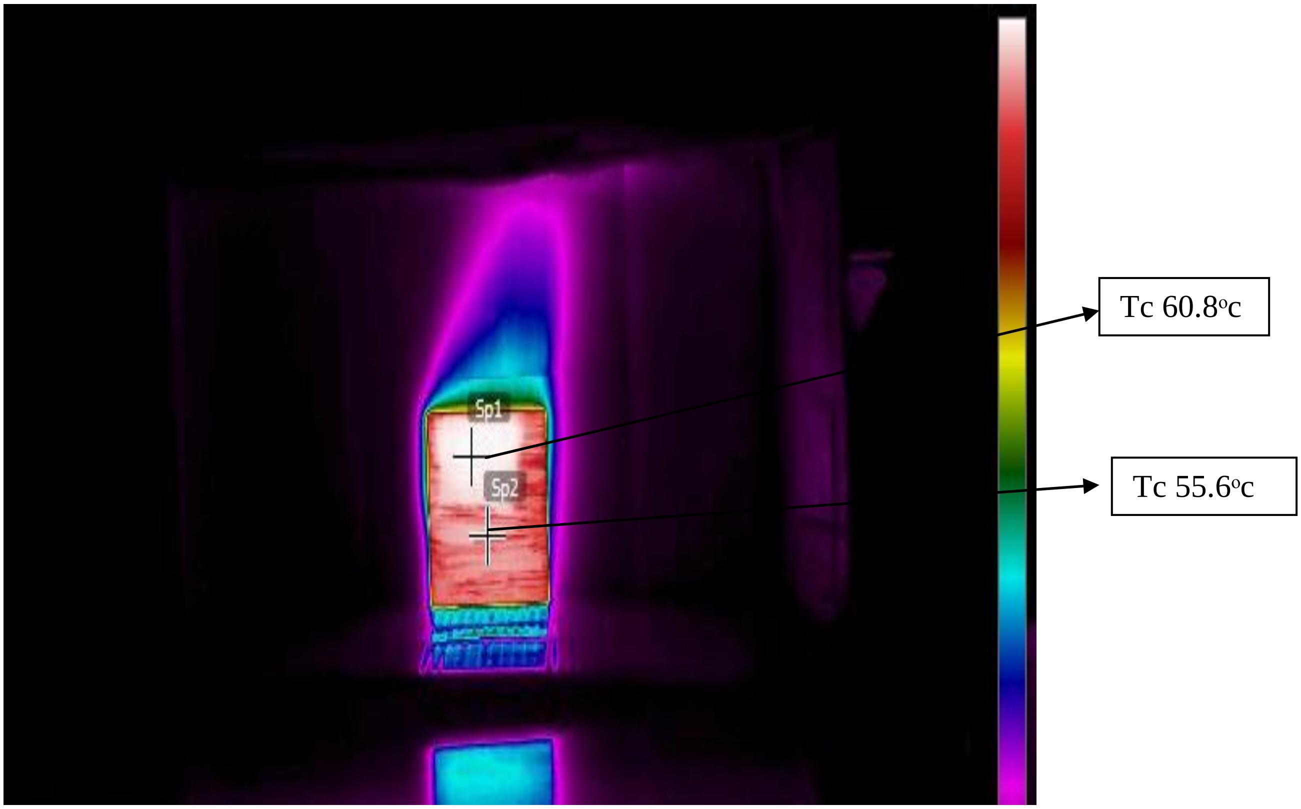


Figure 42. Infrared image of steel at 60 seconds of heating.

From the picture, there is a visible image of the corroded and non corroded part. The corroded area also has a higher temperature compared to the non corroded.

Referring to **Figure 42**, the temperature difference between the two surface conditions is more noticeable compared to when using the heat mat. This result also does support the hypothesis that thermal imaging camera is able to differentiate the different heat of a surface with uneven or different texture. The results also contribute to the confidence of potential of Active Infrared Thermography as early NDT identification method to detect corrosion under paint in steel surface.

Cooling Effect

To carry out this experiment, the method is slightly different compared to the first experiment. The difference is that to measure the heat of the steel, it first has to be cooled down before any result is taken. This is because, using the spot light, the steel will have a greater temperature at first. And if images were taken right after exposing the steel to the heat source, there won't be a clear image as shown in **Figure 43**. After heating, the steel is left to cool for 20seconds. From the image it could barely seen the difference of the corroded and non corroded area.

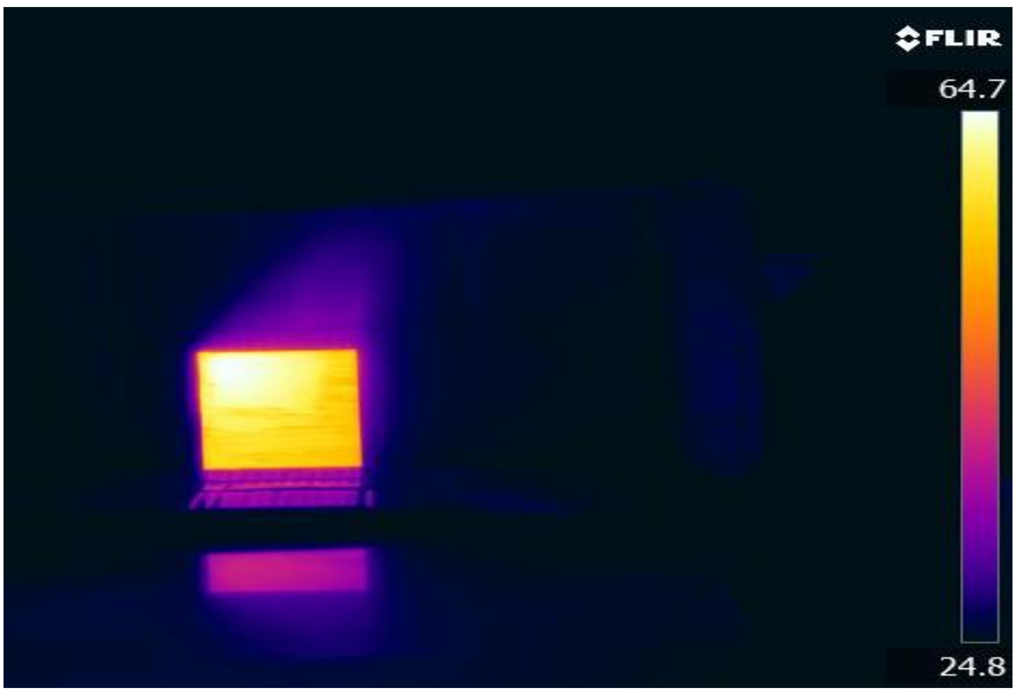


Figure 43. Infrared image of steel after a couple of seconds heating.

Figure 44, **Figure 45, Figure 46** and **Figure 47** are images taken of the steel at zero seconds, 60 seconds, 120 seconds and 180 seconds to show the changes in thermal image.

Figure 44. Thermal image at zero seconds.

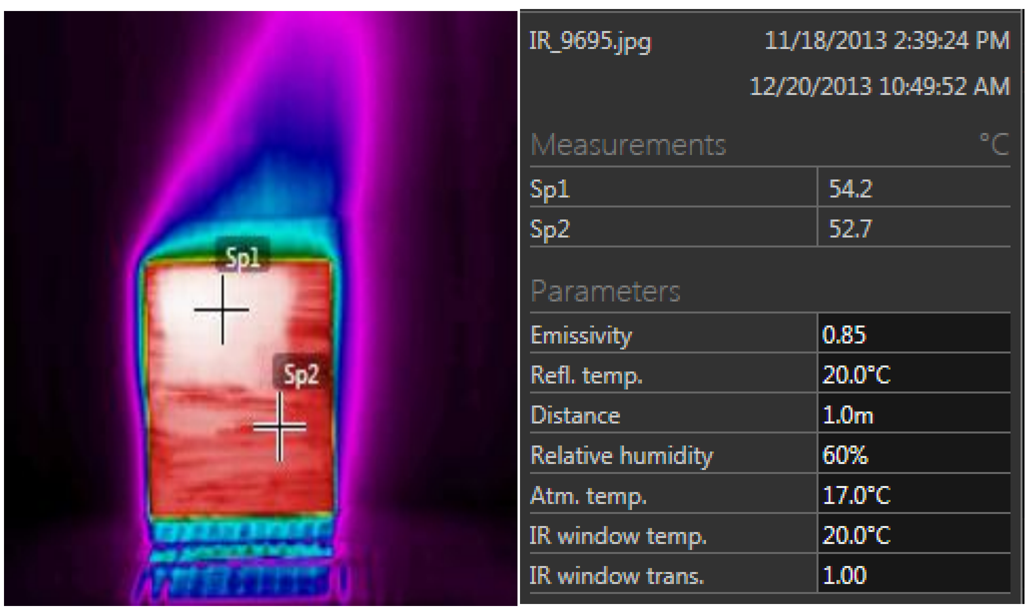


Figure 45. Thermal image at 60 seconds.

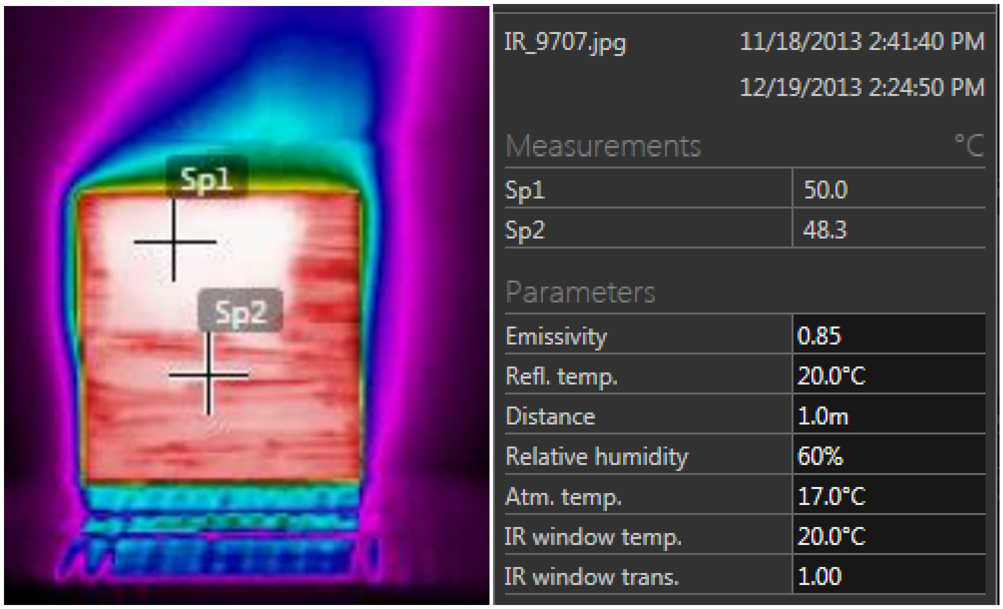


Figure 46. Thermal image at 120 seconds.

Figure 47. Thermal image at 180 seconds.

4.4.3 Color of paint coating of the steel surface.

Most common steel coating primer used in the industry to prevent corrosion is available in two different colors which are red oxide and black oxide. This experiment was conducted by coating the steel with both colors of premier coatings to simulate the real condition in the industry. With the red and black oxide coating, corrosion can easily be detected. Both are dark color, so in order to investigate the color coating that can't be detected by the thermal camera, a light color was used to coat the steel. **Figure 48** and **Figure 49** shows that normal white paint was used as coating as there isn't any white primer paint in the industry at the moment. Primer are only available in black, red or brownish black. (Koleske, J.V, 1995).

Figure 48. A plate with a section of corroded area

Figure 49. Steel coated with white paint.

Before coating the steel, half of the area was grinded to leave a certain fraction corroded. The steel is than heated with a spot light and image of the corroded area is captured in **Figure 50** using the thermal imaging camera**.** From the image it is clearly seen the corroded and non corroded area of the steel. The steel is than coated with 3 layers of white paint - the same amount of layers as the other steels which were coated with the red and black oxide primer. After letting it to cool down, the images were captured as shown in **Figure 51** below. The corrosion under the insulation can't be seen at all and the temperature difference was also inconclusive. After letting to cool down after three minutes, which is nine times longer than the other steel in Experiment II, still there was no sign of corrosion image under the insulation. Refer **Figure 52.**

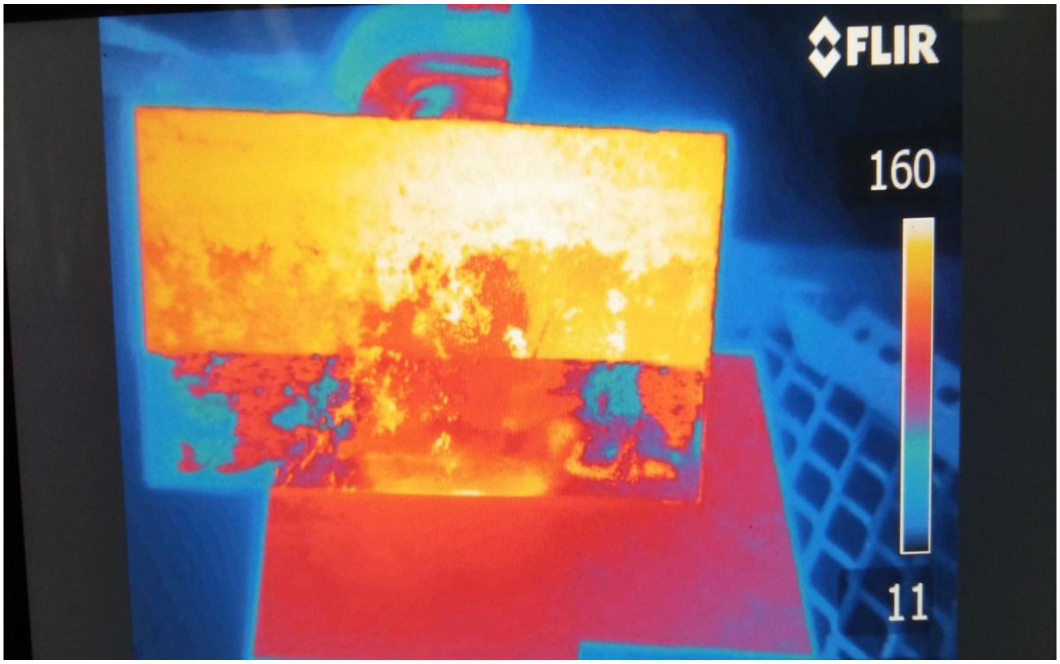


Figure 50. Image of steel before coating.

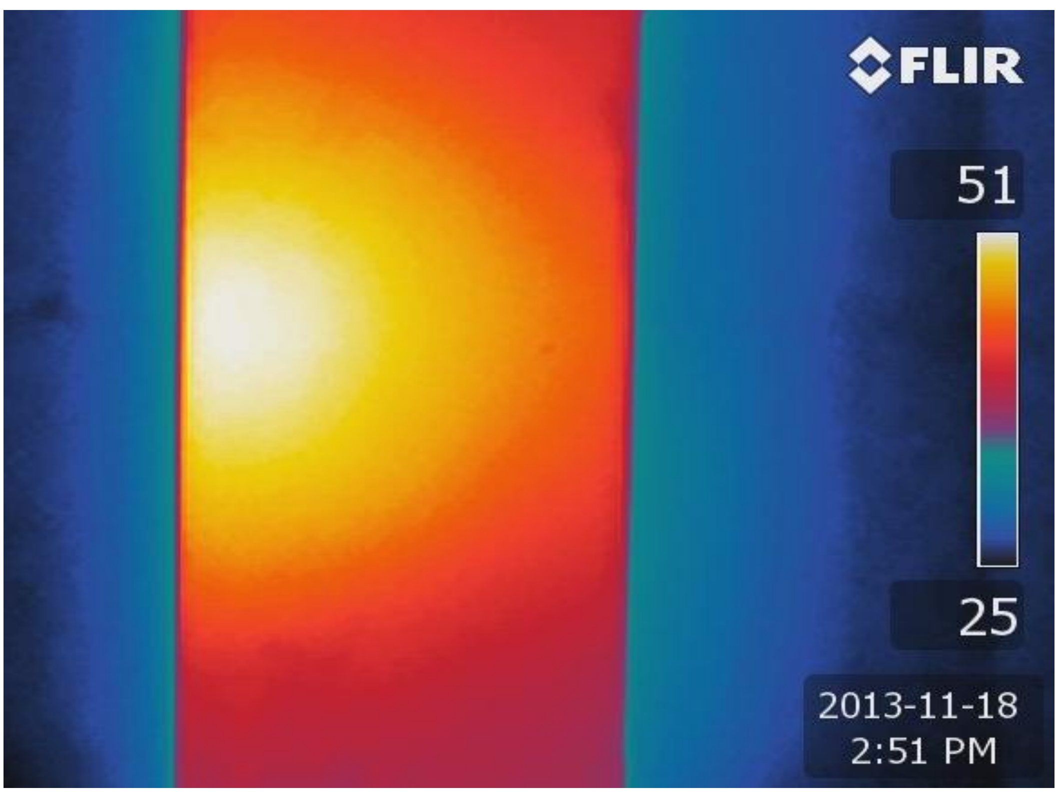


Figure 51. Image of steel after coating.

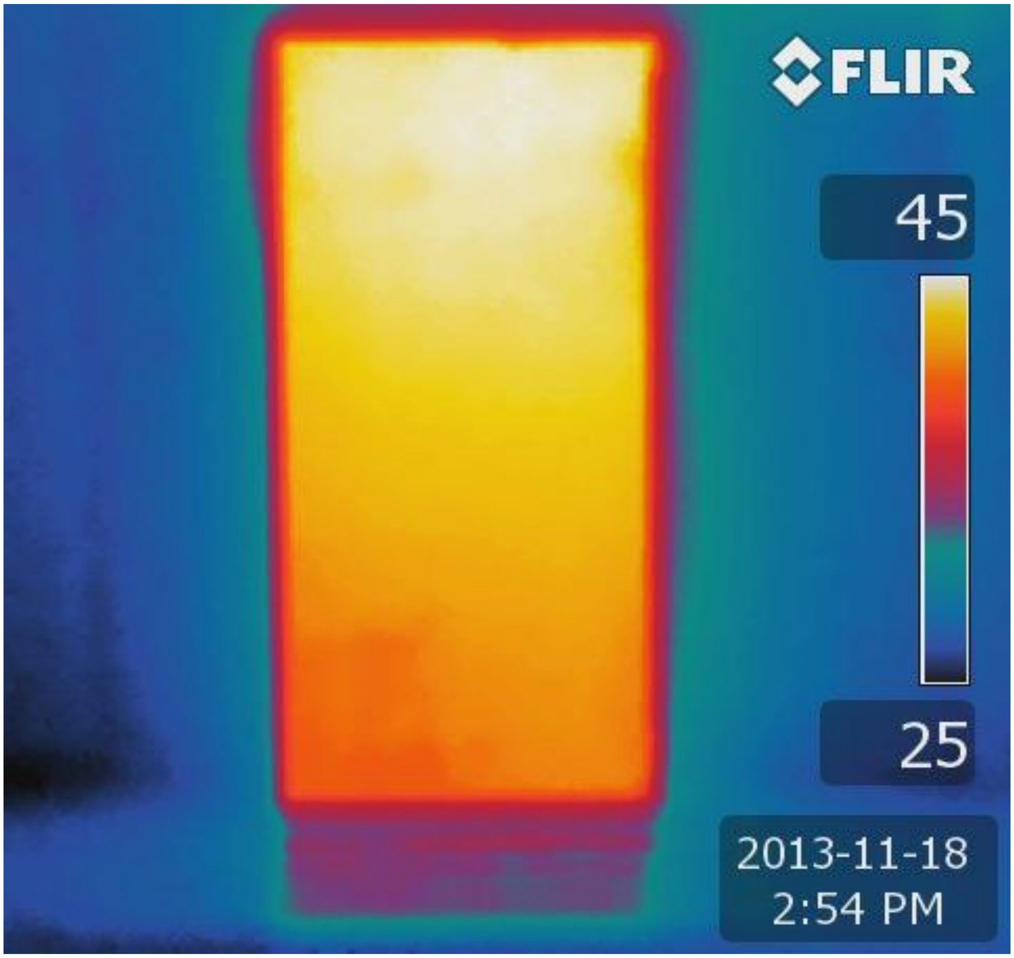


Figure 52. Image of steel after 3minutes.

4.4.4 Measurement depth of corroded area on steel by heat chart.

Although this experiment is a qualitative based experiment, it is possible to measure quantitatively the different depth of a corroded area based on the heat map color from the image taken. The infrared camera has a heat bar on the right side of its screen which shows the different color accordingly to thermal maps. Different temperature has different color as shown in **Figure 43.** For this measurement, only the color pink, red and yellow is used as they have the highest temperature to show for any corrosion under paint.

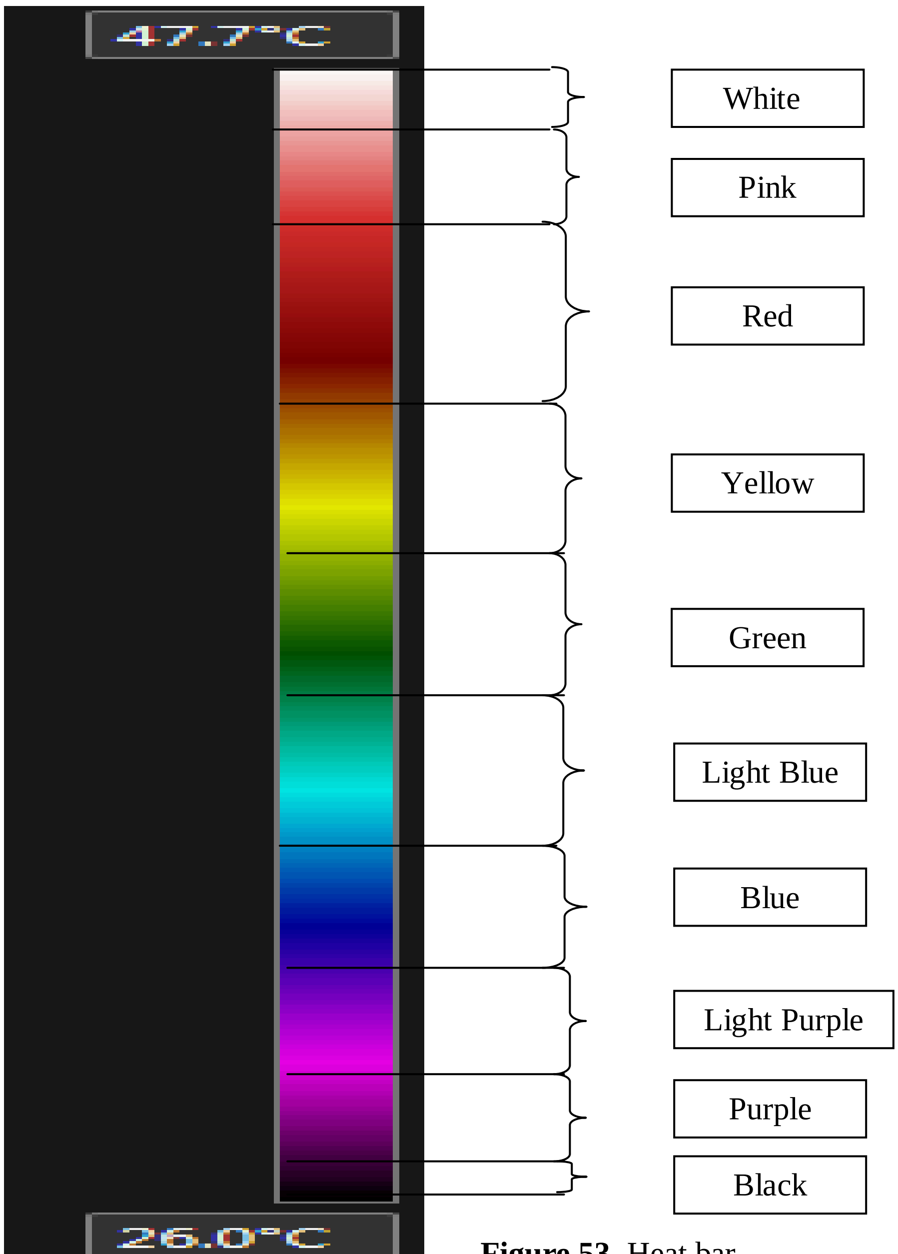


Figure 53. Heat bar

Using the color from heat bar, we can differentiate the depth of a corroded area comparing it from the image of the steel before and after coating. This method may vary as it only depends on the normal human vision with the aid of normal enlargement software to enlarge the image so it could be classified into each color category. From the thermal map of the steel, it was determine that the more corroded a region is, the darker the color it emits. **Table 6** shows the color of each region with a scale from one to five according to the level of corroded an area is with five being the most corroded region on the steel.

Table 6. Color and scale of corroded area.

Color	Temperature	Scale
		5
		4
	Higher temperature and more corroded	3
		2
		1

Figure 54 shows the image of the steel before coating and **Figure 55** shows the thermal imaging of the steel. Each image is label to show the similar place of the area being compared for both steels. Image in **Table 7** is enlarged by 450 percent in order to show the corroded area and given a score from one to five based on which is more corrosive.

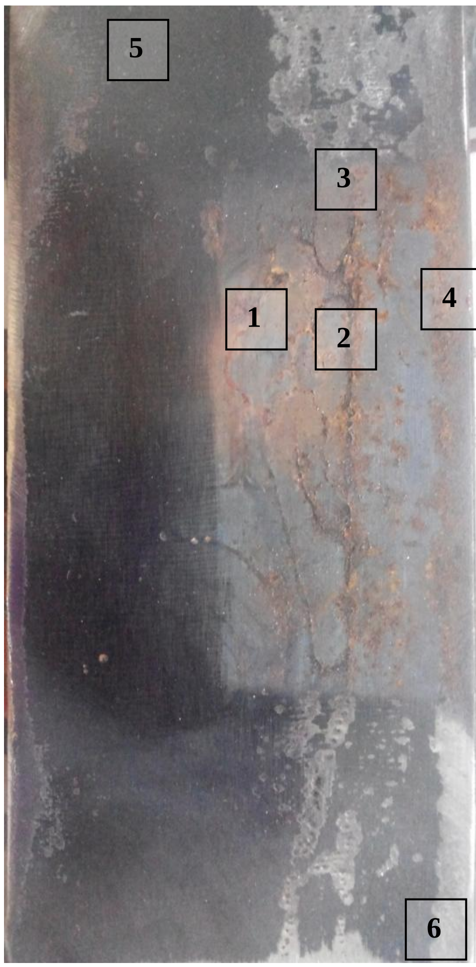


Figure 54. Steel before coating.

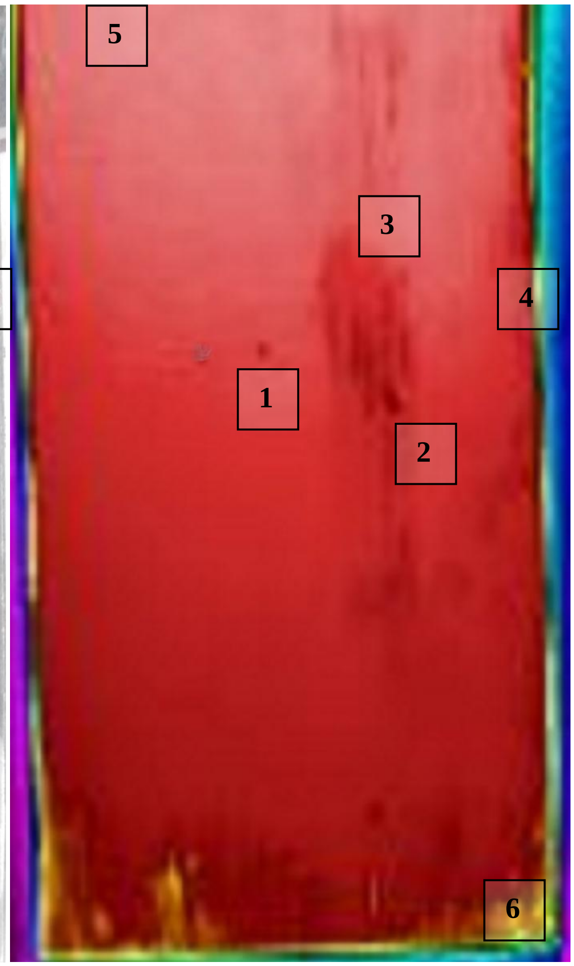


Figure 55. Thermal image of steel after coating.

Table 7. Score of corroded area from both images after enlarge by 450 percent.

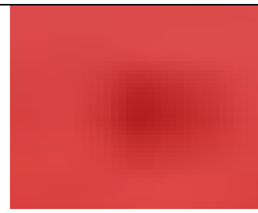
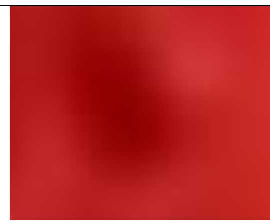
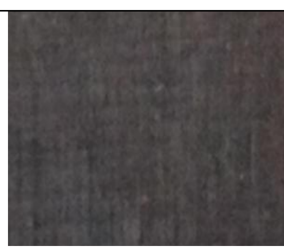
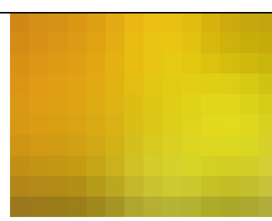
Area	Before coating	Thermal Image	Score
1			5
2			5
3			4
4			3
5			2
6			1

Figure 56 shows the temperature of each spot according to the labeled numbering. From the figure, it is proven that the more corroded the area is, the higher the temperature will be.

IR_9795.jpg		11/18/2013 3:07:27 PM
		12/30/2013 11:24:44 AM
Measurements		°C
Ar1	Max	46.1
	Min	27.2
	Average	44.0
Sp1		45.7
Sp2		44.9
Sp3		43.9
Sp4		43.8
Sp5		43.6
Sp6		41.1
Parameters		
Emissivity		0.79
Refl. temp.		20.0°C
Distance		1.0m
Relative humidity		60%
Atm. temp.		17.0°C
IR window temp.		20.0°C
IR window trans.		1.00

Figure 56. Temperature for each point on the steel.

CHAPTER 5

CONCLUSION AND RECOMENDATION

Based on the results obtained from Experiment I and Experiment II respectively, the objective of this project were successfully achieved. The corrosion under paint can be detected through infrared thermography method.

Further findings also proved that with thermal imaging camera, the severity of corrosion under paint can also be measured. Although more study and research is needed to further strengthen the result gained from this project, the basic requirements are there to ensure that infrared thermography has high potential to be implemented in the industry as early indentification method and complementary to NDT process to detect corrosion under paint on steel surface.

5.1 Recommendation

From experiment carried out and further discussion with FYP Supervisor, it is proposed that while gathering the image of the steel, an aluminum cover is placed over the steel to further reduce the light from the surrounding that could effect on the image captured. Also to find other heating method that is more practical to be used in the industry as to compare to the heat mat which is rather costly.

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APPENDICES

APPENDIX I: Detail drawings and design of rig.

APPENDIX II: Experiment I Infrared Thermography Images

APPENDIX III: Experiment II Infrared Thermography Images

APPENDIX I

Detail drawings and design of rig.

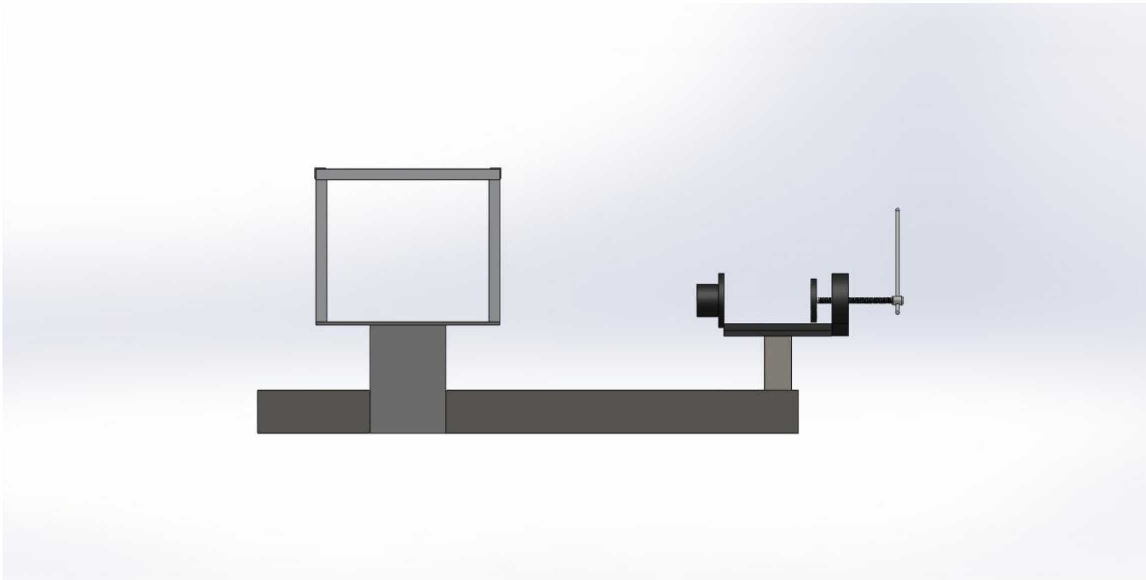

Figure 57. Rig side view

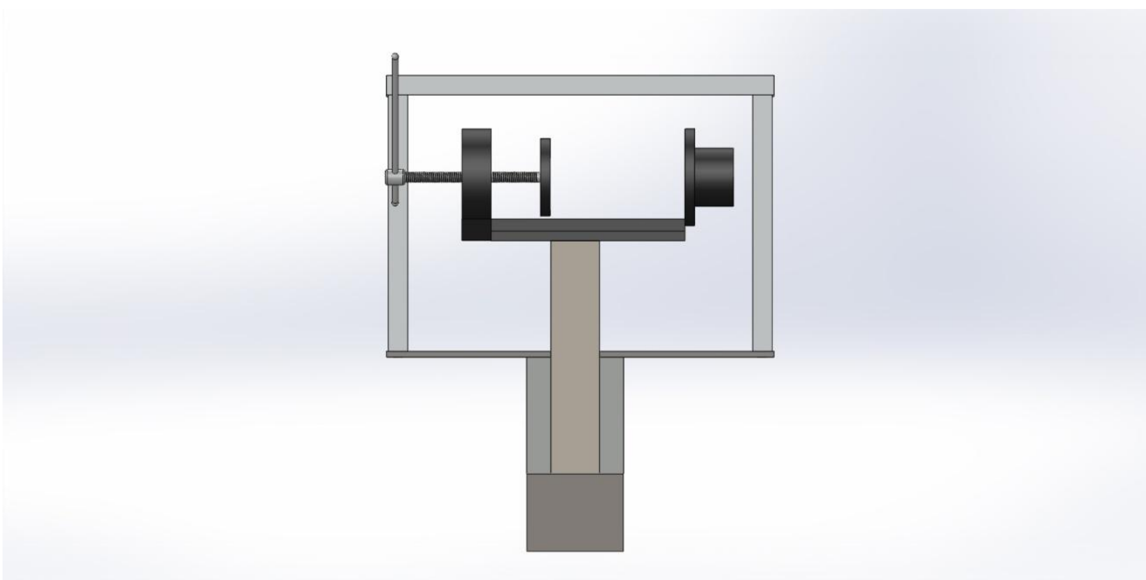

Figure 58. Rig front view

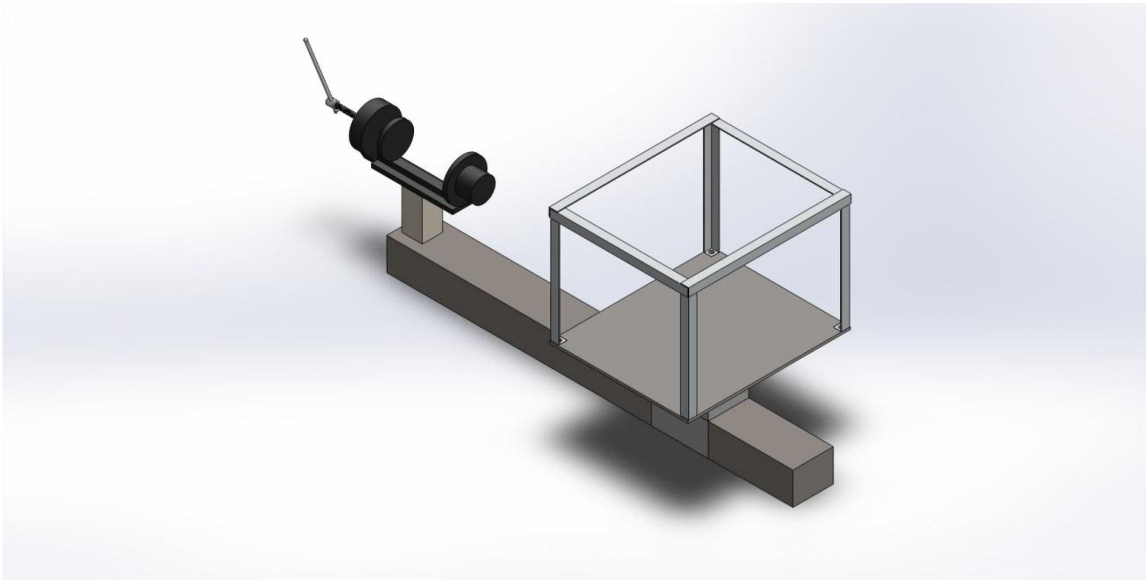

Figure 59. Rig complete view

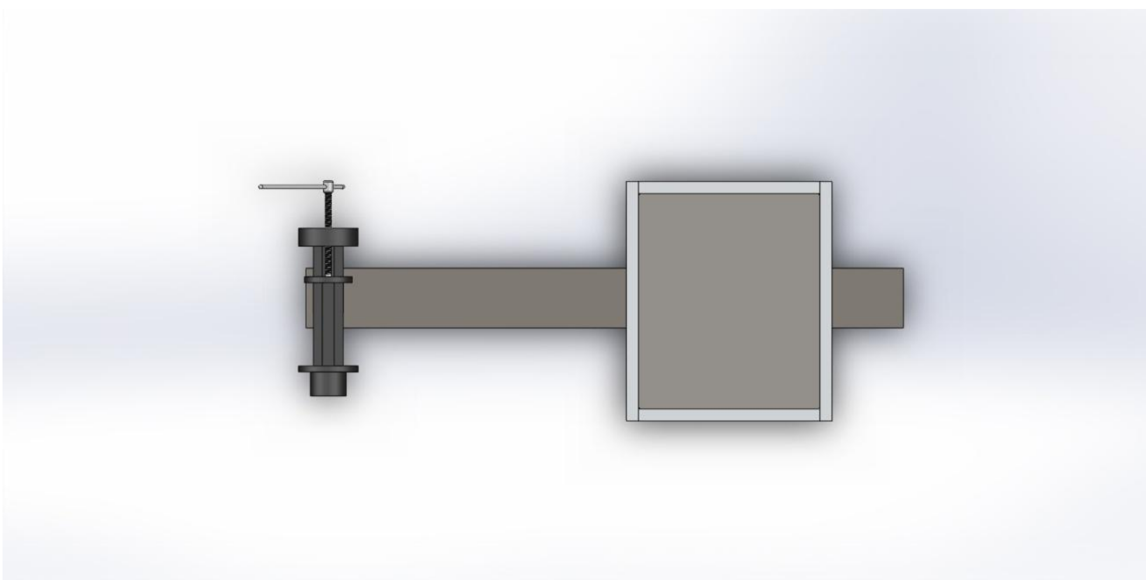

Figure 60. Rig plane view

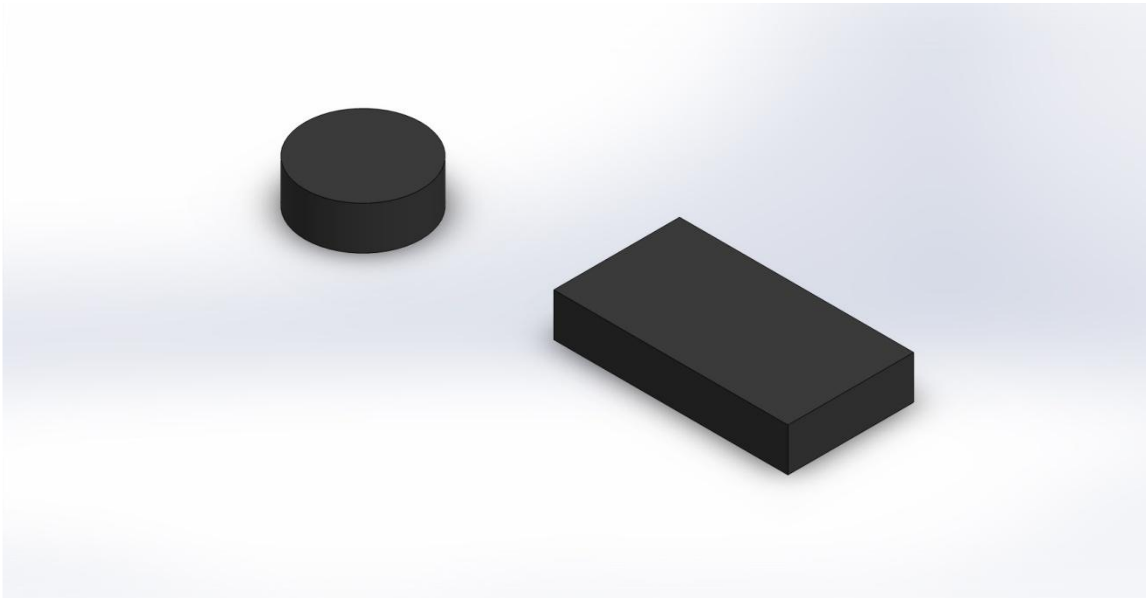

Figure 61. Rig bottom stopper.

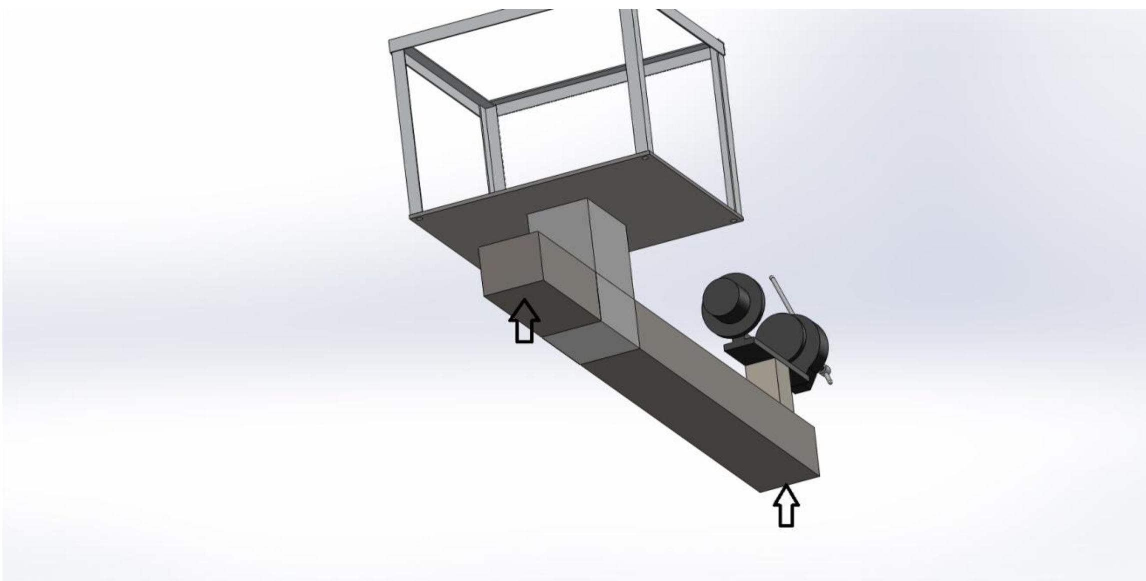

Figure 62. Stopper positioning

APPENDIX II:

Experiment I Infrared Thermography Images

Figure 63. Thermal image at 0 seconds.

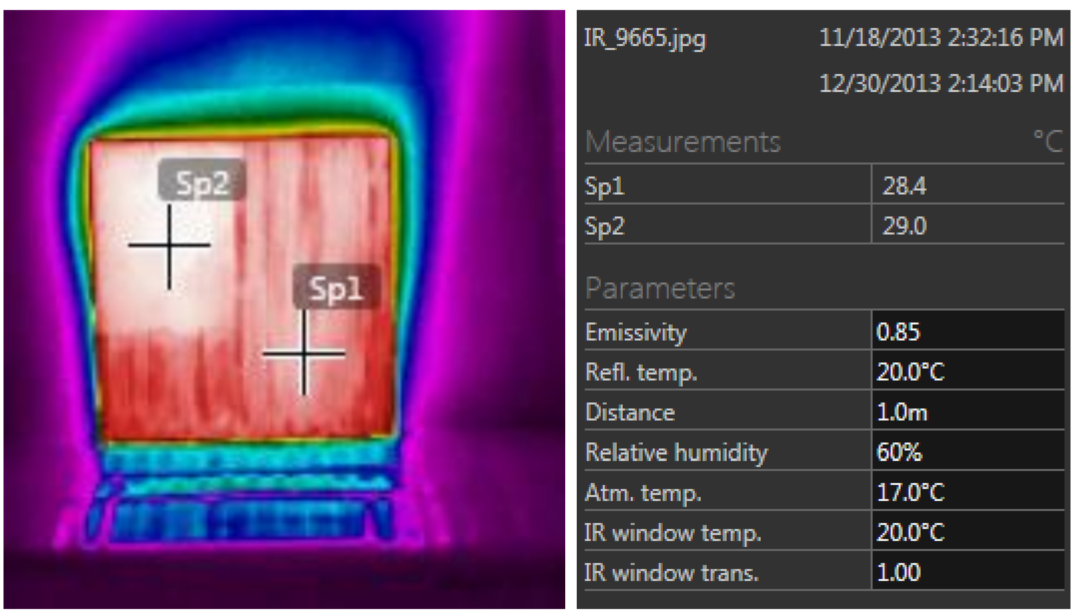

Figure 64. Thermal image at 20 seconds.

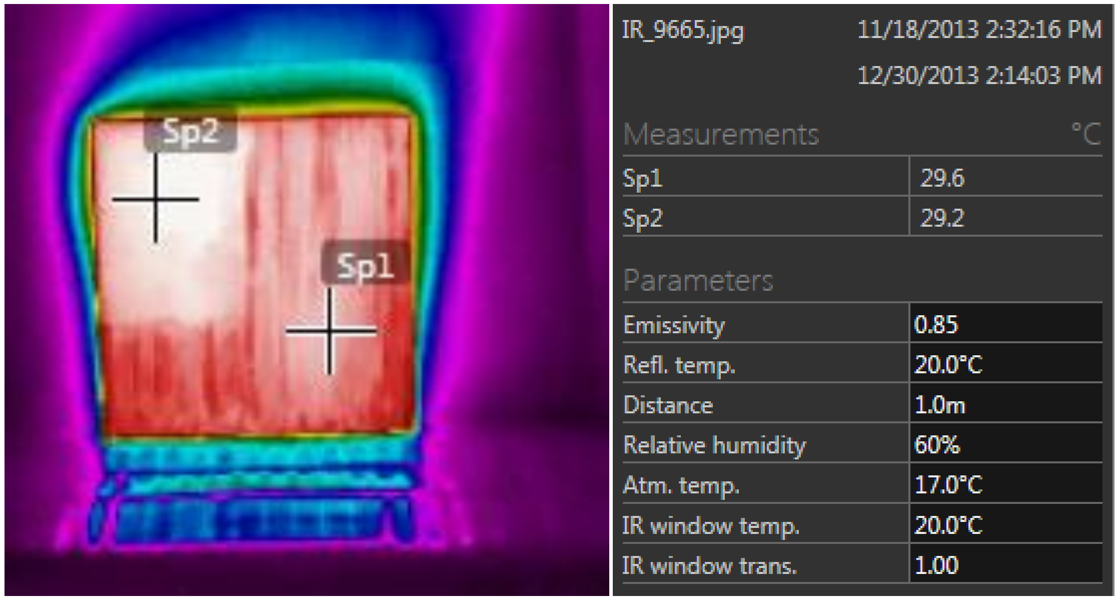

Figure 65. Thermal image at 40 seconds.

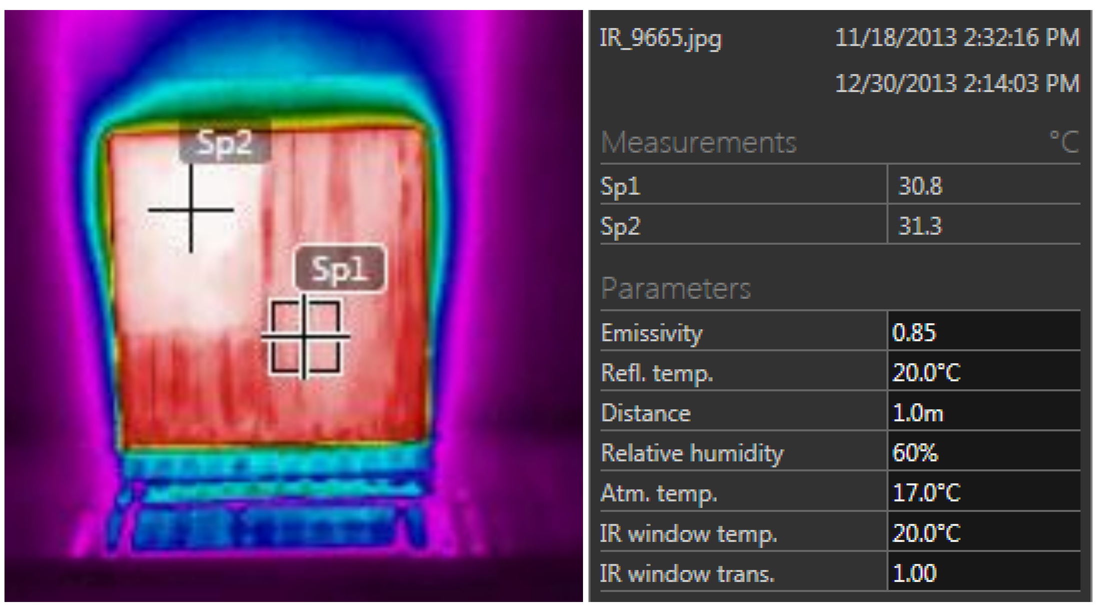

Figure 66. Thermal image at 60 seconds.

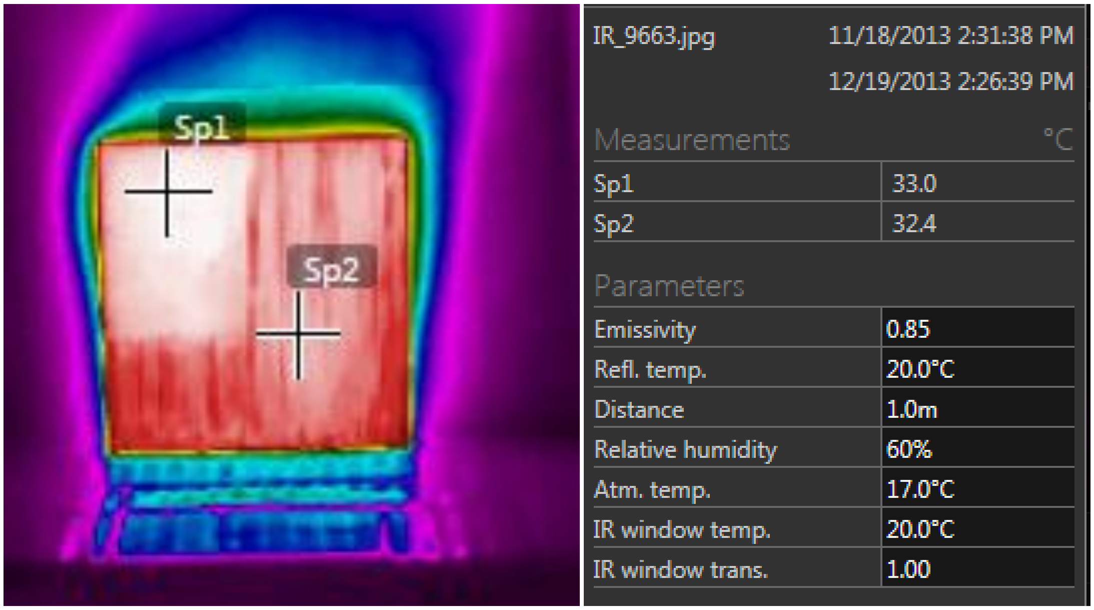

Figure 67. Thermal image at 80 seconds.

Figure 68. Thermal image at 100 seconds.

Figure 69. Thermal image at 120 seconds.

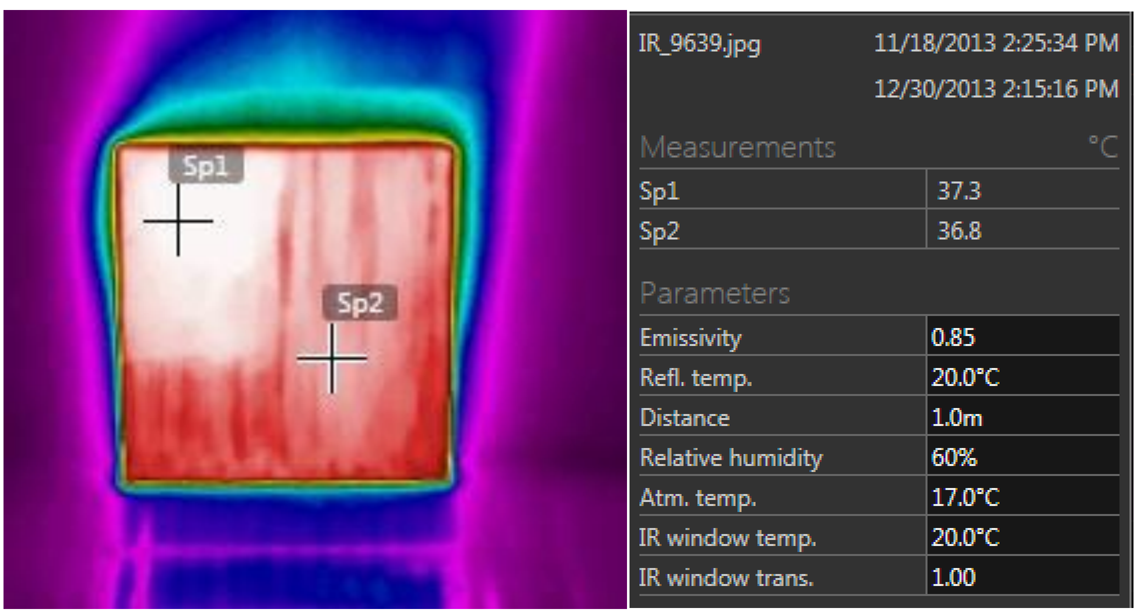

Figure 70. Thermal image at 140 seconds.

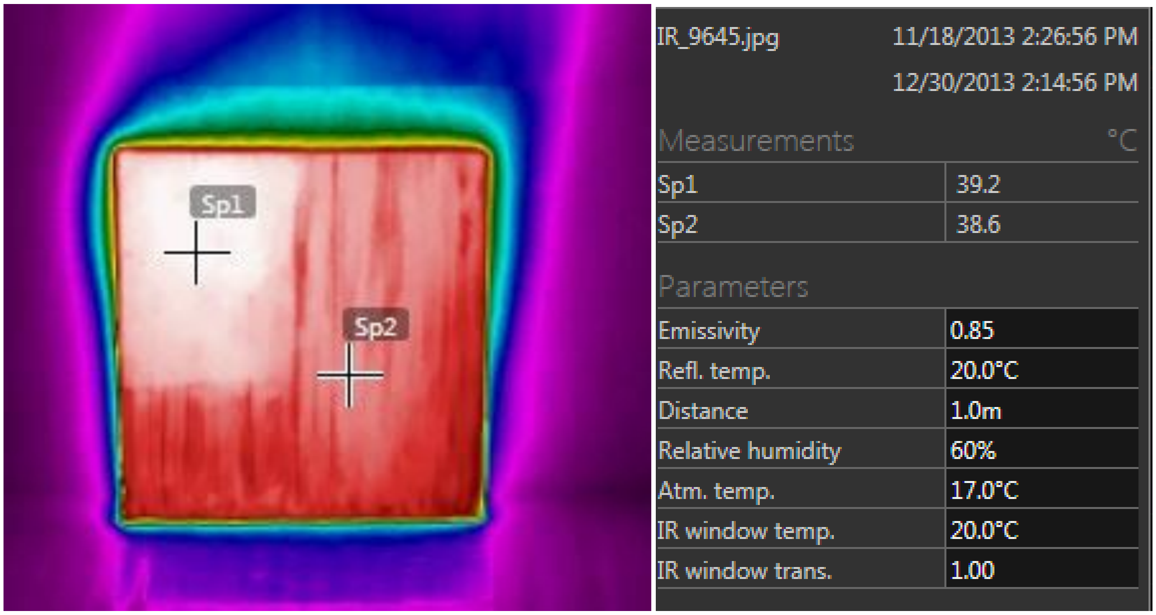

Figure 71. Thermal image at 160 seconds.

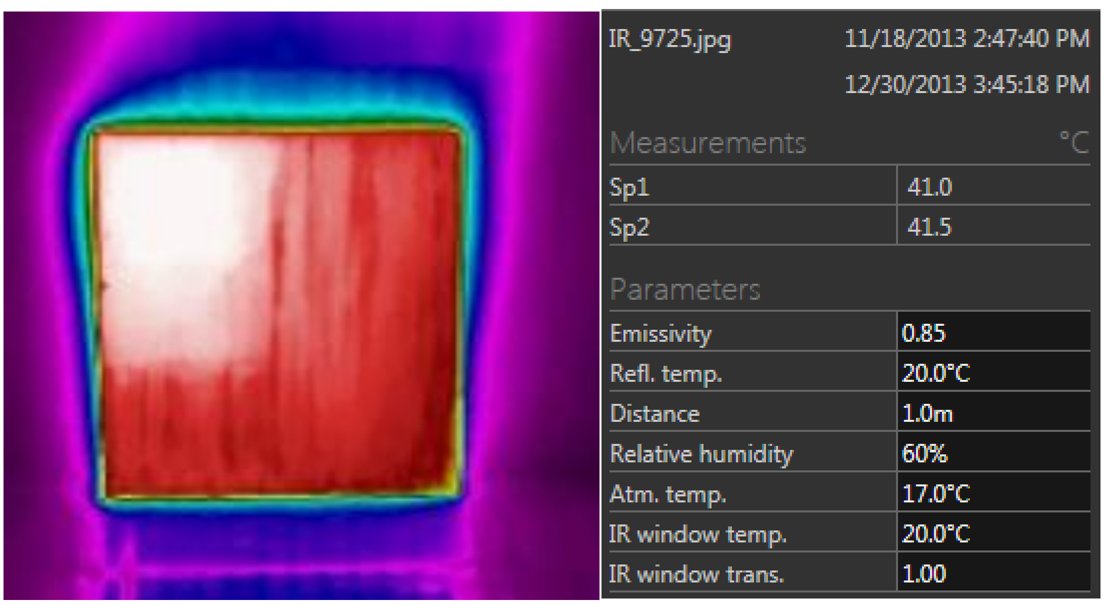

Figure 72. Thermal image at 180 seconds.

APPENDIX III:

Experiment II

Infrared

Thermography

Images

Figure 73. Thermal image at 0 seconds.

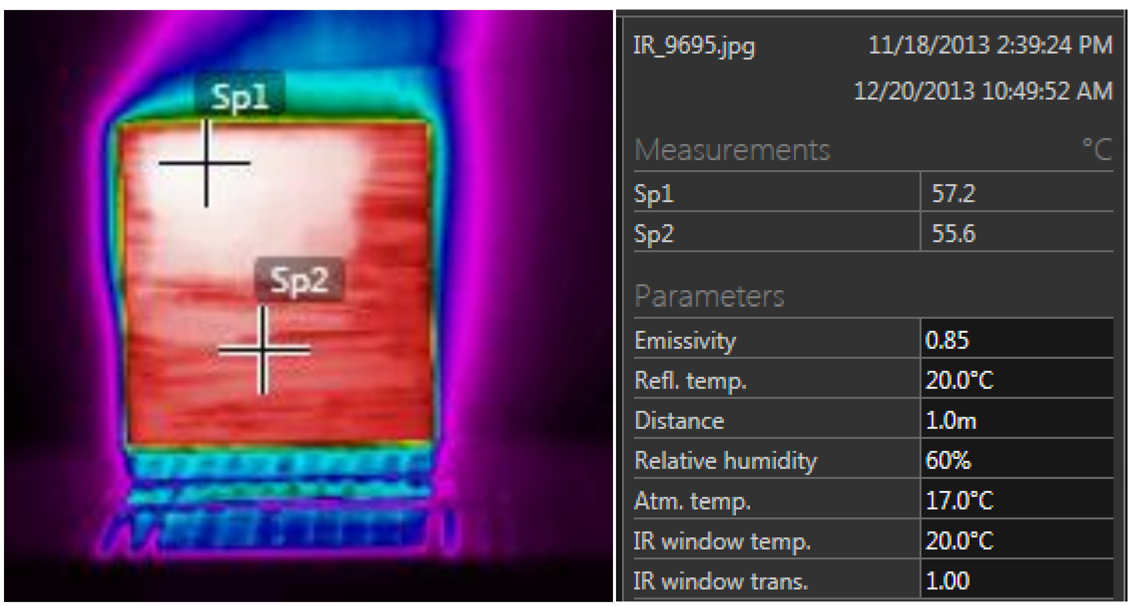

Figure 74. Thermal image at 20 seconds.

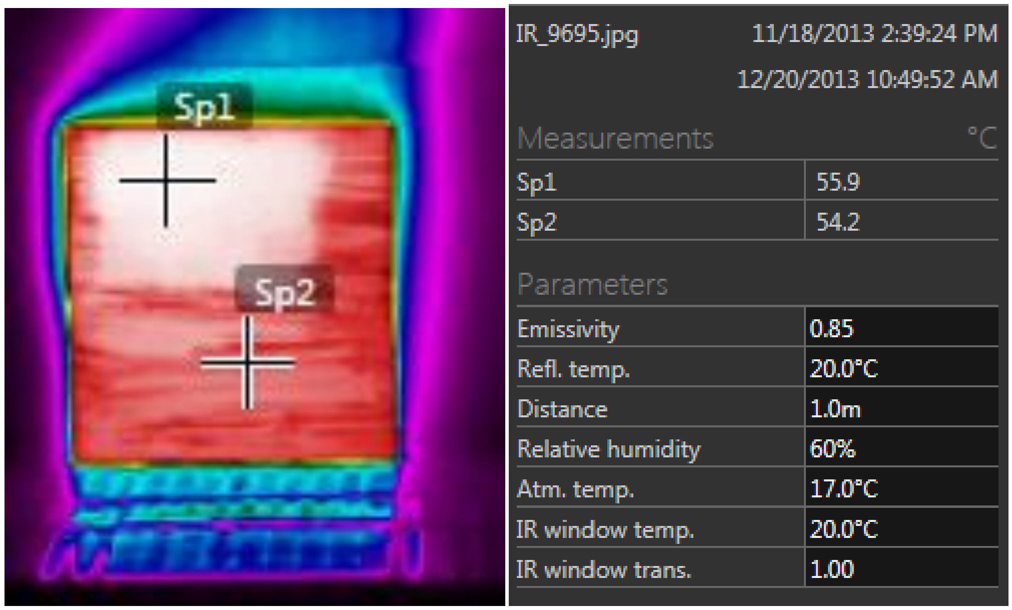

Figure 75. Thermal image at 40 seconds.

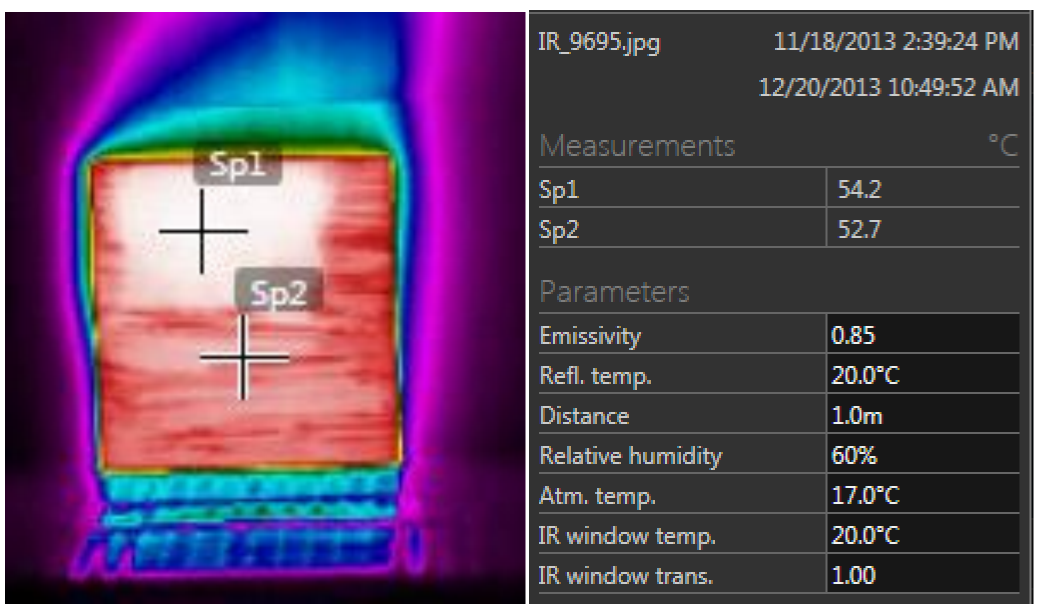

Figure 76. Thermal image at 60 seconds.

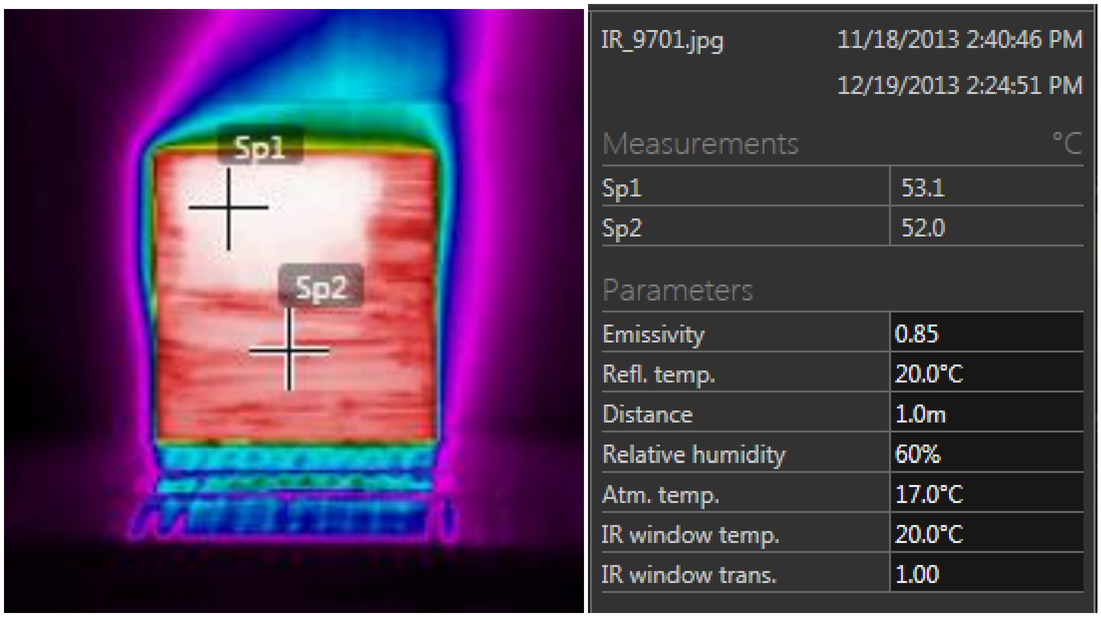

Figure 77. Thermal image at 80 seconds.

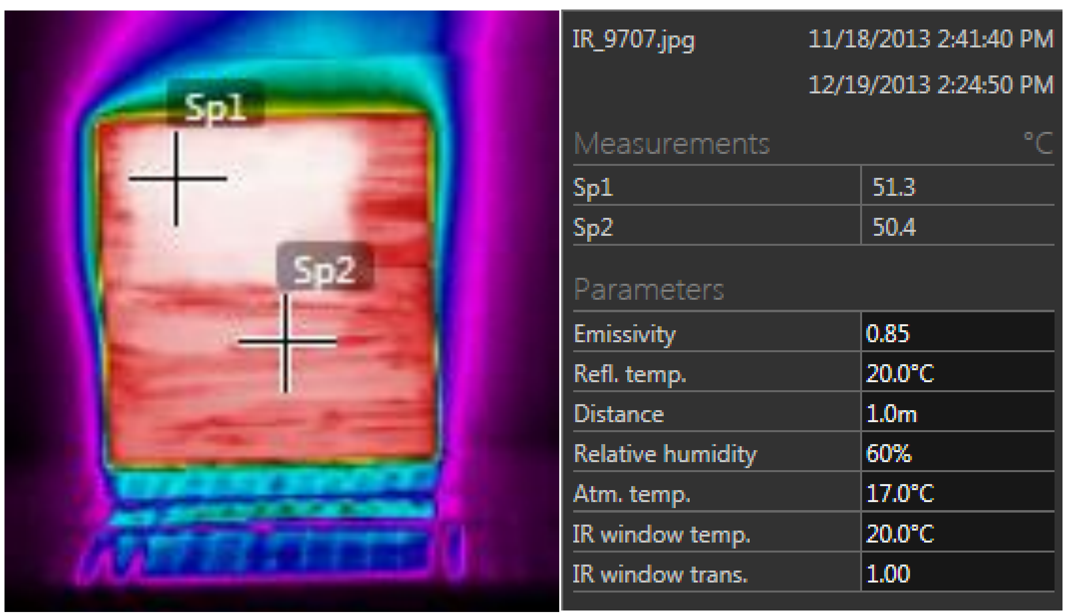

Figure 78. Thermal image at 100 seconds.

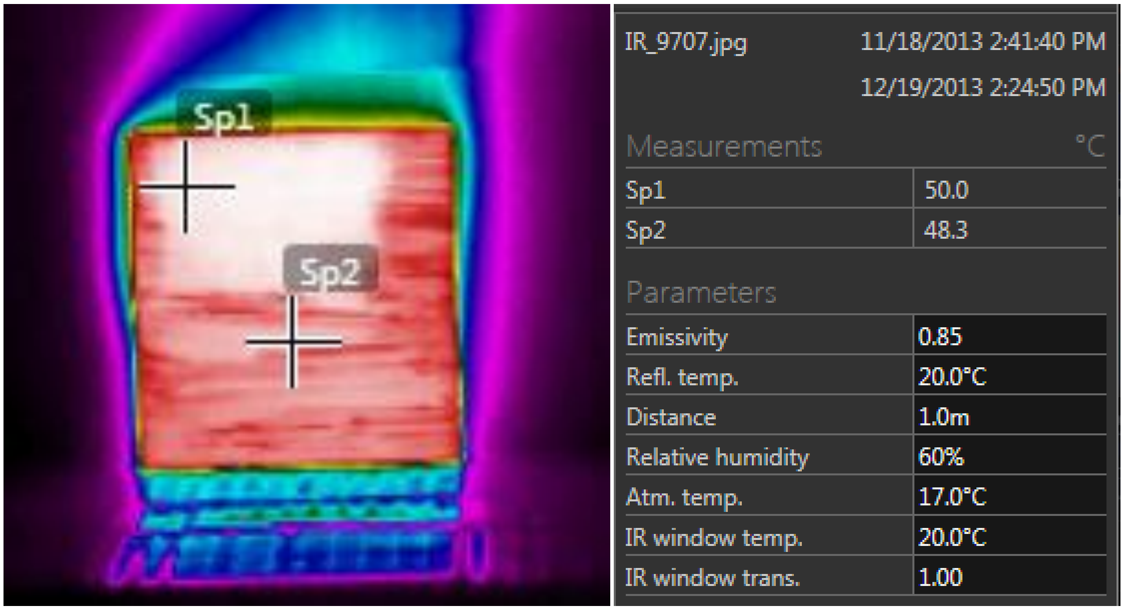

Figure 79. Thermal image at 120 seconds.

Figure 80. Thermal image at 140 seconds.

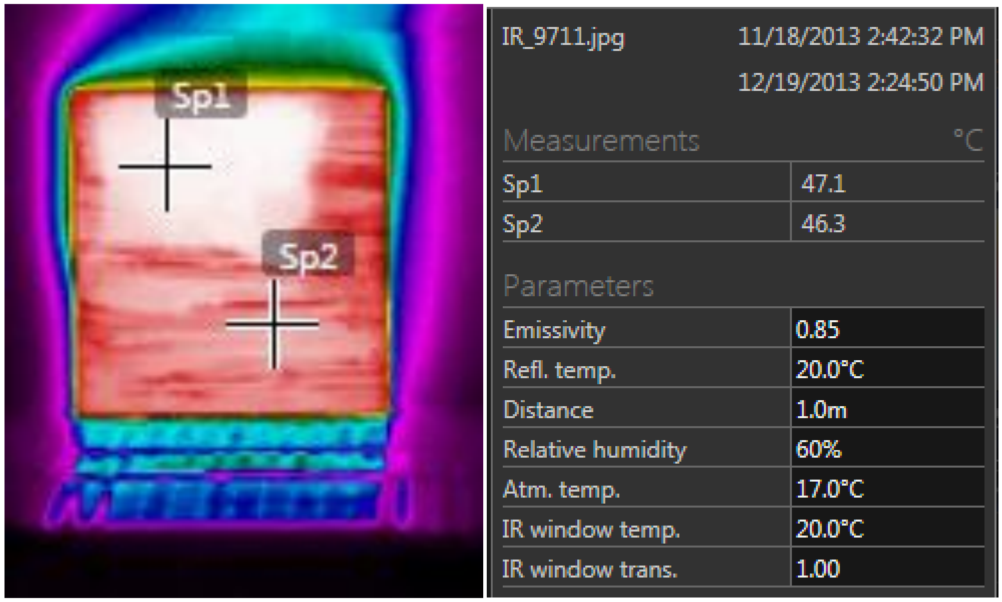

Figure 81. Thermal image at 160 seconds.

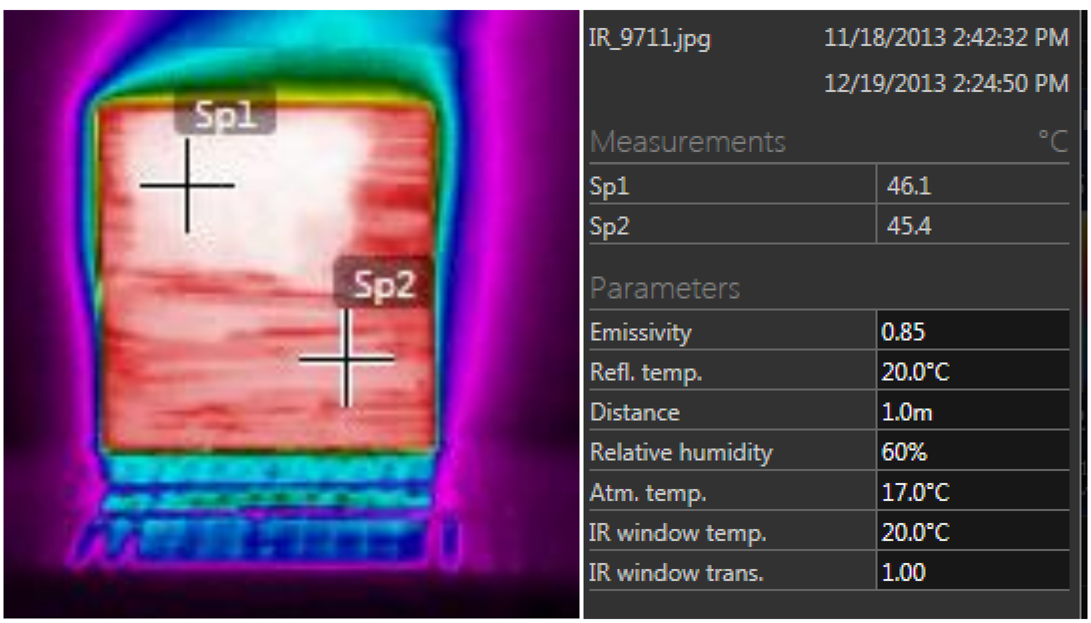

Figure 82. Thermal image at 180 seconds.