Bournemouth University

Sustainable Methodology of Conserving Historic Military Vehicles

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Copyright Statement

Abstract

Research was conducted to analyse corrosion and tribological failures in The Tank Museum Bovington military tanks. Due to the age of the exhibits corrosion of vital components has become a significant issue, it is vitally important to preserve these artefacts for future generations and so to do this effectively we need to monitor and reduce this corrosion as far as realistically possible. A case study of the historic military tanks followed by experimental research analyses is presented. Structural degradation through corrosion and engine wear has been identified and analysed. Materials were processed/manufactured during 2nd World War, their composition was unknown. Therefore state-of-the-art characterisation techniques were performed on samples collected from the M10, Sherman, Centaur and Tiger 1 to obtain material compositions and to identify nearest standards. A bench mark of material loss due to corrosion so far, has been achieved in the M10, Sherman, Centaur, BT – R 60 and King Tiger through ultrasonic corrosion mapping. Material loss because of corrosion was high in the Centaur in comparison to the Sherman, M10, BT R – 60 and King Tiger samples.

Corrosion analyses techniques were conducted on samples from three tanks the M10, Sherman and Centaur to investigate corrosion morphology on the tanks surfaces and corrosion propagation from surface to sub-surface level. During this experimental work various corrosion contaminants, sub-surface cracks and defects were identified. Corrosion layer/residues were relatively thick (approximately 250 µm) on the surfaces of the M10, whereas the phenomenon of corrosion pits was wide spread in the Centaur. Corrosion was influenced by the presence of surface contaminants and sub-surface defects such as slags, sulphide inclusions and corrosive pits. These factors alone and/or in combination were observed to be a serious issue in limiting vehicles’ longevity.

Study of the environments both inside and outside the museum has been conducted to relate corrosion activity within the context. Based upon the data gathered simulated environmental corrosion tests were conducted to quantify corrosion accumulation under a controlled museum environment suitable for the museum visitors. Some degree of corrosion build-up was observed on the samples under controlled environments. Prohesion test was conducted to evaluate viability of the materials, coating and primer. Material ability to resist adverse environmental conditions was negligible. These results are of particular interest for the vehicles which are exposed in uncontrolled environment. Exposure of the primer and coating to prohesion test showed, that the primer was able to resist failures during the entire test duration. However breakdown of the coating was observed during the test.

Wear analyses of the original piston which was designed before/during the 2nd World War showed enhanced material composition and tribological properties than the new replacement piston. Failures in the replacement piston and cylinder-liner could be attributed to inadequate material selection and design.

A sustainable model to extend longevity and to retard structural aging of the military tanks in The Tank Museum has been proposed.

List of Publications

Journal publications

1. **Saeed, A**., and Khan, Z. (2012) “Analytical Research of Environmental Assisted Damage to the Wolverine - M10 Military Tank Destroyer” Corrosion – The Journal of Materials Performance Magazine NACE International (Submitted).
2. **Saeed, A**., Khan, Z., Hadfield, M and Davies, S. (2013) “Material Characterisation and Real Time Wear Evaluation of Pistons and Cylinder-liners of Tiger 131 Military Tank” Tribology Transactions Volume 56, Issue 4, July 2013, pages 637-644.
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5. Smith, K., Khan, Z., **Saeed, A**., and Hadfield, M., “Accelerated Corrosion tests of Waste-gated Turbocharger’s Adjustable and Fixed End Links” 11th International Conference on Surface Effects and Contact Mechanics, Siena Italy 5 -7 June, 2013 (accepted).
6. **Saeed, A**., Khan, Z., Garland, N. and Smith R., (2011). “Material Characterisation to understand various Modes of Corrosion Failures in Large Military Vehicles of Historical Importance”. Fifth International Conference on Computational Methods and Experiments in Materials Characterisation, Kos, Greece, 13 - 15 June 2011.

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Author’s Declaration

This report contains the original work of the author except otherwise indicated.

Nomenclature

Al	Aluminium
C	No of cycles
Ca	Calcium
Co	Cobalt
Cr	Chromium
Cu	Copper
CS	Corroded surface
EDS	Energy dispersive x-ray spectroscopy
EFS	Electrochemical fatigue sensor
F	Fluorine
F	Force
f	Frequency
Fe	Iron
GC	Galvanic corrosion
Hz	Hertz
I	Slip
IGC	Inter-granular corrosion
L	Load (unit Newton N)
MC	Microbial corrosion
Mo	Molybdenum
Mn	Manganese
MQ	Match quality
N	Newton
Ni	Nickel
O	Oxygen
P	Phosphorus
PA	Phased array
PE	Pulse Echo
PC	Pitting corrosion
S	Sulphur
SBS	Sand blasted surface
SEM	Scanning electron microscopy
Si	Silicon
Ti	Titanium
UC	Uniform corrosion
US	Ultrasonic scanning
UT	Ultrasonic testing
V	Vanadium
W	Load
W	Tungsten
WD-XRF	Wave length dispersive x-ray spectroscopy
XRF	X-ray fluorescence
μ	Co-efficient of friction
ΔK	Stress Intensity Factor

Lexicon[1]

Abrasive: Small particles of material that are propelled at high velocity to impact a surface.

Abrasive Blast Cleaning: Cleaning and roughening of a surface produced by the high velocity impact of an abrasive that is propelled by the discharge of pressurised fluid from a blast nozzle or by a mechanical device such as a centrifugal blasting wheel.

Accelerator: A chemical substance when added result faster chemical reaction.

Activator: A substance that starts and increases a chemical reaction, heat and radiation may serve as activators.

Active: (a) The negative direction of electrode potential. (b) A metal in its corroding form.

Aeration Cell: An electrochemical cell, the electromotive force of which is due to a difference in air (oxygen) concentration at one electrode as compared with that at another electrode of the same material.

Air Drying: This is a process in which an applied wet coating converts into a dry coating film by evaporation of solvent or reaction with oxygen as a result of simple exposure to air without intentional using of heat or curing.

Alkyd: Kind of resin derived from the reaction of polyhydric alcohols and polybasic acids, part of which is derived from saturated or unsaturated oils or fats.

Anaerobic: Free from air or un-combined oxygen.

Anion: A negatively charged ion that migrates through the electrolyte towards the anode under the influence of a potential gradient.

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Anode Corrosion Efficiency: The ratio of corrosion (mass loss) of an anode to the theoretical corrosion (mass loss) calculated from the quantity of electricity that has passed between the anode and cathode using Faraday’s law.

Anodic Inhibitor: A substance that may prevent or reduce the oxidation process.

Anodic Polarisation: The change of electrode potential in the noble (positive) direction caused by current across the electrode/electrolyte interface.

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[1] Derived from the NACE Corrosion Engineer’s Reference Book (3rd Edition).

Anodic Protection: Polarisation to a more oxidising potential to achieve a reduced corrosion rate by the promotion of passivity.

Anodising: Oxide coating formed on a metal surface (normally aluminium) by an electrolytic process.

Barrier Coating: (a) A coating that has a high resistance to permeation of liquid and/or gases. (b) A coating that is applied over a previously coated surface to prevent damage to the underlying coating.

Beach Marks: The characteristic marking on the fracture surfaces produced by fatigue crack propagation (also known as clamshell marks, conchoidal marks, and arrest marks).

Brittle Fracture: Fracture with little or no plastic deformation.

Catalyst: A chemical substance, usually present in small amounts relative to the reactants, that increases the rate at which a chemical reaction (e.g. curing) would otherwise occur, but is not consumed in the reaction.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Corrosion: Corrosion resulting from a cathodic condition of structure, usually caused by the reaction of an amphoteric metal with alkaline products of electrolysis.

Cathodic Inhibitor: A chemical substance that prevents or reduces the rate of cathodic or reduction process.

Cathodic Polarisation: The change of the electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface.

Cathodic Protection: A technique to reduce corrosion of metal surface by making that surface the cathode of an electrochemical cell.

Cavitation: The formation and rapid collapse of cavities or bubbles within a liquid which often result in damage to material at the solid/liquid interface under conditions of extreme turbulent flow.

Chemical Conversion Coating: An adherent reaction product layer on a metal surface formed by reaction with a suitable chemical to provide greater corrosion resistance to the metal and increase adhesion of coatings applied to the metal, i.e. iron phosphate coating on steel, developed by reaction with phosphoric acid.

Chloride Stress Corrosion Cracking: Cracking of a metal under the combined action of tensile stress and corrosion in the presence of chlorides and an electrolyte normally water.

Coat: One layer of a coating applied to a surface in a single continuous application to form a uniform film when dry.

Coating: The application of a liquid that converts into a solid protective layer on a surface. It also works as decorative film.

Corrosion: The reaction of a material normally a metal with the surrounding environment, which results in the deterioration of the materials.

Corrosion Fatigue: In a corrosive environment the formation of fatigue cracking in a material together with repeated stresses.

Corrosion Inhibitor: Substance when present, in the environment prevent/reduces corrosion.

Corrosion Rate: The rate at which corrosion progresses.

Corrosion Resistance: In a given environment, the ability of a metal to withstand corrosion.

Corrosiveness: Environment's propensity to cause corrosion.

Critical Humidity: Relative humidity above which atmospheric corrosion occurs rapidly.

Elastic Deformation: Under application of stress, changes in the dimension of the materials within the elastic limit. The material returns to its original shape after the removal of the applied stress without change.

Elastic Limit: The maximum stress to which a material can be subjected without any permanent deformation or damage.

Elasticity: The ability of a material to come back to its original dimensions after the release of the applied stress.

Erosion: Removal of surface particles from a surface when subjected to mechanical interaction between the liquid and material.

Ferrite: Iron based alloys with body centred cubic crystalline phase.

Ferrite Steel: The type of steel whose micro-structure at room temperature remains mostly ferrite.

Film: A thin layer on the surface but may not be visible to eyes.

Galvanic Series: An arrangement of metals and alloys according to their corrosion potential for a given environment.

Heat Treatment: The cooling and heating of a metal for the purpose of obtaining desired properties.

Inclusion: Non-metallic phase such as an oxide, sulphide or silicate particles in a metal.

Internal Oxidation: The formation of isolated particles due to oxidation products underneath the metal surface.

Ion: An electrically charged atom or group of atoms.

Low Carbon Steel: Steel with less than 0.30% carbon and no intentional alloying additions.

Noble: The positive direction of electrode potential, thus resembling noble metals such as gold.

Noble Metal: (a) A metal that exist in nature in Free State.

pH: The negative logarithm of the hydrogen ion activity written as:

$$pH = - \log_{10} (a_{H^+})$$

Where a_{H^+} = hydrogen ion activity = the molar concentration of hydrogen ions multiplied by the mean ion-activity co-efficient.

Plastic Deformation: Permanent deformation as a result of stress beyond the elastic limit.

Plasticity: Permanent deformation of a material without fracturing.

Primer: A coating applied as first coat on an uncoated surface to prepare the surface for subsequent coats.

Protective Coating: Coating applied to a surface to protect the substrate from corrosion.

Relative Humidity: The ratio, expressed as a percentage, of the amount of water vapour present in a given volume of air at a given temperature to the amount required to saturate the air at that temperature.

Rust: Products of corrosion, consisting iron oxides and hydrated iron oxides.

Topcoat: The final coat on the surface also known as finish.

Chapter 1 Introduction

1.1. Background

During their service life large military vehicles operate in various conditions such as aggressive marine environments with salt spray, to desert full of sand particles and extreme working temperatures. After exposure to such environments when these vehicles are kept stationary they endure structural degradation. This degradation is mainly influenced by corrosion, wear, undesired stresses and various surface and sub-surface stress/fatigue cracks.

The Tank Museum Bovington United Kingdom owns a large fleet of around 300 large military vehicles i.e. tanks. These military tanks were exposed to extreme working and operating conditions in the battle grounds in their past service life and therefore exhibit various modes of degradation in their structures. Corrosion is one of the most visible forms of structural degradation in these tanks. Engine wear is another important factor risking their operating performance. Significantly aging large military vehicles which fought during the Great Wars in the museum environment require novel sustainable methods for their longevity. These large military vehicles from WW1, WW2 post war and recent conflicts are key entities; which provide a wealth of information and insight into the past design process, design methods, materials and manufacturing techniques. These rare and historic collections are valuable assets for our and the coming generation. However such vehicles are associated with various modes of structural aging.

Large vehicles especially military tanks are complex objects containing a wide range of materials and mechanical components linked to a variety of various structural deteriorations such as material degradation through corrosion, wear within interacting surfaces, various types of surface and subsurface cracks and undesired stresses. These mechanisms alone or in combination result in partial/complete component failures; higher maintenance costs and risks the structural integrity. Military vehicles from World War I and II were designed according to the automotive technologies in practice at those times [1] with a specified/limited life time expectancy. Moreover during the Wars these vehicles were exposed to harsh physical (different terrain) and chemical (exposure to chemical attacks) environments and operated under extreme working conditions. Majority of these vehicles were then left exposed to the uncontrolled environment for an unidentified period [2].

To sustain structural integrity of military tanks in the museum the development of a framework to identify, repair, prevent and to predict the initiation of structural defects needs to be executed [3]. Although there are methods to retard/diminish such factors, this framework must be able to protect the cultural biography against various preservation techniques.

A case study of the museum vehicles identified corrosion as the major contributor to structural damage together with wear, fatigue/SCC cracks and failures through undesired stresses. Damage because of corrosion was prominent in the case study results. Structural aging of the large metal structures such as military tanks, aircraft, ships and bridges through corrosion is a continuous growing problem [4]. Corrosion alone or in combination with other factors plays a vital role in structural deterioration. Corrosion results deterioration in the materials mostly metals leading to structural failures [5]. Effects of corrosion are immense on some of the tanks and a point is expected when costs associated with corrosion will be significant for The Tank Museum, but most importantly the existence of the tanks itself is at higher risk. Vehicles in The Tank Museum Bovington are kept in two distinct environments controlled and uncontrolled, while some vehicles travels intermittently between these two modes. Vehicles kept inside the museum are sheltered from coming into direct contact with the natural-environment. Nonetheless vehicles kept outside are exposed to uncontrolled environmental conditions such as rain, temperature fluctuations, variable relative humidity and winds etc. Vehicles which are demonstrated intermittently endure transitional environmental change after being kept stationary inside the museum. Environmental conditions together with the operational factors pose significant risks to the longevity, durability and reliability of these vehicles [6].

The accumulations of corrosion enhancing contaminants are expected on the tanks' surfaces which are exposed outside to uncontrolled environment. Similarly when tanks are returned after demonstration in the outdoor environment, accumulation of contaminants on their surfaces is also expected that will result in, indoor atmospheric corrosion [7, 8]. What's more some of the tanks are operating beyond their service life; this poses significant risks of tribological assisted failures in their engines and other interacting components. Tribology plays a prominent role in the degradation of the components such as piston-liner assembly in automotive engines [9, 10]. Engine components develop failures because of tribological mechanisms from time to time in the museum. However component replacement is not favoured as it compromises the cultural biography and heritage value of the tanks.

Research has undertaken two aspects of failures corrosion and wear in consideration. Corrosion degrades materials for that reason characterisation of the materials was conducted which were processed/manufactured before/during the 2nd World War. Factors which play important role in the initiation and progression of corrosion activity such as relative humidity and temperature etc are also considered. Analyses were also conducted to measure and record materials' loss due to corrosion. Real time wear evaluation of the pistons and cylinder-liners from the Tiger 1 are also conducted.

This research is the first of its kind in-terms of the fundamental study to investigate the critical effects of corrosion and wear in The Tank Museum high value military tanks.

1.2. Research Aims and Objectives

The intents of the project were to design and achieve a frame work for all the museums at a National level to adopt a sustainable approach towards the artefacts in their museum environment. Through scientific means the project will try to ensure that the cultural and the historic values are preserved without compromising the artefacts' integrity and valuing the stake holder interests.

Aims and objectives of the research are as follows.

- To understand various modes of structural aging especially through corrosion and engine wear in The Tanks Museum vehicles.
- To identify and characterise corrosion influenced structural defects.
- Analyse the tribological issues while running the vehicles extensively or intermittently.
- To develop sustainable conservation methods able to prevent or retard failure mechanisms.
- Employ conservation methods in a way where the cultural biography of the vehicles are best retained and with minimum possible intervention.
- To devise a framework which can oversee aspects of aging especially corrosion in all operational, static and those vehicles which operate after long periods of non- usage.

1.3. Research Scope

Larger military vehicles are complex objects associated with a variety of failure mechanisms. In this research the role of corrosion has been investigated thoroughly. Engine failures are also considered but are limited to real time wear evaluation.

1.4. Beneficiaries

- **Museums**

Results from this research will provide a framework for decisions regarding conservation of the vehicles.

- **Academia**

This research can be applied in new fields. Predictive models from this research can be employed through academia in other heritage industry for the longevity of their collections.

- **The General Public**

The general public visiting the museum will enjoy the cultural value preserved for an extended time.

- **Government**

Army vehicles display same modes of failures over specific time. Through an understanding of the degradation of the historic vehicles, there will be an opportunity to design-out degradation problems that may not be predictable through conventional methods.

1.5. Project Work Plan

The project plan of this research is shown in Figure: 1.1. This model provides schematic of the research methodologies deployed to conduct this research. Samples from the M10, Sherman, Centaur, BT R - 60, King Tiger and the Tiger 1 were subjected to experimental research.

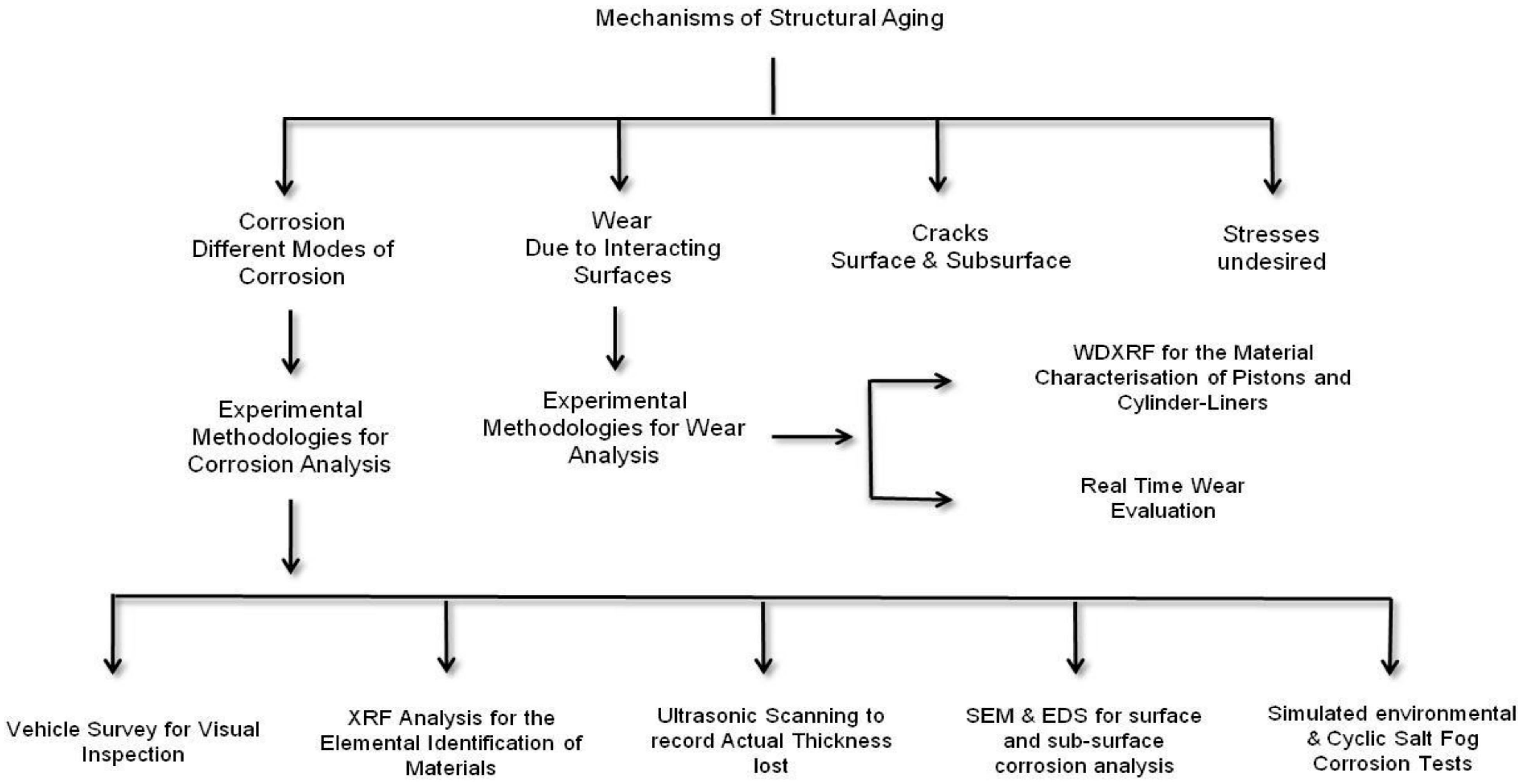
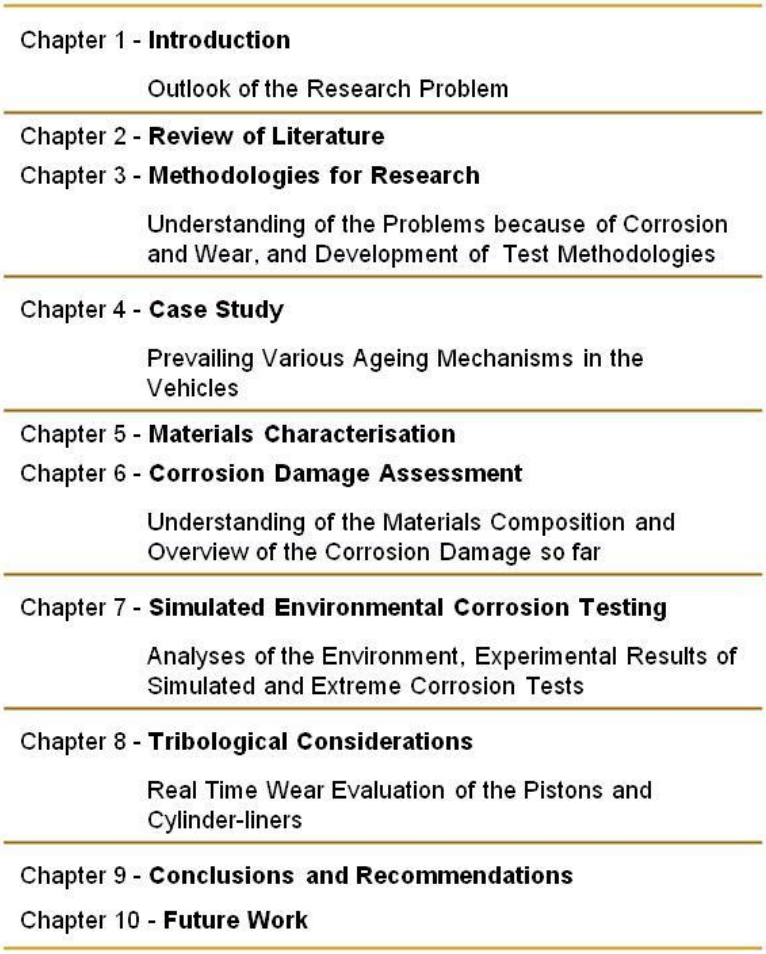


Figure: 1.1 Project Work Plan

1.6. Structure of Thesis

Structure of the thesis is provided in Table: 1.1. Chapter 1 is the introduction to the problems, which provides the project work plan and beneficiaries for this research. Chapter 2 is the review of the literature giving considerations to corrosion and wear, whilst Chapter 3 is an introduction to state-of-the-art research methodologies employed during this project. A case study of the museum vehicles was conducted to understand various prevailing aging mechanisms, and the results are provided in chapter 4. Materials were processed before/during 2nd World War and their compositions were unknown. Thus materials characterisation was conducted to obtain their composition; results are given in Chapter 5. A bench mark of the material loss through corrosion has been achieved in the selected samples of which results are provided in chapter 6. In chapter 7 analyses of the natural and the environment inside the museum is presented. Results from simulated and prohesion corrosion tests are also provided in chapter 7. Chapter 8 presents real time wear evaluation of the Tiger 1 pistons and cylinder-liners. Chapter 9 summarise results and chapter 10 presents future research work.

Table: 1.1 Structure of Thesis



Chapter 1 - **Introduction**	
	Outlook of the Research Problem
Chapter 2 - **Review of Literature**	
Chapter 3 - **Methodologies for Research**	
	Understanding of the Problems because of Corrosion and Wear, and Development of Test Methodologies
Chapter 4 - **Case Study**	
	Prevailing Various Ageing Mechanisms in the Vehicles
Chapter 5 - **Materials Characterisation**	
Chapter 6 - **Corrosion Damage Assessment**	
	Understanding of the Materials Composition and Overview of the Corrosion Damage so far
Chapter 7 - **Simulated Environmental Corrosion Testing**	
	Analyses of the Environment, Experimental Results of Simulated and Extreme Corrosion Tests
Chapter 8 - **Tribological Considerations**	
	Real Time Wear Evaluation of the Pistons and Cylinder-liners
Chapter 9 - **Conclusions and Recommendations**	
Chapter 10 - **Future Work**	

Chapter 2 Review of Literature

Literature about aging mechanism in large structures is extensive and can be divided into a numbers of areas. Among other factors corrosion and tribology related issues play a critical role. It is necessary to understand the prevailing failure mechanisms, measure and monitor the identified issues and to establish their cause.

This chapter documents research work conducted on various large and small metal structures to understand failures because of corrosion and tribology. Research outcomes have been carefully studied for the success of this research.

2.1. Corrosion

The chemical or electrochemical reaction between a material, normally a metal and its surrounding environment which result in the deterioration of the metals and its properties is known as corrosion [11]. Corrosion in metal structures result in higher maintenance costs, compromises the structural integrity, causes mechanical failures and reduces value for commodities [5]. Corrosion is one of the main contributors to risk the structural reliability of metal structures and can be initiated in various modes in a structure depending on their environment, operating conditions, nature of the material and its exposure to environment with respect to time [12]. Not only has the cost of corrosion maintenance risen drastically, there are also major concerns of the integrity, performance and safety of structures [13].

2.1.1. Corrosion Theory

The process of a metal's deterioration when in contact with the environment is called corrosion. This could be a chemical or electrochemical reaction. Most metals corrode when come into contact with water, moisture, acids, bases, salts and aggressive metal polishes. Metals also corrode when come into contact with gases such as sulphur, acid vapours, ammonia gas and chlorine etc. In a chemical reaction of corrosion metals tend to lose electrons and non-metals tend to gain electrons. The loss of electron from a metal is called oxidation and the gain of electron is called reduction. Corrosion process consists of an anodic and a cathodic reaction. During anodic reaction (oxidation) the metal is dissolved and transferred to the solution as ions M^{+2}.

$$\underset{\text{Metal}}{M} \quad >> \quad M^{+2} + 2e^{-} \qquad (1)$$

Cathodic reaction is the reduction of oxygen.

$$O_2 + 2H_2O + 4e^{-} \quad >> \quad 4OH^{-} \qquad (2)$$

The electrons released by the anodic reaction are conducted through the metal to the cathodic area where they are consumed. Metal ions (M^{+2}) conducted towards OH^{-} ions form metal hydroxide and may be deposited on the metal surface.

$$2M + O_2 + 2H_2O \quad >> \quad 2M(OH)_2 \qquad (3)$$

Metal dissolution (anodic reaction) and consumption of electron (cathodic reaction) can be located close to each other on the metal's surface or far apart. A balance must be reached between these two processes. Free electrons generated react with hydrogen ions to form atomic hydrogen, and then molecular hydrogen gas. If the acidity level is high (low pH), this hydrogen will readily become a gas. Dissolved oxygen in water reacts with the hydrogen, converting it to water and destroying the thin film which result further corrosion. High water velocities tends to wash away the thin hydrogen film exposing new surface, also solid particles in the water destroy this layer. High hydrogen ions concentration (low pH) speeds up the release of electrons, and high water temperatures increase all chemical reaction rates [11, 14-17].

A variety of natural and environmental factors strongly influences corrosion rate of metals. Corrosion can start locally from a small pit or could spread out on a surface; corroding it partially and/or entirely. Exposed surfaces are affected mostly from corrosion. Corrosion exist in different forms some are more complex than the others. Factors which influence corrosion are [11, 14-17]:

- Conductivity of electrolyte
  Sea water is good conductor compare to fresh water; hence corrosion is worse in sea water.
- Oxygen
  Generally the amount of corrosion increase in proportion to oxygen.
- Presence of Pollutants
  Sulphur, hydrogen chloride and carbon monoxide etc contribute to corrosion.
- Temperature
  Higher temperature result accelerated corrosion.
- Stress
  Metals under tensile stress in corrosive environment can suffer sudden failure.
- Presence of bio-organism
  Micro-organism can contribute to corrosion either by damaging the protection or causing a corrosive environment.
- Cathode to Anode Ratio
  The area of cathode to anode ratio is critical in corrosion.

Reduction of oxygen is the most common example of reduction accounting for around 90% of corrosion. Therefore amount of oxygen and its presence is an important factor in determining the rate of oxidation or corrosion. Most of the metals show tendency towards oxidation, some oxidise easily than the others. A tabular form of their relative strength towards oxidation is called galvanic series shown in Appendix E. Galvanic series provides knowledge of a metal to make informed decisions about its potential usefulness for a specific use in the structures [11, 14-17].

2.1.2. Corrosion of Iron

The most common example of corrosion is the rusting of Iron (Fe) shown in Figure: 2.1. This is an electrochemical process which involves oxygen, water and electrolyte. Absence of any one of them will result in no rusting of the Fe. Relative humidity above 50% provides necessary amount of water in the air to cause rusting and when relative humidity reaches above 80%, corrosion of bare steel is worse [18, 19]. A droplet of water containing dissolved oxygen on steel surface causes Fe to oxidise. At the edge of the water droplet the oxidising iron provides electrons to reduce oxygen from the air.

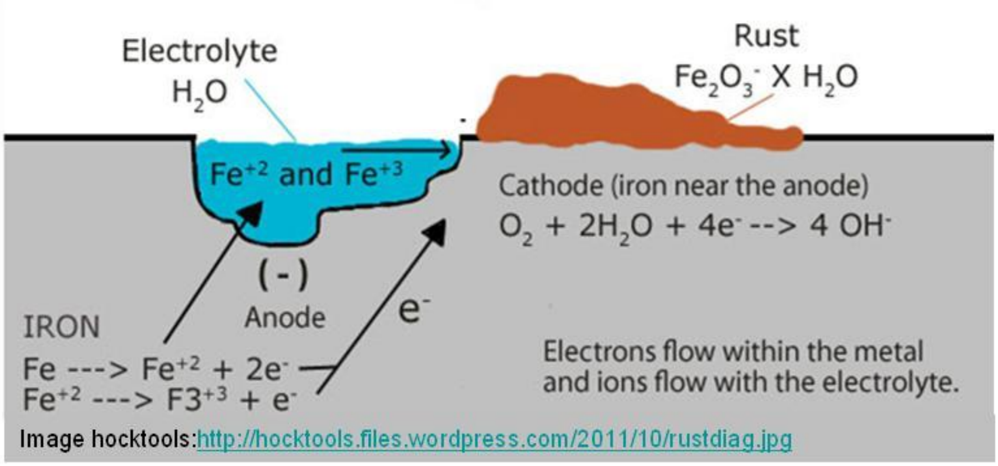


Image hocktools:http://hocktools.files.wordpress.com/2011/10/rustdiag.jpg

Figure: 2.1 Corrosion Process

$$\mathrm{Fe\ (s)} \quad >> \quad \mathrm{Fe^{2+}\ (aq) + 2e^-} \tag{4}$$

Electrons released from the metal (anode) travel through the metallic structure to the adjacent cathodic sites on the surface, where they produce hydroxyl ions (OH^-) after reaction with oxygen and water:

$$\mathrm{O_2\ (g) + 2H_2O + 4e^-} \quad >> \quad \mathrm{4OH^-} \tag{5}$$

(OH^-) react with ferrous ions from the anode to produce iron (II) hydroxide or the rust:

$$\mathrm{Fe^{2+}\ (aq) + 2OH^-\ (aq)} \quad >> \quad \mathrm{Fe\ (OH)_2\ (s)} \tag{6}$$

The resulting iron hydroxide $Fe(OH)_2$ reacts with dissolved oxygen in water thus producing hydrated iron oxide.

Iron (II) ions also react with hydrogen ions and oxygen to produce iron (III) ions:

$$\mathrm{4Fe^{2+}\ (aq) + 4H^+\ (aq) + O_2\ (aq)} \quad >> \quad \mathrm{4Fe^{3+}\ (aq) + 2H_2O} \tag{7}$$

The produced iron (III) ions react with (OH^-) ions and produce hydrated iron (III) oxides also known as iron (III) hydroxides:

$$Fe^{3+}\,(aq) + 3OH^-\,(aq) \quad >> \quad Fe(OH)_3\,(s) \qquad (8)$$

$Fe(OH)_3$ which is the loose porous rust will crystallise to $Fe_2O_3.H_2O$ (red brown rust) and is known as rusting. Since there are hydrogen and hydroxide ions any variations in pH will affect the process [11, 14-16, 18].

Since The Tank Museum is sheltered therefore neutral environmental conditions are expected inside the museum. However corrosion contaminants accumulated during service or when demonstrated on the tank surfaces will influence the corrosion process.

2.2. Reasons of Corrosion

2.2.1. Conditions

The prerequisites for corrosion to continue are, (a) anode which is the metal (b) cathode to collect electrons lost i.e. oxygen (c) Conductive path for the transfer of electrons which is normally electrolyte in the form of surface wetness and contaminants and/or (d) Conductor to carry out electron transfer to cathode. This could be in the form of metal-to-metal contact between metal joints [5, 20, 21].

2.2.2. Material Selection

Metal structures are mostly manufactured from carbon steel, which is inexpensive and readily available. In addition carbon steel can be welded, machined and designed into many shapes easily. Unfortunately oxide layer formed on carbon steel surface in the form of rust cannot create a protection on the surfaces and flakes away resulting in further oxidation. Materials are normally selected on the basis of mechanical & physical properties and costs; and corrosion resistance is given secondary consideration in the design. Other alloys can be used to substitute carbon steel to mitigate corrosion in cases where other means of corrosion control are not practical. However the use of corrosion resistant alloys does not always cure the problem and may lead to galvanic corrosion [14, 21].

2.2.3. Intrusion of Water

Water can intrude into the components and be one of the main reasons to initiate corrosion through free access, capillary action or condensation. Water access to the components and its confinement within the components makes any structure susceptible to corrosion [14, 21].

2.2.4. Environment

Moisture in the air in many cases is enough to start corrosion and it occurs when relative humidity is greater than 80% and temperature rises above 0°C. Factors such as pH factor (acidity or alkalinity), accumulation, stability and variation of the corrosive contaminants (salts, acids), temperature and the presence of biological organisms strongly influence corrosion [22].

2.3. Types of Corrosion

The primary forms of corrosion are explained briefly below. However a corroding part from a metal may endure several types of corrosion depending upon its exposure to different environments at different points. It is unlikely that a corroding component or structure will corrode from one type of corrosion.

2.3.1. Uniform Corrosion

Uniform corrosion (UC) is the direct chemical attack on the metal surface spreading out evenly across the entire surface and/or occupying a lager surface area. On a polished surface, this type of corrosion can be observed as general dulling and discolouration. Breakdown of surface protections is one main reason of uniform corrosion and if not treated could lead to general thinning of the surface and can convert in to another form of corrosion. Results from uniform corrosion are not fatal and is not classified as one of the severe forms of corrosion. Failures caused due to UC are rare and can be identified by visual inspection [11, 14, 23].

2.3.2. Concentration Cell Corrosion

This type of corrosion occurs when a metal surface is in contact with different concentration of the same solution or environments. The difference in the environment can be because of non- uniform deposits on the surface.

Basic mechanism is essentially the same as in galvanic corrosion however in this case the driving force for corrosion is the potential difference between concentration cells in a single metal exposed to different environments. There are three types of concentration cell corrosion phenomenon (1) metal ion concentration cell (2) oxygen concentration cell and (3) active-passive cells.

2.3.2.1 Metal Ion Concentration Cells

A high concentration cell will be formed on the surface area under water and a low concentration of metal ion will exist next to the crevice formed by the area under water. Cathodic action is performed by the area which is in contact with the low metal ion concentration and will be protected; the area in contact with high metal ion concentration will act as anode and corrode faster [11, 14, 24].

2.3.2.2 Oxygen Concentration Cells

The contact between metal surface and water solution containing dissolved oxygen result this type of corrosion. At points where oxygen in the air cannot dissolve uniformly in the air it creates oxygen cells at those points; creating a difference in oxygen concentration between two points. Corrosion will start to function at the area of low oxygen-concentration acting as an anode. Oxygen cell can be generated under gaskets, wood, rubber and other materials in contact with the metal surface [11, 14, 24].

2.3.2.3 Active – Passive Cells

Active-passive cell corrosion is most common in metals which resist corrosion through a tightly adhered oxide film on its surface; such as austenitic corrosion resistant steel. Corrosion contaminants such as salts in the presence of water create cells of oxygen concentration. Corrosion starts as an oxygen concentration cell if the passive film of the metal surface is broken beneath the salt deposit, the surface beneath the film will be exposed to corrosive attack. Large surface under passive film starts to act as cathode and the small area as anode (active metal). This leads to formation of pitting in metal surface [11, 14, 24].

2.3.3. Fretting Corrosion

Corrosion at the interface of two metal surface when operate under load and subjected to vibratory motion is called fretting corrosion (FC). The relative motion may vary from few nano-metres to several micro-metres in amplitude. Objects such as shrink fits, press fits, bolted joints, bearings, connecting rods and assemblies where the interface is under load suffer from this type of corrosion. During surface contact under heavy load pits, grooves and debris are formed, this result newly exposed surface and damage to the oxide film. The newly exposed surface is highly active and oxidises again, and this cycle is repeated. The subsequent oxidation of debris particles and newly exposed surface characterises fretting corrosion damage [17, 25]. During this process metal particles are formed because of adhesive wear, micro-fatigue and delamination. The subsequent oxidation of these debris particles develops brittle and friable oxide particles. This oxidised debris acts as an abrasive media between the interacting surfaces leading to further wear at higher rate. The friction co-efficient is affected by the type of debris. The visual results of fretting corrosion on steel interface are red-brown debris in addition to pits or intrusions which may lead to fatigue cracks. Discolouration of the attacked surface is also possible. Fretting wear and oxidation can be increased by reduced temperature and air humidity, and by increased pressure and slip. Material loss could be expressed through the following equation [17]:

$$W = (k_0 L^{1/2} – k_1 L) C/f + k_2 ILC \qquad (9)$$

Where L is the load, C is the number of cycles, f is the frequency, I is the slip, and k_0, k_1, k_2 are constants. Use of lubricants and restricting oxygen through gaskets, or sealing material to the component can reduce fretting corrosion [11, 14, 24].

2.3.4. Stress Corrosion Cracking

The combine effect of tensile stress and corrosive environment often result stress corrosion cracking (SCC). Stresses may be induced through welding, machining, grinding and heat treatments. Internal stresses are induced by non-uniform deformation during cold working and by unequal cooling from elevated temperatures. Deformation of a component also produce stresses such as press and shrink fits, and in rivets and bolts. Combine with corrosive environment, induced residual stresses tend to approach the yield strength resulting in stress corrosion cracking. Stress corrosion is very difficult to recognise before it has overcome the design safety factor. Magnitude of stress may vary from point-to-point in metal structure.

Corrosion products within small restrained spaces can also generate stresses. Generally most of the surface may look less affected however with inter-granular or a trans-granular morphology illustrated in Figure: 2.2; these cracks penetrate into the surface resulting in fractures. SCC is one of the severe forms of corrosion which is hard to detect and difficult to predict the failures [21, 26].

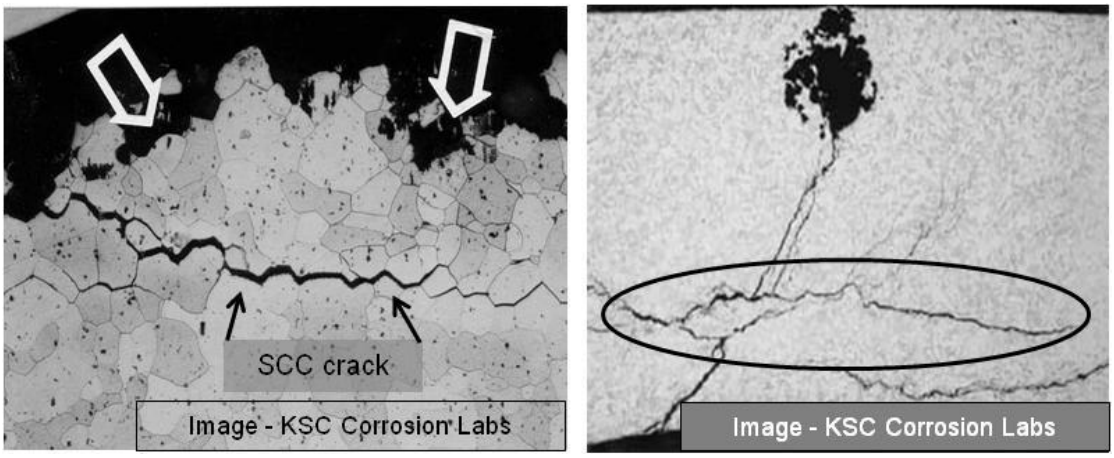


Figure: 2.2 Stress Corrosion Cracking in Aluminium Alloy, Subjected to Residual Stresses and Salts

In metals SCC cracks are normally multiple, branched, and either inter-granular or trans-granular and cleavage like. In some cases both modes of inter and trans-granular may exist simultaneously. When examining through microscopically the SCC cracks may look brittle and discoloured, dull or darkened by oxide-layers. Initiation site may be a pit caused by pitting or deposit corrosion or a defect as a result of forming or machining. SCC can be classified as “brittle” mode of failure, when material fails to manifest its usual tensile strength and ductility. Microscopic strains acting dynamically on the crack tip may also influence crack growth [17, 27]. In a high-strength material, stresses are usually imposed and the growth of SCC can result in the rupture when the fracture toughness is exceeded. Whereas in low-strength alloys stresses are often residual in SCC and result in leakage or gradual plastic tearing [17, 21, 26].

Mechanisms which play significant role in SCC can be categorised in three groups: (1) Environmental an electrochemical factors, (2) Metallurgical factors and (3) Mechanical stress and strain. These factors are multi-disciplinary mainly electro-chemistry/corrosion, physical metallurgy and facture mechanics, and varies from one material- environment system to another significantly [17, 21, 26].

2.3.5. Inter-granular Corrosion

Inter-granular corrosion (IGC) is a localised corrosion attack on the metals or alloys grain boundaries or adjacent to its boundaries. IGC is the result of the segregation of a specific element or the formation of a compound in boundary, this creates zone/zones of poor corrosion resistance. Grain boundary becomes anodic in relation to the remaining surface which becomes cathodic. Localised corrosion in the grain boundary is caused by the anodic dissolution of (i) regions depleted of alloying agents (ii) second phase precipitation (iii) or regions with segregated alloying or impurity elements. Cathodic areas start to function on the exposed surface causing dissolution of the anodic area. Corrosion rate is dependent on the continuing corrosion mechanisms, ratio between anode and cathode, distribution of electrochemically active phases and the distribution of impurity elements [11, 28].

2.3.5.1 Exfoliation Corrosion

Exfoliation is a form of inter-granular corrosion. Corrosion products among the grains boundaries occupy larger surface area and forces surface grains of the metal to lift up also know as leafing or lifting effect in its extreme form. This is a direct result of the expanding corrosive products among the grains of the metals. In this particular form of IGC the expensive force of insoluble corrosion products tends to force the grains apart that severely affect mechanical properties of the materials [11, 14, 28, 29].

2.3.6. Galvanic Corrosion

Galvanic or bimetallic corrosion is an electrochemical reaction between two or more dissimilar metals in the presence of electron conductive path in which one metal corrodes preferentially than the other. The common factors are dissimilar metals, electrical interaction, and a conductive electrolyte. When a conductive path is established flow of electrons takes place from active to noble metal forming a coupling of anode and cathode. One typical example is given in Figure: 2.3 where washer is anodic compared to the stainless screw and rest of the surface. Washer is corroding fast because of the high anode-to-cathode ratio.

Figure: 2.3 Galvanic Corrosion - Stainless Screw v Cadmium Plated Steel Washer

If the conductive path between anode and cathode has been removed the corrosion may not occur. Galvanic corrosion increases other forms of corrosion such as pitting and crevice. It can be recognised by the formation of corrosion deposits at the joint of two dissimilar metals. Galvanic corrosion can also start on a macroscopic level between components of different materials but may also occur microscopically at the pre-existing metallurgical features in steel or where metal ions of a nobler element are present in solution [29-31].

In cases where the noble (cathodic) metal is very efficient cathode, even equal areas of the two materials may cause relatively fast corrosion. Where the area of the noble metal is larger than the less noble (anodic) metal, it may also result in accelerated corrosion due to galvanic coupling. In addition to cathodic efficiency and the area ratio, the conductivity of electrolyte and the geometry of the system play a vital role. The corrosion attack on the anodic area is reduced with increasing distance from the contact interface between the two materials, resistivity of the electrolyte, and the polarisation properties of the metals [17, 19].

2.3.7. Pitting Corrosion

Alloys and metals, such as aluminium, stainless steel, titanium and zirconium remain passive in many corrosive environments. However under certain environments, the passive film on their surfaces can be affected through localised corrosion points. This process of localised is known as pitting or pitting corrosion. Pitting is a localised form of corrosion confined to a very small point. It causes holes or cavities through pits and then penetrates inwards in the metal’s structure illustrated in Figure: 2.4. In some cases most of the surface will remain protected but at a smaller point where the protection of surface has failed a pit is formed. This is happen many times and several pits will be formed. Corrosion products normally cover the pits showing no significant material loss on the surface.

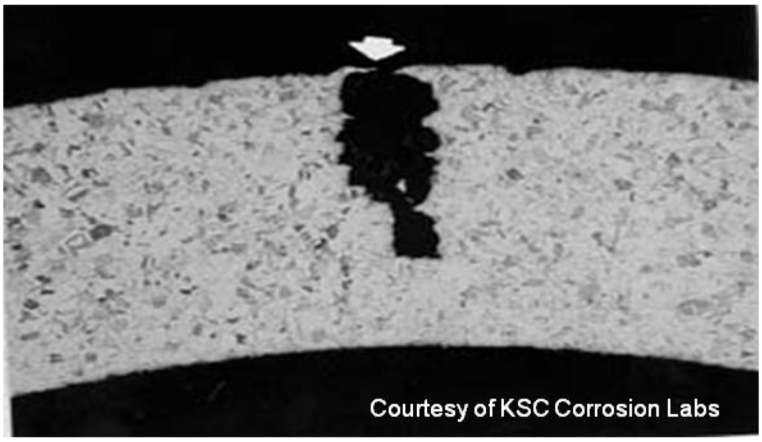

Courtesy of KSC Corrosion Labs

Figure: 2.4 Formation of pit in steel

Main reasons of pitting are (a) localised damage to, poor application of protective coatings (b) the presence of non-uniformities in the metal structure and (c) localised chemical or mechanical damage to the protective oxide film, acidity, low dissolved oxygen concentration and high concentration of chlorides. Pitting is one of the severe forms of corrosion which is difficult to detect and hard to predict the results [32-35].

Materials such as copper, zinc and tin which operate in less pronounce passive states, pitting may initiate in the pores in the existing corrosion layer on the surfaces. Aluminium and stainless steel which are typically passive; pitting may initiate because of the adsorption of halide ions that penetrate the passive film at weak points. The weak points may be due to the irregularities in the oxide film because of grain boundaries or inclusion in the metals. Halide ion adsorption causes significant increase of the ion conductivity in the oxide film so that metal ions can migrate through the oxide film. That result localised dissolution and as a result intrusions are formed in the metal surface [17, 35, 36]. Another theory is that the initial adsorption of aggressive anions at the oxide surface increases catalytically the transfer of metal cat-ions from the oxide to the electrolyte and thus results in local thinning of the oxide film. In another possibility the attack starts at fissures in the passive layer [37].

Generally, the anodic dissolution occurs inside the pit mainly at the bottom, whereas the cathodic process is outside the pit at the inclusions and/or at the surface area of the metal. Hydrolysis in the pit leads to an acidic, aggressive, pit solution which may allow an additional cathodic reaction known as reduction of hydrogen ions. Metal cat-ions from the dissolution reaction migrate and diffuse towards the mouth of the pit where they react with OH^- ions from the cathodic reaction, forming metal hydro-oxide deposits that may cover the pit. These corrosion products which cover the pits further facilitate corrosion by preventing the exchange of electrolyte making it very acidic and aggressive [17, 35, 37].

2.3.8. Corrosion Fatigue

The combine effect of alternating stress and corrosion often result corrosion fatigue. It may also be defined as fatigue simulated and accelerated by corrosion. In a component in corrosive environment fatigue failures can occur at lower loads and in short time. Characteristics beach marks on the smooth part show the form and position of the crack front at different stages. Normally corrosion fatigue gives beach marks, however sometimes these beach marks may be less visible due to corrosion products. Fatigue failures are brittle and mostly trans-granular and the damage caused is often more than the damage caused by stresses or corrosion alone. The main site for crack initiation is generally the material surface, as the grain may deform plastically and crack more easily than other grains, because not only they are exposed to the environment which play important role in fatigue damage, but they are also not constrained i.e. surrounded by other grains [17, 38].

Corrosion fatigue normally initiates at surface defects, stress concentrations near notches, corners and holes. Crack initiate from the free surface, normally at the largest grain along a shear slip plane at 45° to the loading axis. Plasticity induced in the grain drives the crack until a dissolution build-up occurs as the crack tip reaches the grain boundary between grains 1 and 2. When crack tip approaches the first grain boundary, growth rate of the crack decreases. This reveals two possible outcomes (a) if the stress is below the fatigue limit, crack decelerates and may arrest or when (b) the stress level is above the fatigue limit, the crack grows into the next grain and continues to propagate through the structure. Crack growth can be divided into four stages: 1) Initiation, 2) Crack growth stage I with crack growth direction about 45º relative to tensile stress direction, 3) Crack growth stage II, 4) Fast fracture. Fatigue process breaks the protection due to which corrosion accelerates [17, 38-41].

2.3.9. Microbial Corrosion

Microbial corrosion is also known as microbiologically influenced corrosion (MIC). The presence and activities of microbes on the metal surface leads to this type of corrosion. Microorganisms tend to colonise and proliferate on metals surfaces. They produce different acids both organic and mineral and form bio-films, which as a result create an environment which has different pH, dissolved oxygen, organic and in-organic species. Bio-film on the solid surfaces creates non-uniform surface conditions. This result localised corrosion normally in the form of a pitting. These colonies created by microbes result a corrosive environment. Microbial corrosion is a great problem in stagnant water systems such as fire protection and storage tanks etc [42-44].

2.3.10. Erosion Corrosion

Erosion corrosion is the result of relative motion of high velocity surface-fluids in metal structure. This can be the result of fast fluid flow in a stationary object i.e. oil flow through a pipe or rapid motion of an object through stationary fluid i.e. ship’s propeller motion in ocean. Erosion corrosion can be caused by defects which restrict the smooth flow of fluids. Any roughness in the surface leads to localised turbulence and high flow velocities. A combination of erosion and corrosion can initiate severe pitting and eventually to leaks.

Soft alloys such as copper, aluminium and lead alloys mostly suffer from erosion corrosion. Alloys which exhibit formation of surface film in an environment show limiting velocity above which corrosion rapidly progresses. Flow induced corrosion problems are generally termed as erosion-corrosion, around flow accelerated dissolution and impingement attack. Fluids can be aqueous/gaseous and/or single/multiple phases [45].

2.3.10.1 Cavitation

Cavitation is sometime referred as the special case of erosion corrosion. This is the result of formation and collapse of vapour bubbles in a liquid near a metal surface. The sudden and immediate implosion leads to the formation of cavities. This results in significant wear and tear in of the component. Vaporisation at low pressure, air ingestion, turbulence in the flow and internal re-circulation of the fluid leads to cavitation [45].

2.3.11. Crevice Corrosion

This is a localised form of corrosion which is the result of micro-environments created by stagnant solution in crevices which are adequately wide for liquid to penetrate and narrow such that the liquid remains stagnant. Stagnant solutions under gaskets, washer, insulation materials and fasteners etc tends to produce crevice or contact corrosion in the regions of contact between metals or non-metals. Similar mode of corrosion develops under deposits i.e. corrosion products, leaves, dirt and marine organisms, and therefore known as deposit corrosion. Change in the chemistry such as (a) Depletion of inhibitor (b) Depletion of oxygen (c) Shift to acidic conditions and (d) Build-up of aggressive ion species (e.g. Chloride) in the crevices characterises crevice corrosion [18, 42-44].

Materials such as low alloy steel, stainless steel and aluminium when exposed to aggressive species i.e. chlorides endure breakdown in their surface oxide-layer. Stainless steel can be attacked by deposit corrosion in stagnant or slowly flowing seawater. Studies indicate that a critical velocity of 2 m/sec can cause deposit corrosion in conventional steel however it may result at higher velocities also. At the start metal corrodes outside and inside the crevice at the same rate. When the metal is passive, oxygen is consumed slowly within the crevice. When oxygen is consumed completely inside the crevice OH^- can no longer be produced and therefore the dissolution of metal inside the crevice starts, which is supported by the oxygen reduction outside the crevice. As the environment becomes more aggressive, the surface oxide layer is attacked, resulting in the transformation of the crevice surface to active state and the corrosion rate increases [17, 46].

2.3.12. Filiform Corrosion

Filiform corrosion occurs when moisture permeates through small cracks or even microscopic defects in the coatings. Filiform corrosion is common in coatings which exhibit poor water vapour transmission. Lacquers and quick dry paints are commonly affected by such corrosion [42-44].

2.4. Wear

Wear is another main contributor to the aging/damage of mechanical structures and can be defined as the progressive material loss from the interacting surfaces in relative motion. Wear occurs in mechanical bodies in two forms mechanical and chemical. Mechanical form generally depends on the nature of shapes/design of the interacting surfaces, environmental conditions in which they operate, and the applied forms of loads. Chemical wear involves the chemical attack in the form of corrosion and the material removal from the surfaces due to chemical action.

Wear between two surfaces subject to relative motion is generally termed as sliding and/or adhesive wear. Sliding wear can occur in lubricated and dry surface contacts. Sliding contact can be lubricated when lubrication is present between the surfaces or dry when the contact takes place without any lubricant. Several factors play a vital role in sliding wear, these include distance of the sliding, its velocity which influences the rate of frictional energy dissipation and the temperature of the interface, contact pressure between the surfaces and duration of the test. Wear exists in the form of abrasive, adhesive, surface fatigue and fretting [47-49].

2.4.1. Abrasive Wear

Abrasive wear is the most common form of wear mechanism and is the same as of machining, grinding, polishing or lapping used for shaping materials. It develops when two surfaces are in direct contact with each other. Harder material abrades the softer material subjected to loads, asperities on the harder material penetrates into the softer material causing plastic deformations and formation of scratches, wear grooves and material removal from the surfaces [49]. Abrasive wear take two forms (a) two body wear in which harder surface remove material from the softer surface while in (b) three body there are hard particles present between the contact areas which work as an abrasive media between the surfaces. If the particle between the surface is harder than the counter-face than it will indent the surface and cause plastic flow, where particle is less than 1.2X the hardness of the surface it will itself be blunted and not indent the counter-face [48].

2.4.2. Adhesive Wear

It is the result of localised welding between the sliding surfaces of contact. Adhesive wear can be determined by the formation of micro-welds between the surfaces subjected to friction. Furthermore it can be characterised by high wear rate and unstable coefficient of friction. If the formed micro-welds/junctions are weak shear occurs at the interface of contacting surfaces and wear is negligible. But when junctions are strong, the softer material is subjected to shearing which develops debris formation and material transfer from softer to harder material surface. Surfaces are held apart from each other by lubrication, which reduce the tendency of adhesive wear to take place. Adhesive wear because of breakdown in the lubrication is termed as scuffing [48, 50].

2.5. Tribo-corrosion

Tribo-corrosion is the result of surface degradation through mechanical wear and chemical/electrochemical interactions working together. Many mechanical and electrochemical interactions involved in tribo-corrosion are time dependent and non-linear. Tribo-corrosion includes corrosion, erosion corrosion, abrasion, adhesion, fretting and fatigue wear mechanisms. An example of tribo-corrosion is the accelerated anodic dissolution of stainless steel. Protection of stainless-steel relies on thick passive film (1-10 nm) from aggressive corrosive environment. This film forms instantaneously by reaction with the environment but abrasion can result in the localised rupture or complete failure of this film which leads to exposure of the substrate to corrosive environment. Rapid corrosion may occur on the exposed surface areas unless repassivation is not reformed [51, 52]. Some mechanisms affecting tribo-corrosion are discussed below.

2.5.1. Friction

The force opposing relative motion between two objects in contact is referred to friction. Friction co-efficient is the ratio of the force resisting tangential motion between two bodies to the normal force pressing those bodies together. In two bodies sliding contact the friction force is tangential to the interface.

Friction can be represented by the following equations

$$F = W \times \mu \qquad (10)$$

W denotes applied load and μ co-efficient of friction. Force of friction is proportional of the applied load but is independent of the apparent contact area and sliding velocity [53]. Co-efficient of friction exists in two forms (a) when surfaces are stationary relative to each other in this case it is known as static friction and (b) when surface are in relative motion in this case it is called kinetic friction.

For contact separated by film of lubricant the co-efficient of friction μ, is very low (< 0.1) and can be as low as 0.1, even when the lubricant film is only few nanometres thick. For un-lubricated/dry contact, μ is normally ~ 1.0. Mechanisms which influence frictions are quite complex and its value can be derived experimentally.

Frictional force arises from adhesive forces and deformation forces induced by the abrasive ploughing nature of the harder asperities interacting with the softer ones of the counter surface. Ploughing is developed when the asperities of the harder material embed across the surface of the softer material, generating ploughing wear scars.

$$F = F_{\text{Adhesion}} + F_{\text{Abrasion}} \qquad (11)$$

The adhesive force is related to the asperity contact which makes up the real area of contact between surfaces and the junctions between them. The shear strength of these junctions affects the level of friction. Adhesion is also a result of intermolecular interactions that exist at the asperity contacts.

During the contact there is also a likelihood of chemical reactions, for example oxidation. Oxidation can result in coherent films and their composition can affect rate of friction. The shear strength of the asperities is weakened due the presence of oxide layers and absorbed films on the metal surfaces. Therefore lower adhesion resist contact motion and low friction occurs. However when the oxide layer is partially removed higher adhesion occurs on the newly exposed surfaces especially in soft ductile materials [51, 54].

2.5.2. Environmental Factors

The influences of environmental factors on tribo-corrosion are very system dependent. Environmental conditions such as pH, dissolved oxygen, salinity, temperatures and bio-fouling determine the rate and various types of tribo-corrosion. They all can be time and system dependent. Bio-fouling is often ignored but it can have detrimental effects. Among these factors, temperature of the surface affects the rate of wear-corrosion. Many contacts between surfaces in relative motions are caused in an increased heating of the contact regions due to friction. Temperature affects pH, solubility of gases (i.e. oxygen, carbon dioxide), ionic species and diffusion rate of the reactant species. Temperature also influences kinetics of oxidation on the oxide-metal interface. Higher hydrogen diffusion occurs at elevated temperatures, which result hydrogen embrittlement [51].

2.5.3. Tribo-films

Corrosion resistant materials in most cases depend on a thin surface film, thus to provide a barrier between relatively active material and corrosive environment to retard corrosion. The morphology and mechanical properties of these tribo-films depend upon the properties of the materials in contact. These layers are not only consists of the materials removed from the surfaces in contact, but contain corrosion products; wear debris and remains of the passive film. During sliding wear the composition and thickness of these films determine tribo-corrosion. Thickness of such film is mainly dependent on time, temperature, interfacial potential and the concentration of environment. Formation of these films in tens to hundreds of angstrom can occur in less than one second. Surfaces become passive in the presence of these films, but where the induction of solid particles and/or cavitation has taken place in fluid machinery flows this film can be removed by mechanical wear or bubble collapse/shockwave/ impingement processes. Where the film is removed this allows the transfer of charge at the interface without any restriction. Compositional changes and the presence of stresses affect the stability of the film. In addition the density and hardness of the film on the surface will affect the micro-contact mechanics of the tribological processes [51, 55, 56].

2.6. Cracks

Materials subjected to fluctuating loading and unloading cause fatigue. Loads above a certain threshold will result in minute cracks in the materials and their continuation to a critical size could lead to a sudden fracture in the structures. In such cases number of cracks can be formed depending on the grain boundaries, defects in the microstructures and any other non-metallic inclusions in the materials. The most common forms are fatigue cracks, SSC cracks and hydrogen induced cracking [57, 58].

2.7. Stresses

In a deformable body the average force on a unit area is called stress in mechanics. External forces applied on the surface result internal forces among the particles of the deformable body. These internal forces are distributed continuously within the volume of the material body. The volume of these forces could cause deformation in the shape of the structure if exceed the material strength [59]. Machining, uneven cooling, heat treatment and welding induce type of stress known as residual stress. This mode of stress remain in the body even after the original cause is removed which could lead to premature failures [60, 61]. Other forms of stresses such as tensile, compressive and shear stresses can also result deformation in the shape of the bodies.

Chapter 3 **Methodologies for Research**

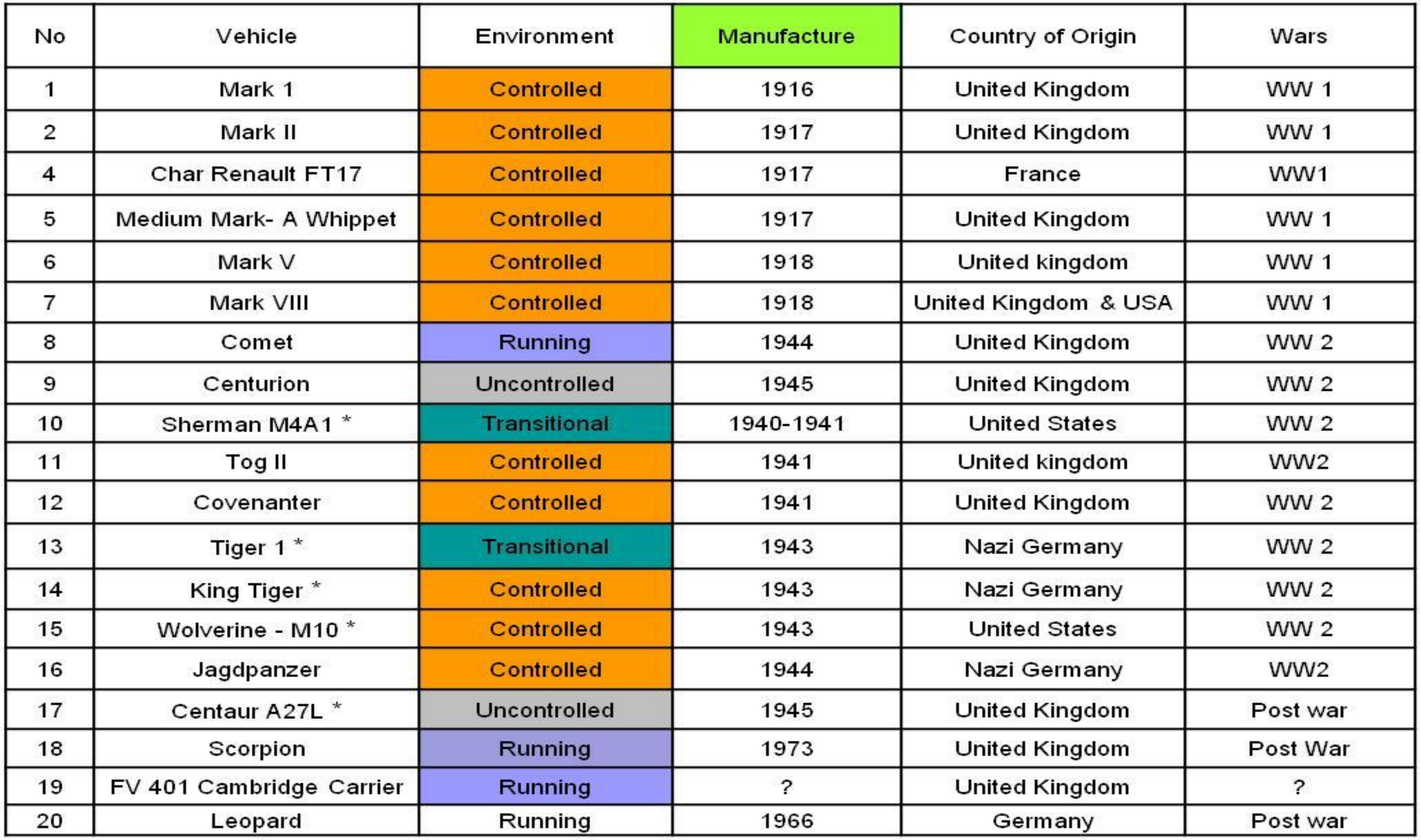
This chapter documents research methods, deployed to conduct this research work. In the first part a case study of 20 vehicles is presented shown in Table: 3.1. In the second part samples were collected from 6 military tanks for experimental research shown in Table: 3.2. Two aspects of aging corrosion and wear are given consideration.

- Corrosion
    - Case Study
    - Optical Microscopy
    - X-ray fluorescence (XRF)
    - Ultrasonic Scanning (US)
    - Scanning Electron Microscopy (SEM)
    - Energy Dispersive X-ray Spectroscopy (EDS)
    - White light Interferometry
    - Simulated Environmental Corrosion Testing (SET)
    - Prohesion (ASTM G 85 A5) Corrosion Test
    - Corrosion Quantification and Image Analysis
- Wear
    - Tiger 1 Engine and King Tiger's Gear Box Analysis
    - Optical Microscopy
    - Wave Length Dispersive X-ray Fluorescence (WDXRF)
    - White Light Interferometry

3.1. Case Study of The Tank Museum Vehicles

Corrosion can be classified as one of the major contributor to structural aging of the military tanks. For this reason twenty vehicles were surveyed for signs of corrosion and other associated risks shown in Table: 3.1. The case study revealed that several types of corrosion were prevalent and some vehicles displaying severe corrosion problems in their structures.

Table: 3.1 Vehicles Survey for signs of Corrosion and other Aging Mechanisms



No	Vehicle	Environment	Manufacture	Country of Origin	Wars
1	Mark 1	Controlled	1916	United Kingdom	WW 1
2	Mark II	Controlled	1917	United Kingdom	WW 1
4	Char Renault FT17	Controlled	1917	France	WW1
5	Medium Mark- A Whippet	Controlled	1917	United Kingdom	WW 1
6	Mark V	Controlled	1918	United kingdom	WW 1
7	Mark VIII	Controlled	1918	United Kingdom & USA	WW 1
8	Comet	Running	1944	United Kingdom	WW 2
9	Centurion	Uncontrolled	1945	United Kingdom	WW 2
10	Sherman M4A1 *	Transitional	1940-1941	United States	WW 2
11	Tog II	Controlled	1941	United kingdom	WW2
12	Covenanter	Controlled	1941	United Kingdom	WW 2
13	Tiger 1 *	Transitional	1943	Nazi Germany	WW 2
14	King Tiger *	Controlled	1943	Nazi Germany	WW 2
15	Wolverine - M10 *	Controlled	1943	United States	WW 2
16	Jagdpanzer	Controlled	1944	Nazi Germany	WW2
17	Centaur A27L *	Uncontrolled	1945	United Kingdom	Post war
18	Scorpion	Running	1973	United Kingdom	Post War
19	FV 401 Cambridge Carrier	Running	?	United Kingdom	?
20	Leopard	Running	1966	Germany	Post war

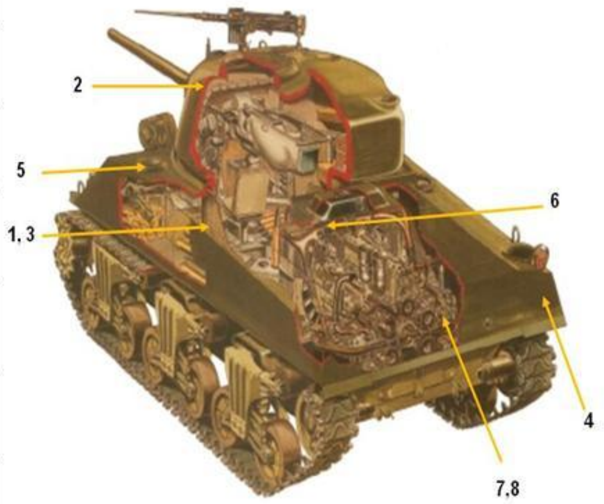
***On** 5 tanks from this table experimental research was also conducted.

3.2. Sample Selection for Corrosion and Wear Evaluation

Sample collection from the tanks was a big challenge. Non-destructive testing and evaluation (NDT/E) research methods were given priority in conducting experimental research work. However NDT/E options were limited for extensive analyses and therefore the use of some destructive research methods were inevitable. Every effort was made to follow The Tank Museum guidelines when handling samples.

The Tank Museum Bovington has almost 300 military tanks; accordingly for a comparative research it was important to collect samples from representative vehicles. Samples were collected from six military tanks shown in Table: 3.2. The approximate location of the samples is also indicated in Appendix B. Since the environment plays a vital role in corrosion, therefore environmental exposure of the vehicles' is taken in to account. Samples preparation has been explained in the relevant sections. A brief introduction of each tank is given below. Moreover Appendix B shows a brief introduction of the tank structure.

Table: 3.2 List of Samples Collected for Material characterisation, Ultrasonic Corrosion Mapping, Corrosion Assessment and Wear Analysis

S. No	Tank	Environment	Manufacture	Country of Origin	Era	Sample Description\ Location	Indicative Sample Locations
1	Wolverine - M10	Controlled	1942-43	US	WWII	Part from Inside Armour	
2	Wolverine - M10	Controlled	1942-43	US	WWII	Part from the Turret	
3	Sherman - M4A1	Transitional	1941-42	US	WWII	Part from the Armour	
4	Centaur – A27L	Uncontrolled	1942-45	UK	WWII	Part from the Armoured Skirt near Sprocket	
5	BT – R 60	Uncontrolled	1960-76	USSR	1st Gulf War	Inspection Compartment Cover	
6	King Tiger	Controlled	1943-45	Nazi Germany	WWII	Part of Bulkhead	
7	Tiger 1	Transitional	1941-45	Nazi Germany	WWII	2 Pistons – 1 Original & 1 Replacement	
8	Tiger 1	Transitional	1941-45	Nazi Germany	WWII	2 Liners – 1 Original & 1 Replacement	Image - http://science.howstuffworks.com/m-4-sherman-medium-tank.htm (©2007 Publications International, Ltd.

3.2.1. M10 Tank Destroyer (Wolverine)

M10 went in to production in the USA by Grand Blanc Arsenal/General Motors around 1942-43. It was designed to disrupt armoured attack and was one of the main armaments of the US army's tank destroyer battalions. M10 was later used by the British Army during WW II who named it to Wolverine [62, 63]. It is stationed inside the museum in a controlled environment permanently with no exposure to any harsh weather such as rain and changing temperatures etc. The overall corrosion damage to the vehicle can be rated at medium-low risk.

3.2.2. Sherman Main Battle Tank (M4A1)

Sherman M4A1 was designed by Lima Locomotives in 1941-1942 in the USA and was used by British army during WW II [62, 63]. It is one of the oldest examples in the museum collections of Sherman to survive. This Sherman was provided by Royal Armoured Corps Gunnery School, Lulworth Camp United Kingdom in 1955 to the museum. This tank operated occasionally and is now inside the museum in a controlled environment. Intermittent change in environments along with other operational risks could lead to significant failures. Corrosion in general can be classified as medium-low threat to this vehicle.

3.2.3. Centaur Main Battle Tank (A27L)

Centaur was manufactured by Leyland Motors Ltd in the United Kingdom during 1942-1945 and served in WW II [62, 63]. This tank was given to the museum by the Ministry of Defence (MOD) in 1994. Its current location is outside the museum exposed to changing environments, temperature fluctuations and variable humidity. This vehicle is severely corroded and the deterioration of the structure is in high state. The risk of corrosion to structure of this tank can be categorised as high.

3.2.4. Brone - Transporter Armoured Transport (BT - R 60)

Brone-transporter Armoured Transport 60 (BT - R 60) was manufactured by Gorkovsky Avtomobilny Zavod in the former USSR during 1960-1963. It is one of the most widely used personnel carriers. It remained in production till 1976 [63]. It was captured during the First Gulf War. This vehicle is outside the museum and is exposed to uncontrolled environment. It is severely corroding too.

3.2.5. King Tiger Main Battle Tank

Sd Kfz 182 Panzerkampfwagen VI Ausf B was the official German name for King Tiger and is also known as Tiger II. King Tiger was designed/ Manufactured by Henschel & Son during 1943-1945 in the Nazi Germany. Its first place of action was Normandy in July 1944. The King Tiger was one of the most powerful tanks to be deployed during the 2nd World War; together with the Panther it formed the lead of the German offensive in Ardennes [63, 64]. The Gear Box of the King Tiger was disassembled after almost fifty years for corrosion investigation.

3.2.6. Tiger 1

It was a formidable German heavy tank designed by Henschel & Son in the Nazi Germany. Panzerkampfwagen Tiger Ausf. E was the official German designation for this tank but is commonly known as Tiger 1. The Tiger 1 engine is a Maybach HL 230 P 45. Tiger 1 participated in the 2nd World War against the former USSR and Allied Forces. It was captured in Tunisia and was sent to the School of Tank Technology for evaluation. The Tiger 1 is now kept in The Tank Museum and is the last operating Tiger in the World [2] [63]. Original and replacement pistons and cylinder liners were collected to assess real-time wear in the piston-liner assembly.

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[2] http://www.tankmuseum.org/ixbin/indexplus?_IXSS_=_IXMENU_%3d%26ALL%3dm10%26_IXACTION_%3dsummary%26%252asform%3d%252fsearch_form%252fbovtm_combined%26TYPE%3darticle%26_IXFPFX_%3dtemplates%252fsummary%252f&_IXFIRST_=3&_IXSPFX_=templates/full/tvod/t&_IXMAXHITS_=1&submit-button=summary&_IXSESSION_=&_IXMENU_=Vehicles (Access date 06/06/2013)

3.3. Experimental Techniques and Samples’ Preparation

3.3.1. Optical Microscopy

Optical Microscopy was conducted using Olympus BX 60 shown in Figure: 3.1. Microscopy method was deployed for the surface analysis of corroded samples and to analyse wear in the pistons and cylinder-liners. Optical microscope uses visible light and a combination of lenses, which can be used for the extensive surface analysis of samples. Microscope is fitted with a digital camera to capture micrographs. The micrographs can be transferred to the computer and can be displayed and effective surface measurements can be obtained through the software.

http://www.caeonline.com/listing/product/125750/olympus-bx60m

Figure: 3.1 Olympus BX 60 Microscope

3.3.2. X-ray Fluorescence

3.3.2.1 Samples’ Preparation

X-ray fluorescence (XRF) was conducted on samples from the M10, Sherman and Centaur. This method was conducted on the same prepared samples discussed in ultrasonic scanning. These samples were corroded on one side; other side however had paint protection. Each sample was scanned for at least 30 seconds at three points on corroded (A, B, C), sand-blasted (G, E, F) and once on the cross sectioned (D) surfaces as shown in Figure: 3.2.

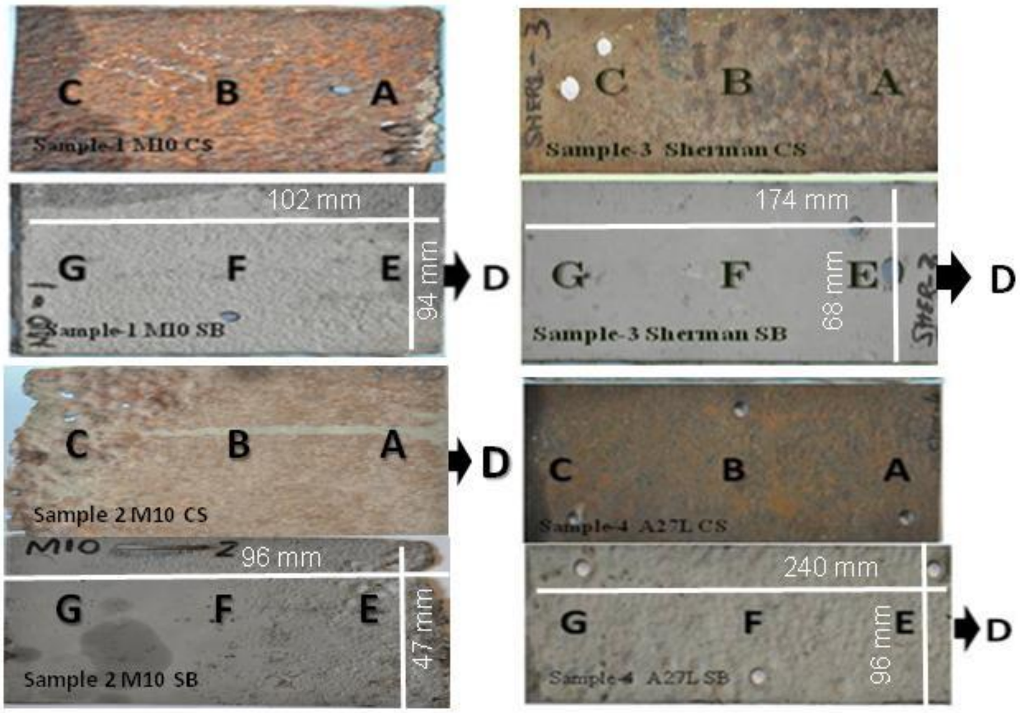

Figure: 3.2 Points Locations for XRF Analysis on the Samples A, B, C are on the Corroded Surface, G, F, E are on the Sandblasted Surface and D is at the Cross Section.

3.3.2.2 XRF Process

Bruker S1 Turbo silicon drift detector (SSD) shown in Figure: 3.3 was utilised. The S1 Turbo^{SD} can be configured with calibrations that are optimised for a variety of sample materials including a wide range of alloys and various mining and environmental soil samples. S1 technical specifications include a) Detector 10 mm^2 X-Flash SDD, peltier cooled, b) resolution 145 eV at 100,000 cps c) X-ray Tube; Ag target with maximum voltage of 40kV and d) five position motorised filtre changer[3]. XRF analysis is a non-destructive method, used for the material characterisation. During this process the samples are bombarded by an intense X-ray beam leading to the emission of fluorescent x-rays. These emitted fluorescent x-rays can then be detected by a wavelength dispersive or energy dispersive detector, which identify elements of materials by measuring the energies of emitted x-rays and counting number of the rays of each energy spectrum. SDD can be used to analyse low alloy steel, stainless steel, tungsten alloys and light elements such as magnesium, aluminium and silicon [65, 66].

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[3] http://www.bruker.com/products/x-ray-diffraction-and-elemental-analysis/handheld-xrf/s1-turbo/technical-details.html (Access date 06/09/2013)

Figure: 3.3 Bruker S1 Turbo XRF Analyser

3.3.3. Ultrasonic Scanning for Corrosion Mapping

3.3.3.1 Sample Preparation

Samples from the M10, Sherman and Centaur shown in Figure: 3.2 were sectioned to the required specifications. Sample conditioning was performed to remove previously applied coating through sandblasting. Figure: 3.4 show coating removal of the BT – R 60 sample. Sandblasting was performed on coated side only using Guy-Son International Super - 4 with a tungsten nozzle of 6.40 mm bore and at a pressure of 120 psi using fine industrial grit to achieve viability for ultrasonic scanning. During ultrasonic scan, the test object surface must be able to transmit ultrasound waves while employing this method. The requisite dimensions of the sample for our research were to have at least minimum of 2-3 mm remaining thickness, with considerable widths and lengths.

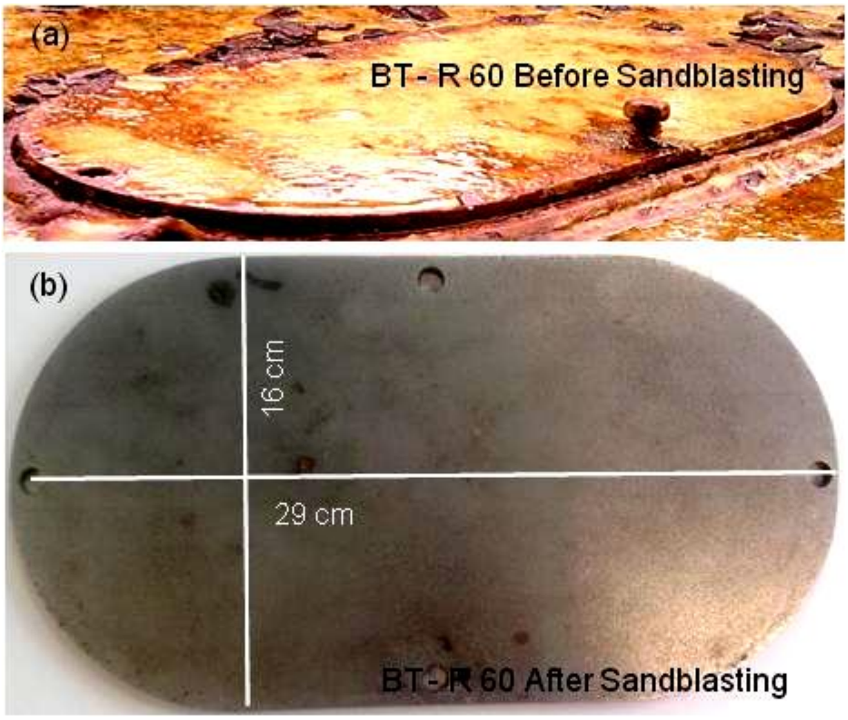

Figure: 3.4 BT - R 60 Tank Sample

3.3.3.2 Experimental Set-up

Ultrasonic scanning was performed on three samples 1, 3 and 4 from the M10, Sherman and Centaur shown in Figure: 3.2, King Tiger and BT – R 60 using pulse echo method followed by phased array scanning. This method uses pulse-waves with a frequency range from 0.1 to 15 MHz to measure thickness loss, cracks and other dimensional anomalies in the test objects. Ultrasonic systems mainly consist of a transducer, pulser, receiver, transmitter and display equipment. The transducer works both as a receiver and transmitter for a pulse echo system and is separated from the test object through a coupling medium such as water or oil during operation. Transducer produces sound waves which propagates through the medium and reflects back to display device after striking a discontinuity. The reflected wave signal is transformed in to an electrical signal by a transducer and the results can then be seen on the display screen [67, 68].

Corrosion mapping was conducted using TD Focus-Scan, a multifunction ultrasonic inspection system shown in Figure: 3.5. The system is designed to map corrosion using multichannel Phased Array, Time of Flight Diffraction (ToFD) and Pulse Echo techniques. The corrosion mapping kit included the following components[4].

1. TD focus scan
2. Video camera with infrared filtre
3. Infrared LED
4. Twin crystal and phased array probes

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[4] http://www.agr.com (accessed: 04.11.2010)

5. Camera tripod
6. Celesco single axis encoder for phased array probe

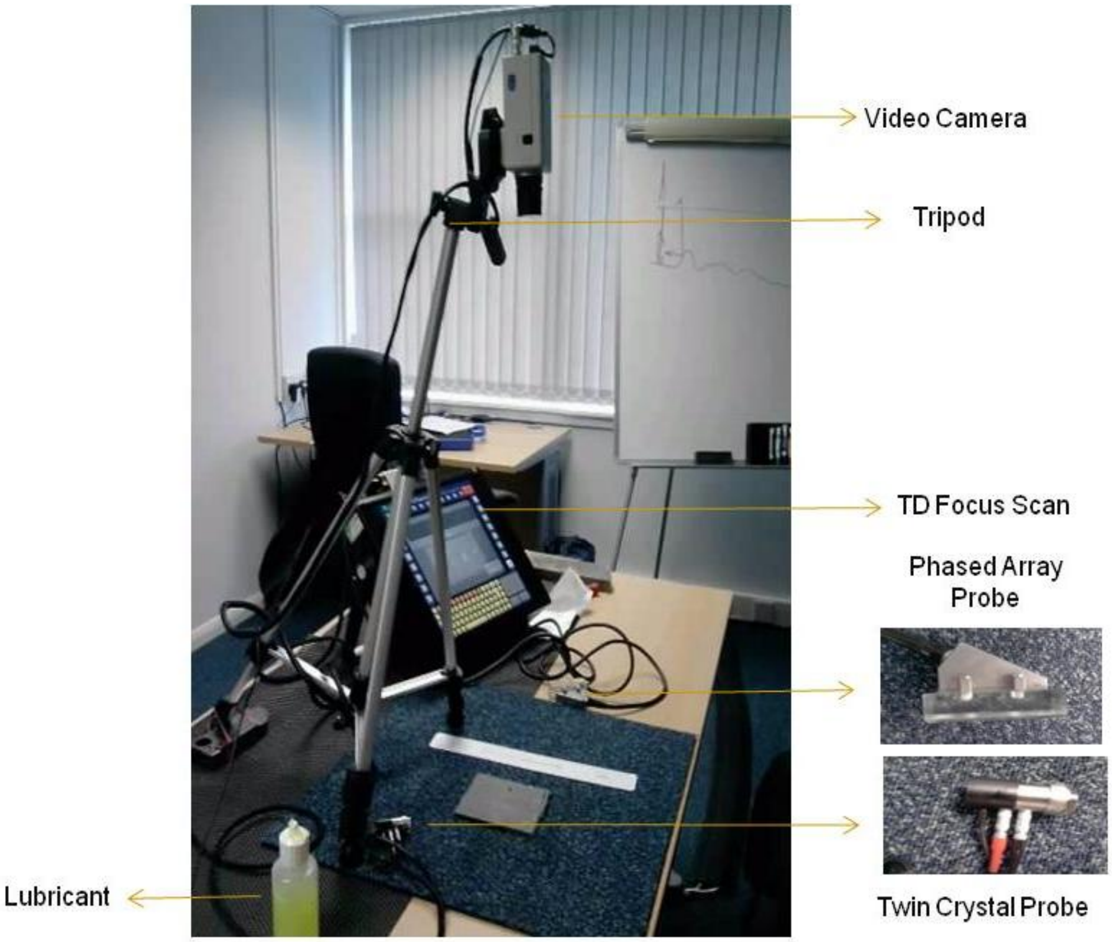

Figure: 3.5 Experimental Setup of Ultrasonic Scanning

Twin crystal probe and video tracking system were calibrated and the probe position was determined by placing the LED cup on top of the probe for pulse echo. CCD (charged coupled device) camera detects and follows the movement of probe on which the LED is mounted. Positional calibration was checked by moving the probe alongside the measurement scale. This ensures that the position of probe is registered correctly when the scan starts. Also it is vital to keep the line-of-site intact between the LED and camera. Data was collected every 2.00 mm on every sample.

Second ultrasonic scan was conducted, using a 64 element phased array probe using a 0° Roxelite wedge. Phased array transducer consists of a number of individually connected piezo-electric elements. In a multi-element probe the elements are excited individually or in groups using electrical pulses. The excitation of multiple piezo-composite elements individually in a sequence at slight time intervals generates packets of energy that are strengthened by constructive interference to form a wave front. Ultrasonic beam parameters such as angle, focal distance and focal size are dynamically altered through the software. The reflected energy or echo from a desired target hits the various transducer elements at computable time delays. The echoes received by each element are time-shifted before being summed together for further analysis [68].

For phased array scanning positional recording was calibrated using Celesco SP1 string pot encoder[5]. The linear measurement device utilizes a flexible cable, a spring loaded spool and a potentiometer. This measurement device was then attached to the phased array probe. Displacement of the probe was verified with a measurement scale to ensure that the position of probe was registered correctly. Data collection was performed every 1.00 mm. In order to efficiently transmit the energy from the probe to the test object, Sona-Gel W1 ultrasonic couplant[6] was used. The product works effectively on uneven, rough and pitted metal surfaces allowing a smooth probe movement without losing signal during scan.

3.3.4. Scanning Electron Microscopy

3.3.4.1 Sample Preparation

Sectioning of the samples from the M10, Sherman and Centaur were performed and mounted in Bakelite. Polishing of the cross sections was performed using SiC abrasive grinding papers of various grades in order to create, flat and defect free surface for scanning electron microscopy (SEM). Samples were conditioned with a diamond suspension spray of 3µm, rinsed with water and then dried. No chemical treatment on the samples was performed. For surface corrosion analyses SEM was performed on corroded surfaces of the samples without any polishing, surface conditioning and without any mounting in Bakelite.

3.3.4.2 Test Procedure

SEM was conducted on state-of-the-art Zeiss EVO LS 15 shown in Figure: 3.6. This method proved to be extremely useful to understand corrosion behaviour and its morphology on the tanks' surfaces.
SEM is used for the examination and analysis of the micro-structural characteristics of the solid objects in high resolution. The examination area is irradiated with finely focused electron beam, which scans the entire surface point by point on the test object. The incident electron beam at a point result emitted electrons, which can be further classified into two types (i) secondary electrons and (ii) back-scattered electrons. These emitted electrons determine the external morphology and the grain structure with its orientation of the materials. Secondary electrons with its low energy (less than 50eV) emitted from the surface produces the SEM images where as back-scattered electrons emitted deep from within the sample with high energy determine the material's grain structures [69-71].

3.3.5. Energy Dispersive X-ray Spectroscopy

Energy dispersive x-ray spectroscopy (EDS)analysis was conducted at the Zeiss EVO LS 15 fitted with Oxford Instrument X-Max 80 mm^2 EDS detector

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[5] http://www.celesco.com (Access date: 06.09.2013)

[6] http://www.sonatest.com (Access date: 06.09.2013)

shown in Figure: 3.6. EDS was performed on the same samples used for the SEM. Through EDS corrosion products were identified.

Emitted x-rays from a sample’s surface because of the bombardment of electron beam during SEM are characterised by EDS, to obtain the chemical microanalysis and the elemental composition of the analysed volume. EDS measures the number of emitted x-rays against their energy. Energy of x-ray is the characteristic of the element from which the x-rays were emitted. Elements such as (Be) and (U) atomic numbers 4 and 92 respectively can also be detected and analysed. A qualitative and quantitative determination of the elements is obtained and evaluated from the energy spectrum versus relative counts of the detected x-rays [69-71] .

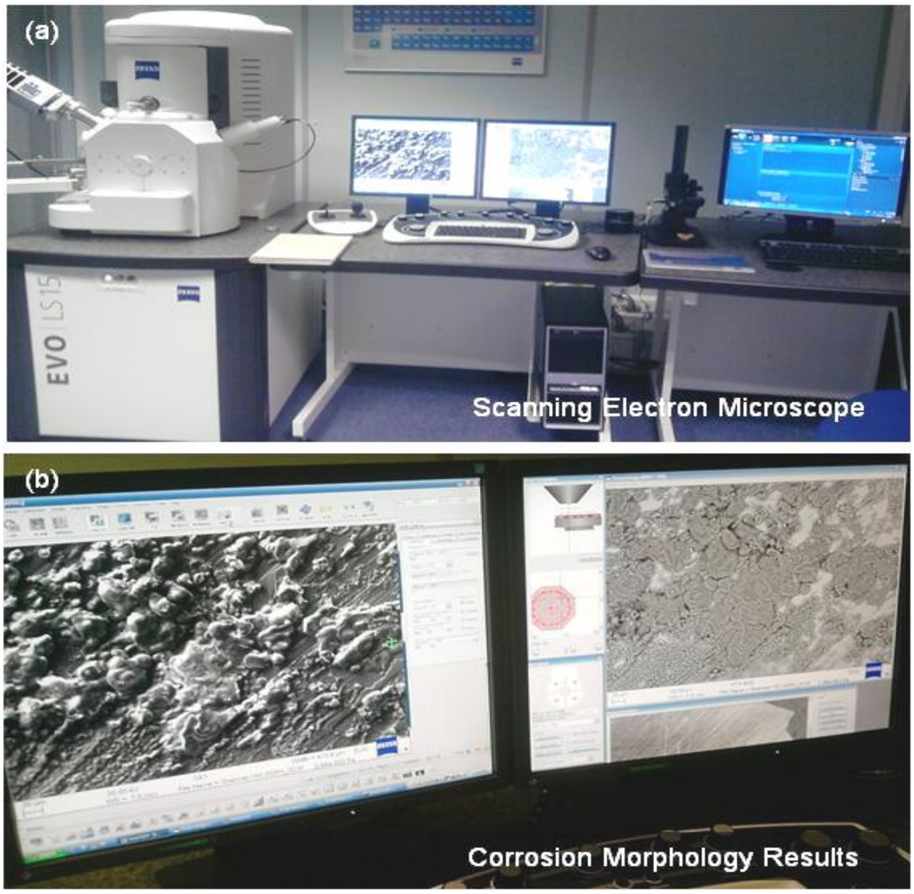


Figure: 3.6 Zeiss EVO LS 15

3.3.6. Simulated Environmental Corrosion Testing

3.3.6.1 Sample Preparation

Samples collected from the M10, Sherman and Centaur shown in Figure: 3.2 were sectioned for this test. Twelve samples of approximately (4 cm X 3cm) dimension shown in Figure: 3.7 were prepared. Samples location and description is provided in Table: 3.2. Also surface profile specifications are given in Table: 3.3. These samples were previously corroded, thus corrosion from the surfaces was effectively removed using SiC papers of different grades. Samples were polished to a good standard to achieve surface uniformity, rinsed with water and no chemicals were utilised during preparation.

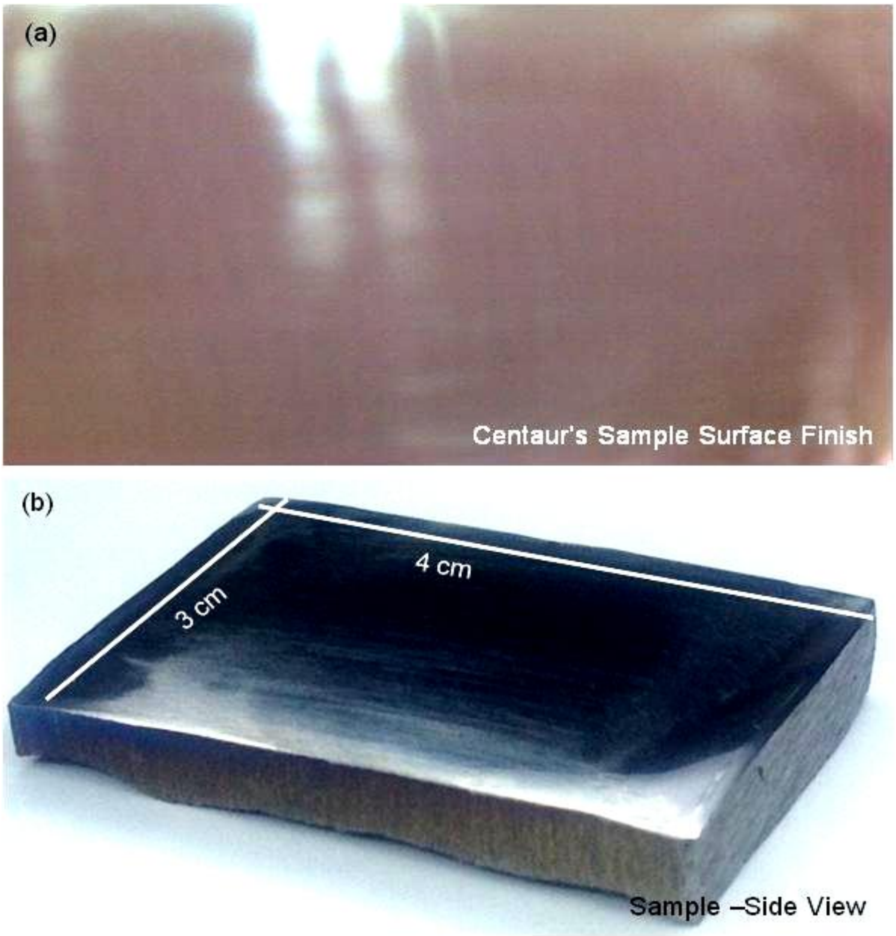
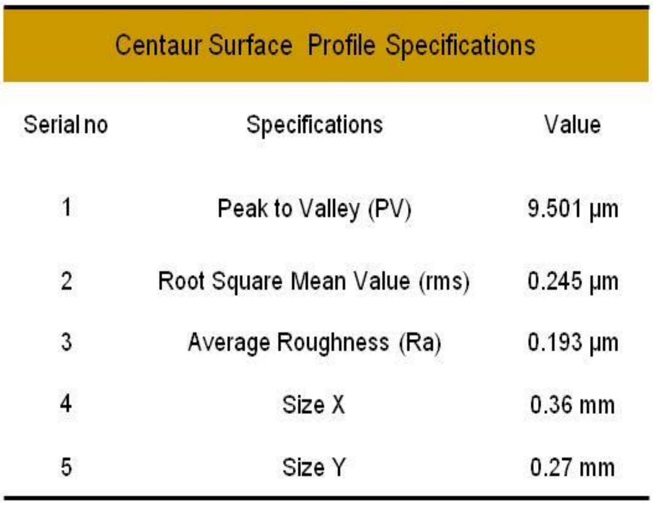


Figure: 3.7 Centaur's Sample Finish for Simulated and Accelerated Corrosion Tests (a) Surface Finish (b) Side View and the dimension of the same sample

Table: 3.3 Centaur Sample Roughness Profile after Preparation



Centaur Surface Profile Specifications

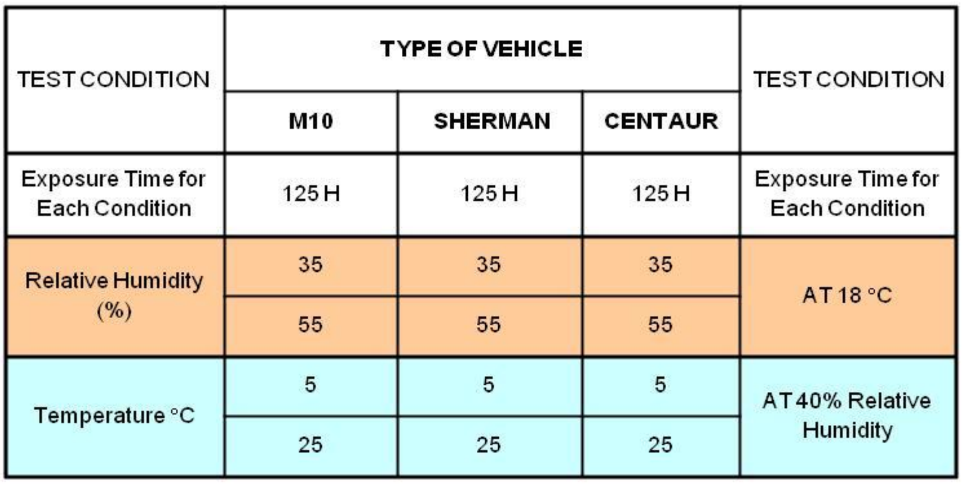
Serial no	Specifications	Value
1	Peak to Valley (PV)	9.501 μm
2	Root Square Mean Value (rms)	0.245 μm
3	Average Roughness (Ra)	0.193 μm
4	Size X	0.36 mm
5	Size Y	0.27 mm

3.3.6.2 Test Conditions

Simulated environment tests were conducted using environmental chamber TAS LT CL 600 shown in Figure: 3.8.

A set of simulated environments were designed taking into account the comfort level of museum visitors and to avoid wet-dry cycles in the museum [72, 73]. Four samples from each tank the M10, Sherman and Centaur were inserted into the chamber simultaneously for 125 hours to selected temperatures and relative humidity (RH) illustrated in Table: 3.4.

Table: 3.4 Test Conditions for Simulated Environment Corrosion Testing



TEST CONDITION	TYPE OF VEHICLE			TEST CONDITION
	M10	**SHERMAN**	**CENTAUR**	
Exposure Time for Each Condition	125 H	125 H	125 H	Exposure Time for Each Condition
Relative Humidity (%)	35	35	35	AT 18 °C
	55	55	55	
Temperature °C	5	5	5	AT 40% Relative Humidity
	25	25	25	

Each condition shown in Table: 3.4 was operated for 125 hours. In first part of the test, temperature of the chamber was kept constant at 18ºC and two values of RH 35% and 55% were used consecutively for 125 hours each. In second part of the environmental test, RH was kept constant at 40% and two temperatures 5ºC and 25ºC were used consecutively for 125 hours.

Figure: 3.8 TAS ECO 135 and Series 3 MTCL 600

3.3.7. Prohesion (ASTM G 85 A5) Corrosion Test

3.3.7.1 Sample Preparation

Prohesion test was conducted on 23 samples shown in Table: 3.5 to evaluate the viability of materials, coating and primer. Twenty three samples of required dimension were prepared. Three samples from the M10, Sherman and Centaur were polished with SiC papers without using any chemicals, to remove previous corrosion and to achieve surface uniformity. In order to replicate conditions at the museum ten samples were painted with the coating and ten in the primer. The coating currently used on the tanks surfaces is Air Drying Alkyd (Electrostatic Thinner) and the primer is red-oxide zinc phosphate (Electrostatic Thinner). The dry film thickness (DFT) for both coating and primer was kept approximately 25 µm respectively (minimum recommended thickness by the manufacturer). In Figure: 3.9 film thickness of the primer is shown. The drying was conducted at room temperature and conditions for a minimum of 4 Hours in the Tank Museum workshop

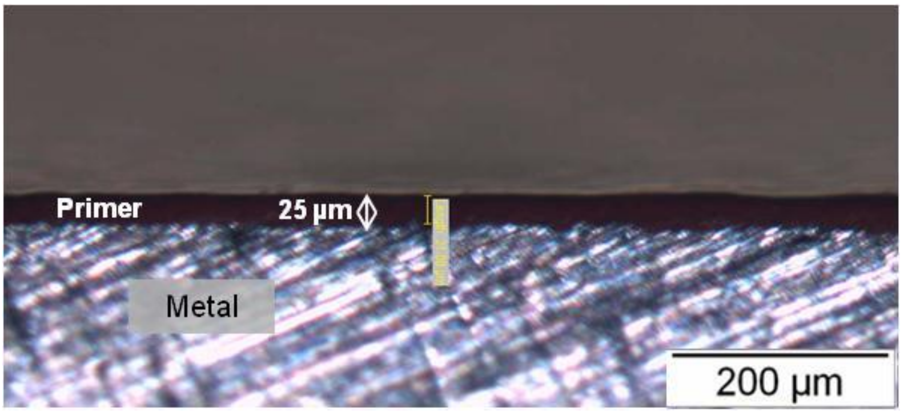


Figure: 3.9 Primer Red -oxide approximately 25 µm Dry Film Thickness

3.3.7.2 Test Conditions

Dilute Cyclic Salt Fog/Dry (ASTM G 85 Annex 5) also known as Prohesion Test is particularly applicable to paints on steel surfaces. This test provides good correlation with real time exposure tests, particularly in areas where airborne contaminants such as nitrates and sulphides are present. ASTM G 85 A5 is in practice in the Society of Automotive engineers (SAE), American Iron and Steel Institute (AISI) for automotive applications[7] and is used in researches to simulate actual atmospheric corrosion at the laboratory level [74-77].

In this test the electrolyte is a solution of NaCl (0.05%) and $(NH_4)_2SO_4$ (0.35%) by mass. pH of the solution should be kept between 5.0 and 5.40. The wet/dry cycle consists of 1 hour fog and 1 hour dry off. The fog portion of this test is conducted at ambient room temperature (24 ± 3°C) and conditions. The dry-off portion, however, is performed at an elevated temperature (35 °C). The temperature throughout the exposure zone during

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[7] http://www.qualityinstruments.com.mx/pdf/Q-Fog-LF-8144_2_web.pdf (Access date: 06/09/2013)

the dry-off phase is constant at (35 ± 1.5°C) within 3⁄4 - hr of switching from the fog period to the dry period. The dry-off is achieved by purging the chamber with fresh air, such that all visible moisture should dry-off in ¾-h [75].

Samples (23 in total) were inserted in Q FOG[8] cyclic corrosion chamber shown in Figure: 3.10 at the same time, test conditions are provided in Table: 3.5. First set (bare samples) were taken out from the chamber after 48 hours of exposure, the second set at 72 hour while the last was at 264th hour.

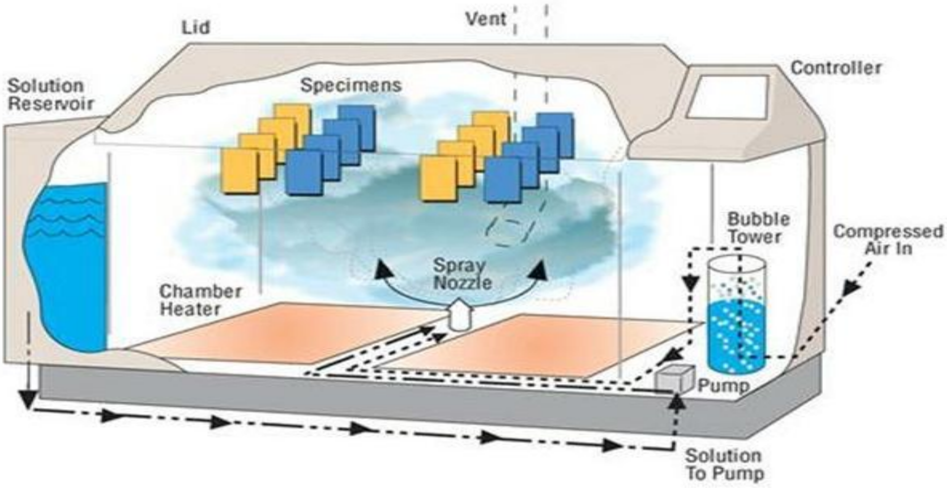

Figure: 3.10 Q FOG Cyclic Corrosion Test Chamber

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[8] http://www.q-lab.com/en-us/products/q-fog-cyclic-corrosion-chamber/q-fog-ssp-cct (Access date: 06/09/2013)

Table: 3.5 Samples' Exposure to ASTM G 85 A5

Sample Condition	Samples without Protection			Samples Painted in Coat (Colour Green)										Samples Painted in Primer (Colour Red)									
Test Condition	ASTM G 85 Annex A5			ASTM G 85 Annex A5										ASTM G 85 Annex A5									
Sample Type	Centaur	Sherman	M10	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
No of hours	48	48	48	48	72	96	120	144	168	192	216	240	264	48	72	96	120	144	168	192	216	240	264

3.3.8. Corrosion Quantification and Image Analysis

Corrosion was accumulated on the samples after exposure to both simulated environmental and prohesion corrosion tests. Extremely complex morphology was observed in the accumulated corrosion. First high definition images of the samples were taken using Nikon D7000 fitted with Sigma EX 105 mm DG Macro lens shown in Figure: 3.11, secondly these high definition images were analysed through Adobe Photoshop CS5 to quantify corrosion build-up areas.

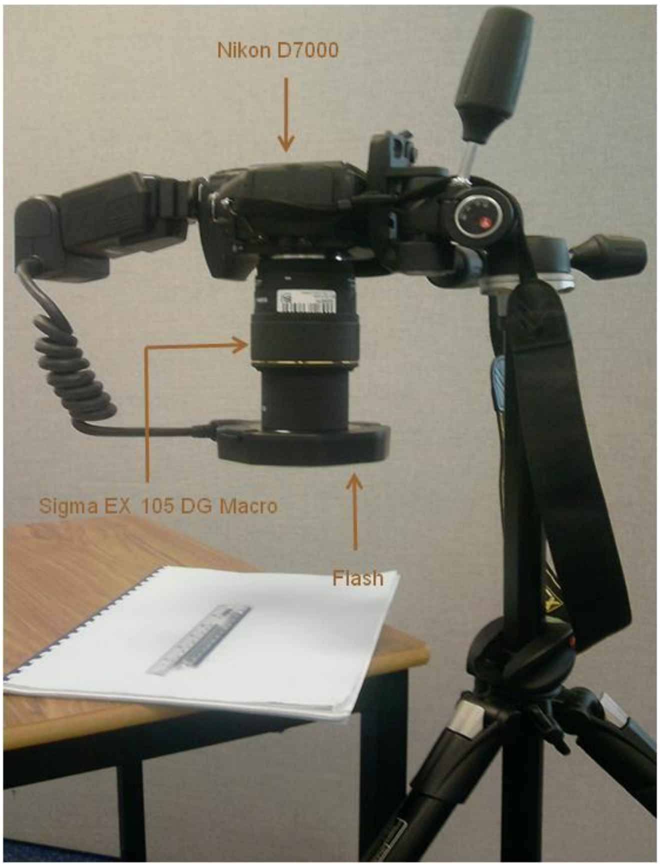


Figure: 3.11 Nikon D7000 Fitted With Sigma EX 105 mm DG Macro

3.4. Tiger 1 Engine and King Tiger's Gear Box Analysis

Tiger 1 engine and King Tiger's gear box were disassembled in August 2010 for the purpose of any prevailing corrosion and tribological issues. Results from visual analysis identified various modes of failures which are provided in chapter 4. Original and replacement piston and cylinder- liner were collected from the Tiger's 1 engine.

3.5. Wave Length Dispersive X-ray Fluorescence

3.5.1. Sample Preparation

Materials' characterisation of the pistons and cylinder-liners was obtained through XRF and Wave Length Dispersive X-Ray Fluorescence (WD-XRF). XRF was conducted on the surfaces of each component. For WD-XRF, a piece measuring approximately 1 cm^2 was taken from each piston and cylinder-liner. In this state-of-the-art method the materials' characterisation of the original piston and cylinder-liner manufactured during the 2nd World War, and that of the replacement piston and cylinder-liner, used as a replacement in the Tiger 1 engine was obtained.

3.5.2. WD – XRF Process

Material characterisation of the samples was conducted using a PANalytical Axios wavelength dispersive x-ray fluorescence spectrometer illustrated in Figure: 3.12. The measurements were processed using PANalytical's Omnian Standardless Software. WD - XRF is an elemental analysis technique capable of determining the elemental content of various materials including metals, oils, plastics and a variety of powder materials. The standard measurement program takes approximately 20 minutes and contains ten scans to cover the elements from fluorine (F) to uranium (U). All major and trace elements quantitatively analysed.

Figure: 3.12 Axios ^{mAX} X-ray Fluorescence Spectrometer

3.6. White Light Interferometry

Surface analyses of the pistons and cylinder-liners were conducted using Zygo OMP – 0375G white light interferometer illustrated in Figure: 3.13. White light interferometry is one of the novel methods to measure surface roughness, shape and waviness of a few millimetres wide sample in a single measurement. Surface roughness, pits and grooves depth, size and periphery of the cracks and the volumes loss can be measured in 3D surface mapping. MetroPro 8.3.3 software was utilised to measure 3D surface defects.

Figure: 3.13 Zygo OMP - 0375G

Chapter 4 **Case Study of The Tank Museum Vehicles**

This chapter documents case study results from twenty tanks described in Table: 3.1. Each tank has its own characteristics in terms of manufacturing, design and exposure in the wars. The case study presents corrosion in its various modes and results from engine wear. In this chapter section 4.1 discusses mainly corrosion in its various forms in the vehicles, whereas sections 4.2, 4.3 and 4.4 briefly introduces wear, cracks and stress related issues in the museum vehicles.

4.1. Various Modes of Corrosion

During the case study of 20 vehicles (Table: 3.1), corrosion was identified as one of the most important aging factors. Corrosion existed in the vehicles in its various forms. Some observations are given below.

4.1.1. Uniform Corrosion

Uniform Corrosion was identified in King Tiger's flywheel Figure: 4.1, Tog II Figure: 4.2 and FT 17 Figure: 4.3. Flywheel of the King Tiger showed the formation and propagation of this type of corrosion. Corrosion was not only confined to flywheel but other gearbox components were also affected. Tog II shown in Figure: 4.2 were amongst the mostly affected tanks with this mode of corrosion. Many part of the Tog II were under attack and the area occupied by corrosion was significant.

Figure: 4.1 King Tiger's Gear Box Flywheel Showing Signs of Uniform Corrosion

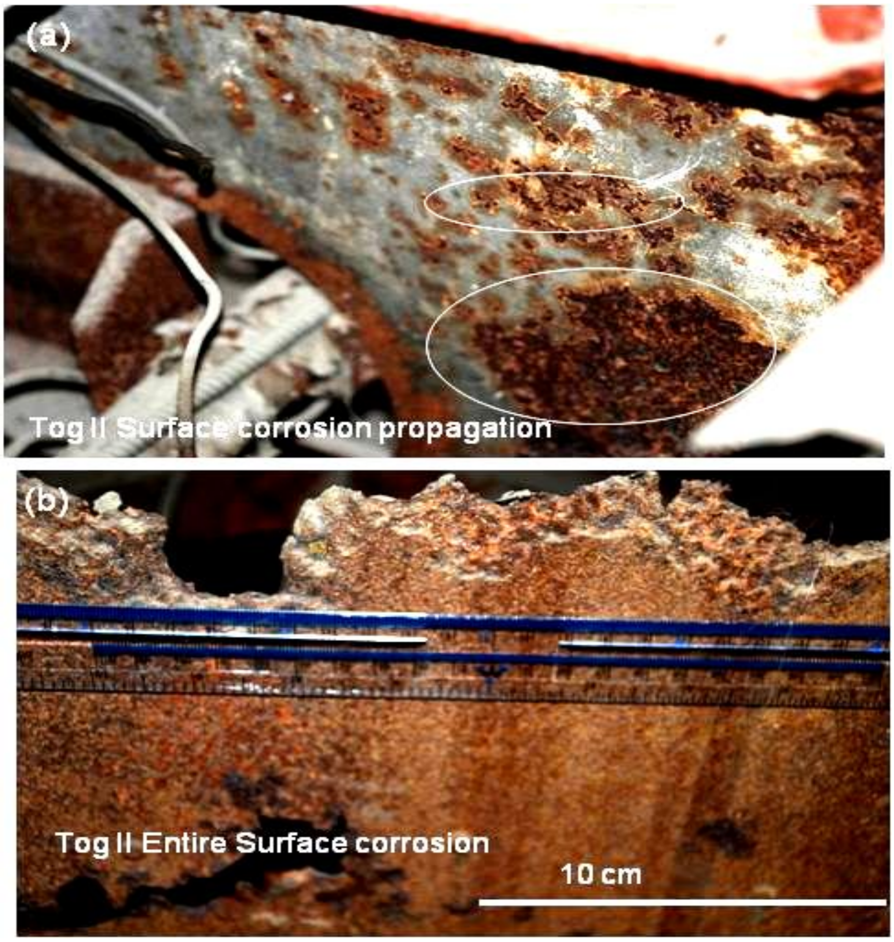


Figure: 4.2 Tog II Surfaces Showing Signs of Uniform Corrosion

Renault FT 17 shown in Figure: 4.3, was also under the attack of general corrosion. Corrosion on FT 17 is not severe, however if not treated it could result in component degradation [11, 14, 23].

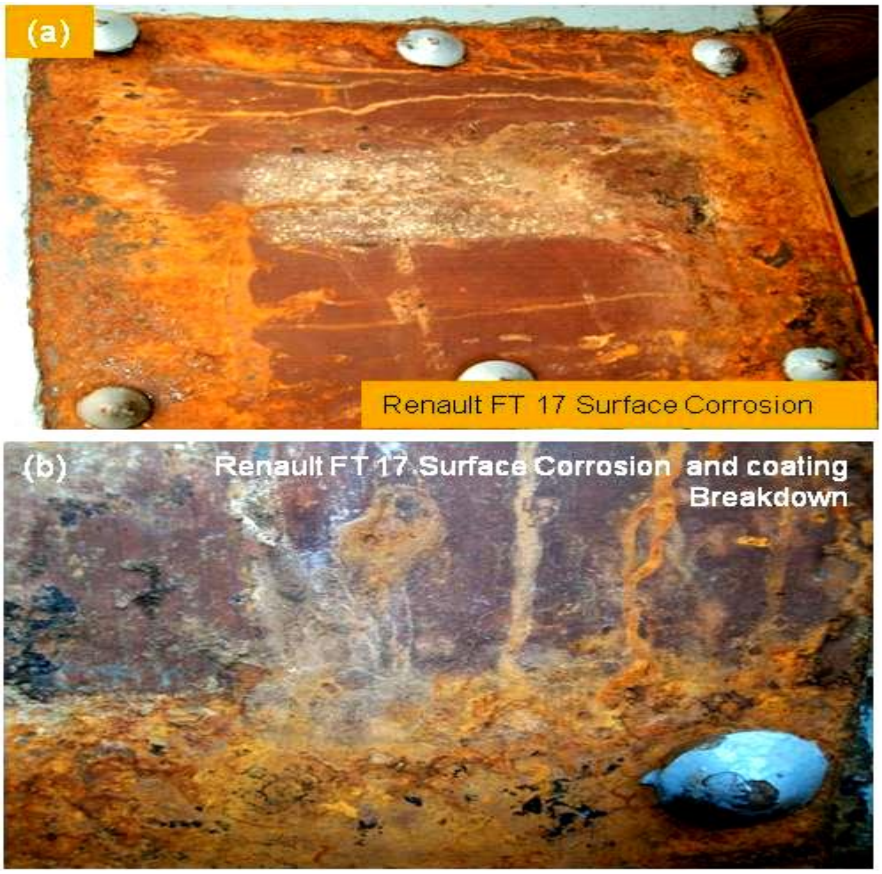


Figure: 4.3 FT 17 Uniform Corrosion

Mark II was affected considerably on larger scale through surface corrosion shown in Figure: 4.4. The magnitude of corrosion damage to Mark II structure can be classified as high because majority of the tank structure display accumulation of corrosion.

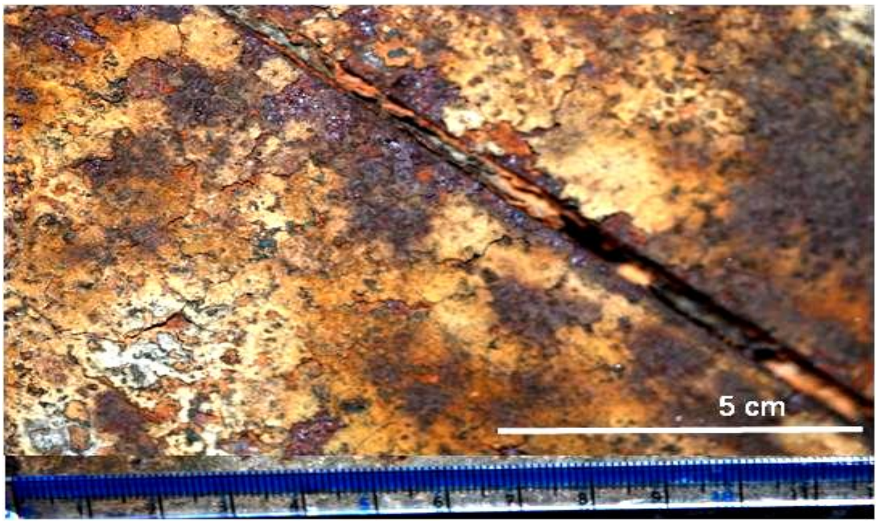


Figure: 4.4 Mark II Uniform Corrosion

4.1.2. Galvanic Corrosion

Galvanic corrosion was observed in the Scorpion shown in Figure: 4.5. The washer and fastener have anodic characteristic and are corroding fast, compare to the rest of the bulk surface.

Figure: 4.5 Scorpion Galvanic Corrosion of Washer on the Hull

Mark II Figure: 4.6 also illustrate galvanic corrosion its structure. Bolts' heads show anodic behaviour whereas the rest of the bulk surface could act as cathode. Mark II endures severe corrosion in different forms.

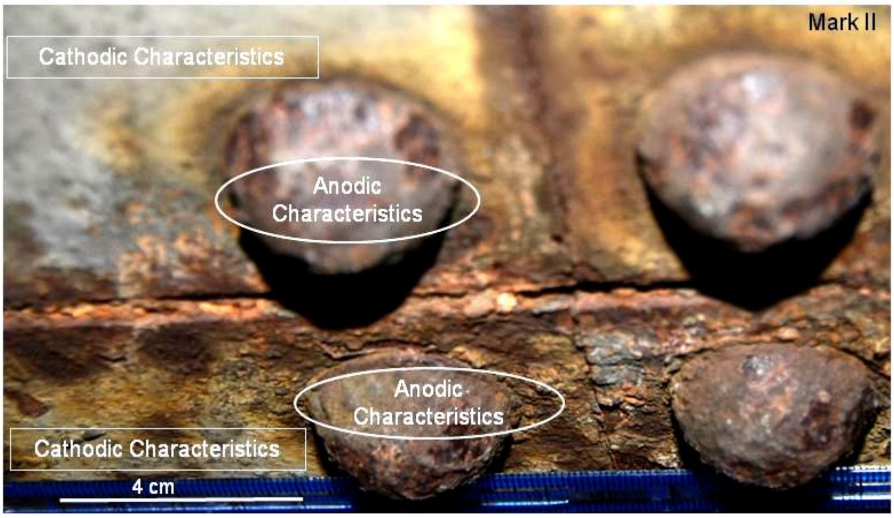


Figure: 4.6 Mark II Glacis Plate Shows Galvanic Corrosion

In both of the above conditions the access of moisture on the surfaces will create a conductive path for galvanic corrosion cycle to complete and continue [29-31].

4.1.3. Stress Corrosion Cracking

Stress corrosion cracking is one of the severe forms of corrosion and their contributions to structures failures are significant. This mode of corrosion was also indentified in the tank museum vehicles. Figure: 4.7 from the Mark II glacis plate shows stress corrosion crack penetrating through the surface with no significant material loss on the surface. Also a sub-surface crack was observed in sample collected from the armoured skirt of the Centaur shown in Figure: 4.8. Surface and sub-surface cracks may lead to sudden components failures in both vehicles. High degree of failures leading to catastrophic structural damage may happen unexpectedly [21, 26, 78].

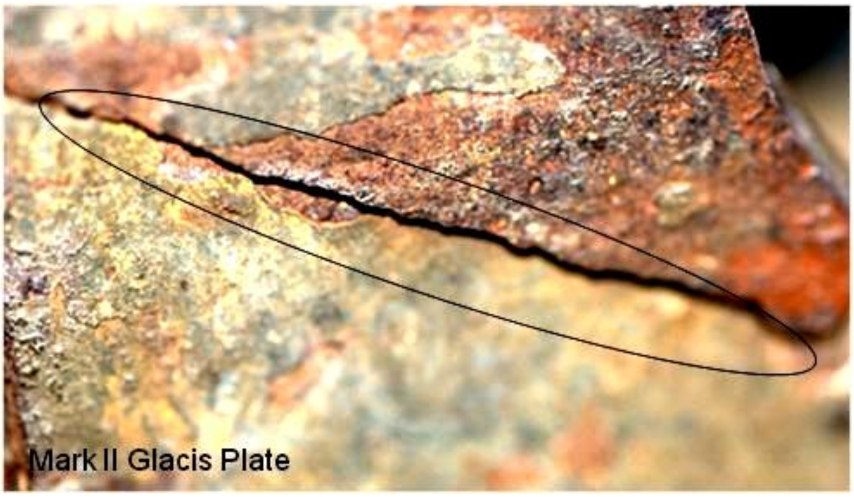


Figure: 4.7 Mark II Stress Corrosion Cracking

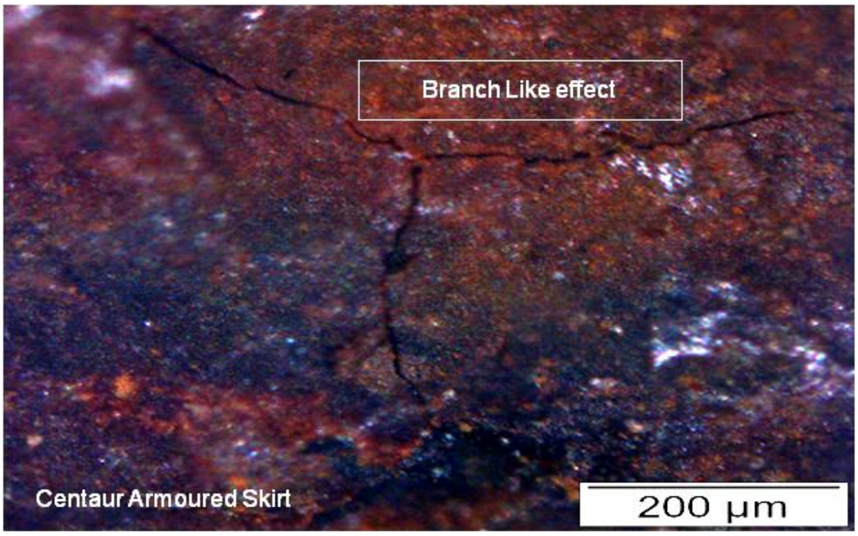


Figure: 4.8 Centaur Armoured Skirt Sub-surface SSC

4.1.4. Pitting Corrosion

The influence of corrosion was vast in the structure of the Centaur in various modes. Corrosion was found in more than one form in the Centaur. These forms of corrosion were actively degrading the Centaur individually and/or together. Corrosion mechanism was complex and extreme in the Centaur. Among other forms pitting was also observed in the Centaur shown in Figure: 4.9. Formation of pits were visible on the surfaces, red colour indicate that pitting was progressive. The accumulation of corrosion deposits can be noticed covering the actual pits. This large number of pits will risk the Centaur’s integrity [32-35].

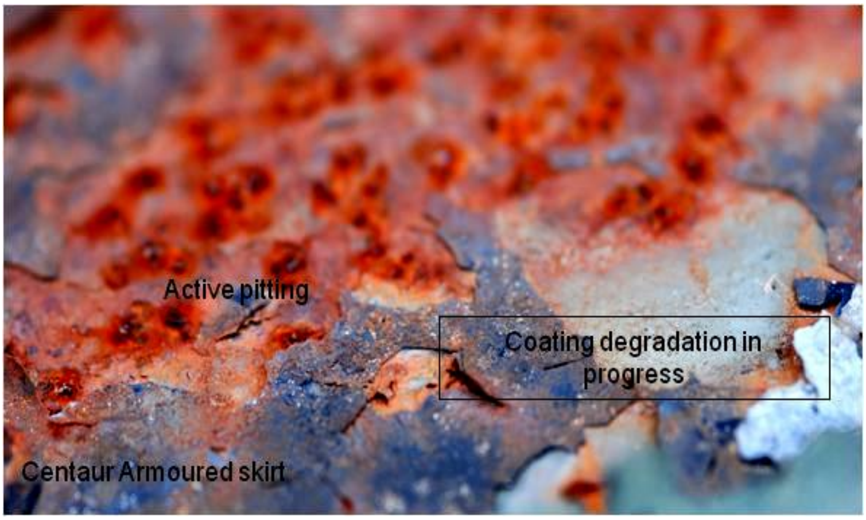


Figure: 4.9 Centaur Pitting in the Armoured Skirt

4.1.5. Inter-granular Corrosion

Centaur was badly affected from various corrosion modes. This form of corrosion was also observed in its armoured skirt shown in Figure: 4.10. Inter-granular (IGC) corrosion is a localised corrosion attack on or at the grain boundaries propagating into the material. Anodic dissolution of the grain boundaries is caused by a) regions depleted of alloying elements b) second phase precipitates and/or c) regions with segregated alloying or impurity elements. IGC reduces the toughness of the material at early stage and fracture may occur as a result. Impurities and/or alloying elements at the grain boundaries become galvanic elements due to difference in concentrations. As a result a zone of less noble material in the grain boundaries develops acting as an anode whereas the other parts become cathodic. In $CuAl_2$ alloys precipitate at the grain boundaries may become noble than the bulk material causing grain boundary attack [17, 29]. The disintegration of materials through IGC in this form is also referred as leafing or lifting effect. During this process corrosion deposits occupy larger surface area taking the material apart. Figure: 4.11 show the exfoliation of the entire structure leaving behind leaf like structure.

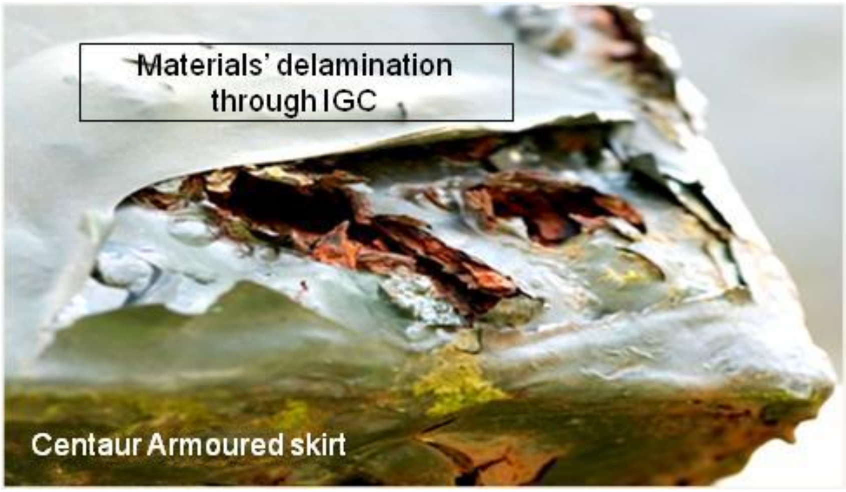


Figure: 4.10 Centaur Signs of Inter-granular Corrosion in the Armoured Skirt

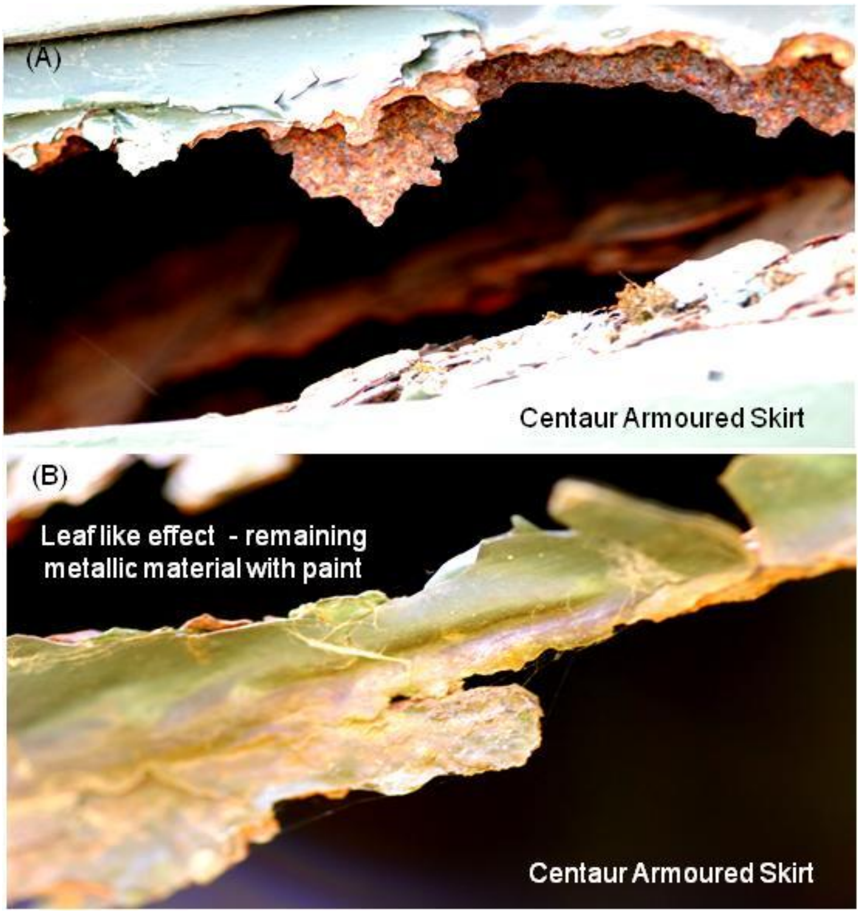


Figure: 4.11 Centaur Inter-granular Corrosion in the Armoured Skirt

Steel alloys can be liable to inter-granular corrosion. In ferritic stainless steel in addition to Cr carbides, Cr nitrides may be precipitated and thus contribute to the depletion of Cr at the grain boundaries. Cr depletion is the most common for steel alloys to initiate IGC. The degradation of grain boundaries is known as sensitisation, which is the result of chromium rich phases i.e. carbides, nitrides or inter-metallic phases. IGC develops at these chromium depleted regions when the sensitised stainless steel is exposed to oxidising media. In ferritic steel IGC can occur at a wider spectrum of environments [29, 79].

4.1.6. Corrosion Fatigue

Corrosion fatigue failure was observed in the structure of Mark II shown in Figure: 4.12. This mode of failure is often the result of fatigue accelerated and simulated by corrosion. Fatigue under corrosion may reveal beach marks but usually they may be less visible due to corrosion products on the affected surface [17, 38]. In the Mark II, a long crack with noticeable widening and size was observed. The crack appears to be initiated as a result of “dry fatigue”. There is a lower limit for stresses causing fatigue in structural steels under dry fatigue known as fatigue limit. When corrosion is introduced two effects can be developed a) the number of cycles to fracture decreases and fatigue limit is reduced, and b) the number of cycles to fracture becomes dependent on load frequency. The crack development can be divided into four stages 1) Initiation 2) Crack growth stage I, with crack growth direction about 45° relative to the tensile stress direction 3) Crack growth stage II and 4) Fracture. Figure: 4.12 of the Mark II appear to be a facture. Growth of cracks is expected under corrosive environment and in the presence of cyclic loading [17, 39-41].

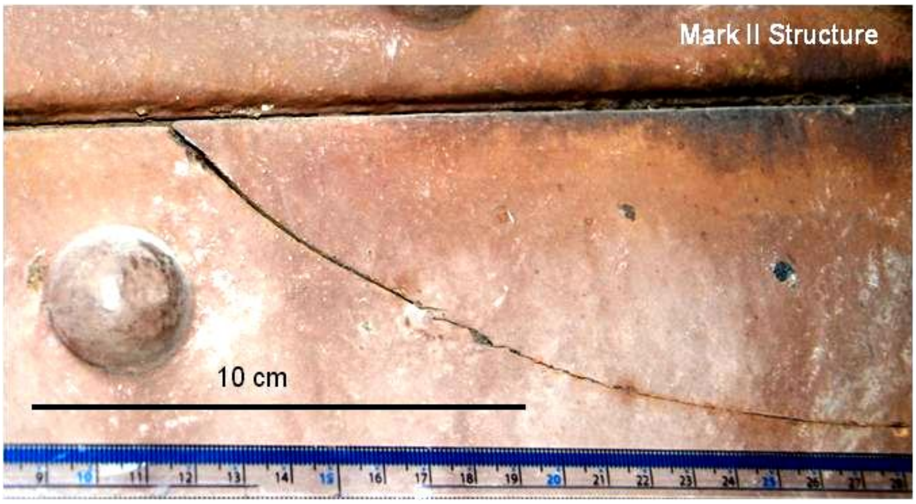


Figure: 4.12 Mark II Corrosion Fatigue

An empirical model is used to predict fatigue crack life using Paris-Erdogan law). Under stress fatigue regime it associates stress intensity factor range to sub-critical growth.

$$da/\, dN = C\, \Delta K^{m} \qquad (12)$$

In this equation ‘a’ denotes crack length; ‘N’ is the number load cycles, ‘C’ and ‘m’ are materials’ constant, and ΔK is the range of the stress intensity factor. Range of stress intensity factor (ΔK) is obtained by the following equation.

$$\Delta K = K_{max} - K_{min} \qquad (13)$$

K_{max} and K_{min} represent maximum and minimum intensity factors. This model is helpful to predict residual life for the crack [80].

4.1.7. Microbial Corrosion

Microbial corrosion is referred to the degradation of metals because of the activities of the bio-organisms. Micro and macro organism in various environments, such as industrial, seawater, soils, and natural petroleum products contribute to corrosion. Figure: 4.13 of the Sherman outside the museum in an uncontrolled environment shows accumulation of moss and vegetation on its surfaces. In such environment the growth and multiplication of a wide range of microbial species is possible. This surface condition can be a source of carbon food, nitrogen and phosphorous. Microbes decompose organic and mineral matter and precipitate in the cycle of carbon, nitrogen and sulphur. Many microbes can adapt to temperatures between (-10°C) and 99ºC, pH range of 0% to 10.5% and concentration of oxygen between 0% to almost 100%. These species produces mineral and organic acids leading to a corrosive environment on the surfaces [19, 81]. These species also form microbiological surface colonies and establish bio-films. Such bio-films on the surfaces become corrosive and material degrade rapidly [42-44].

Figure: 4.13 Sherman Target Tank - Accumulation of Moss and Vegetation could result in Microbial Corrosion

The methods through which corrosion is increased by micro-organisms are: 1) Production of metabolites, 2) Destruction of protective layers, 3) Hydrogen embrittlement, 4) Formation of concentration cells at the metal surface and, in particular oxygen concentration cell 5) Modification of corrosion inhibitors and 6) Stimulation of electrochemical reactions [82]. Such surface conditions are not favourable for the tanks and it could lead to microbial corrosion.

4.1.8. Crevice Corrosion

Crevice corrosion was identified in the Centaur, Centurion, Tiger 1, Comet, Sherman, Renault FT 17, Lynx Reconnaissance and Medium Mark A - Whippet. Figure: 4.14 an example of crevice corrosion in (a) Lynx (b) Centurion and (c) Medium Mark A.

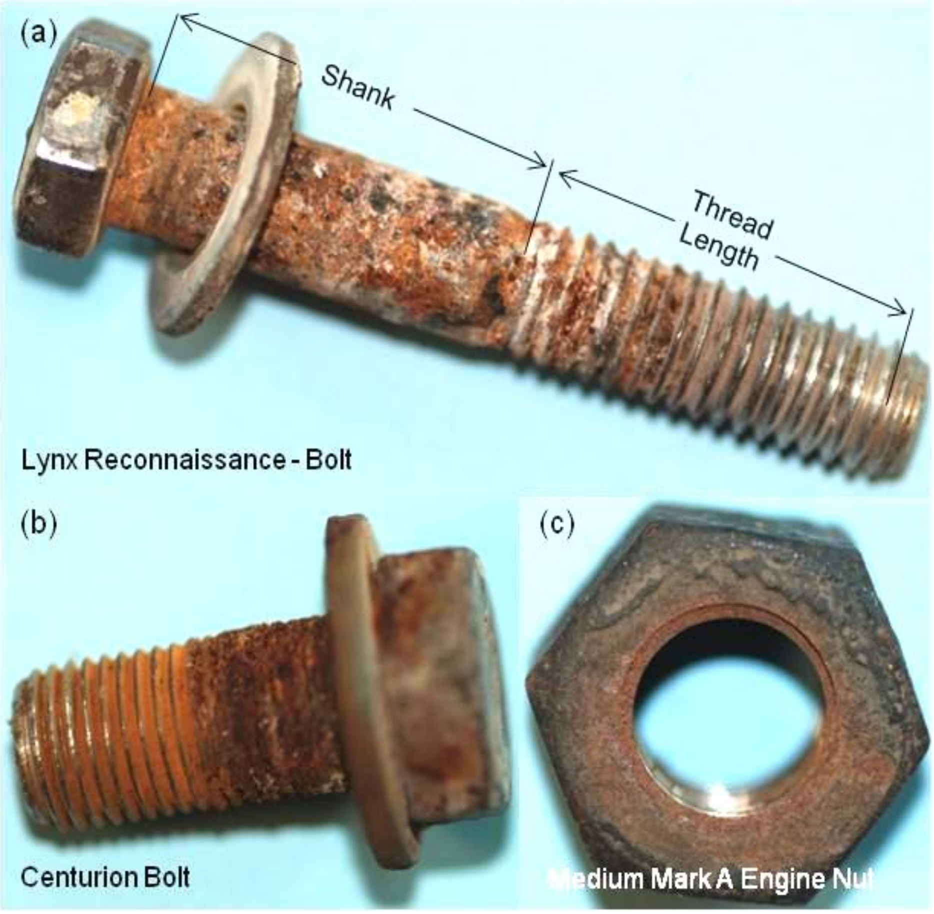


Figure: 4.14 Crevice Corrosion

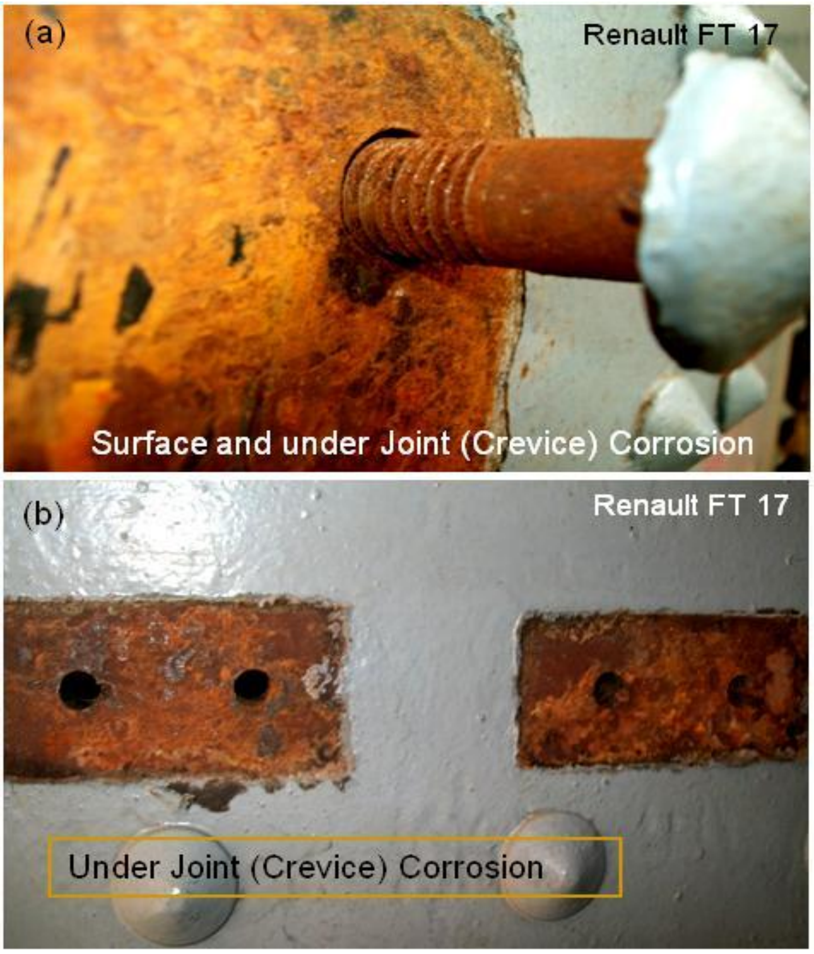


Figure: 4.15 FT 17 - Crevice Corrosion of Joints

The access of stagnant solution (moisture/water) has created micro-climate in joints where the bolts were used. Figure: 4.14 (a) is an example of this type of corrosion. Limited oxygen concentration at the shank and pitch compare to the external surface (bulk environment) where oxygen concentration is more resulted crevice corrosion. Reduction of oxygen starts to occur in the crevice area giving it a cathodic behaviour; oxygen content on the surface is however more on the external surface giving it a cathodic character. This form of corrosion results from the environmental difference on the same surface/component and can be aggressive [14, 18]. Figure: 4.15 shows crevice corrosion of the a) bolt and b) joints in FT 17. In these joints it appears that the gap was wide enough for liquid to penetrate into the crevice. This liquid remained stagnant in the crevices resulting in corrosion.

4.2. Wear

Tiger’s engine piston Figure: 4.16 and connecting rod Figure: 4.17 show wear scars due to mechanical surface interactions. Scuffing is visible on the piston’s surface and surface integrity has been lost completely [83]. Materials composition, failure in lubricants and elevated temperatures play a vital role in such failures. Wear of Tiger 1 pistons and cylinder-liners has been discussed in more detail in chapter 8.

Figure: 4.16 Tiger 1 Piston Skirt Thrust Face

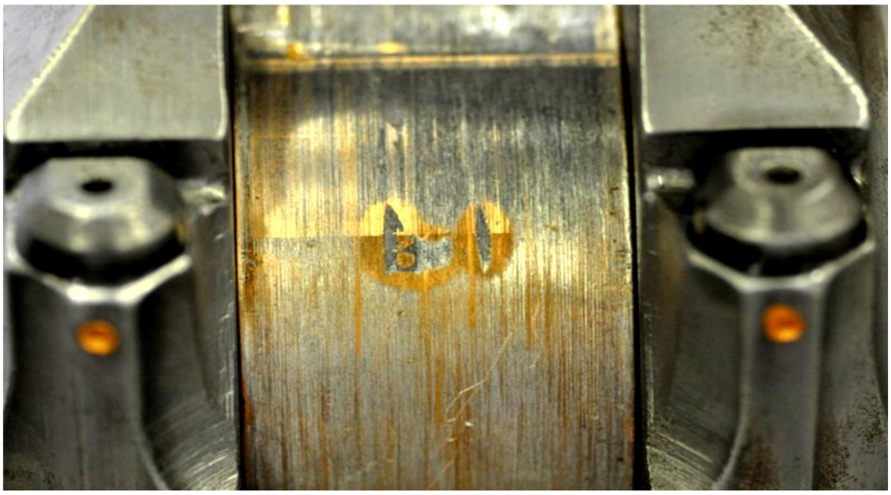


Figure: 4.17 Tiger 1 Piston Connecting Rod

4.3. Cracks

Various types of cracks were identified in some vehicles. Mark II glacis plate Figure: 4.18 and Jagdpanzer’s armoured skirt Figure: 4.19 were mostly affected by various types of cracks. The cracks are converted into fractures, their sizes are considerably large and would cause rupture in the structures.

Figure: 4.18 Mark II Fatigue Cracks

Figure: 4.19 Jagdpanzer signs of Stress Corrosion Cracking in its Track Guard

4.4. Stresses

Stresses are major contributors to the aging of large metal structures and were noticed in some tanks. Compressive stresses were observed in Jadgepanther (Figure: 4.20) and Challenger 2 (Figure: 4.21). The body weight has causing enormous stress on the suspension of the vehicles. Conventional methods to overcome these issues are in practice.

Figure: 4.20 Jadgepanther

Figure: 4.21 Challenger II

4.5. Conclusions

All factors of aging exist in the tanks in The Tank Museum. Their impact on the structural integrity was huge. Among other, corrosion is one of the major dilemmas for the tank museum vehicles. The magnitude of corrosion is different in many vehicles, which could be the result of their past operating environment in different terrains and/or the current environment. Corrosion was observed in many vehicles including WW1, 2 and recent conflicts. Corrosion existed in its simple from (uniform corrosion) to severe forms of corrosion such as stress corrosion cracking and pitting corrosion. The occurrence of corrosion in the tanks is extremely complex. Damage caused by corrosion is never restricted to one form acting alone, but various forms of corrosion working together. The overwhelming phenomenon of corrosion is matter of serious concern, the damage is visible and the enormity is rising. Corrosion also manipulates many forms of failures when combined with stresses as shown in Figure: 4.20 by reducing any endeavours of extension of life or conservation. Continuation of the corrosion problems will immensely affect tanks' structures and the result could be devastating if allowed to continue.

Wear was also an important factor towards component failures. Tiger 1 engine showed tribological related issues in its various components as shown in Figure: 4.16 and Figure: 4.17. Tiger 1 operates occasionally; when it is stationary there is a possibility of corrosion build-up in the engine, an example is shown in Figure: 4.22 of the Tiger 1 cylinder-liner. Corrosion and wear together will have a detrimental impact on the engine performance. High rate of wear occurs initially when the engine starts to function and/or when engine operates cold or extremely hot. The combine damage of corrosion and wear "corrosive wear" will be significant for the Tiger's engine components [84]. In dry contact conditions when engine starts to function will further facilitate failures.

Figure: 4.22 Tiger 1 Corrosion Build-up in the Cylinder - Liner

Structural deformation due to component failures was also observed in some vehicles in the museum. The King Tiger shown in Figure: 4.23.

Figure: 4.23 King Tiger - Structural Deformation due to Component Failure

These aging mechanisms alone, or in combination will play a significant role in the deterioration of tanks in the tank museum.

Chapter 5 **Materials Characterisation**

This chapter presents elemental identification of the alloys' samples collected from the M10, Sherman, Centaur, original and replacement pistons and cylinder-liners of the Tiger 1. Through XRF alloy composition was obtained for the samples from M10, Sherman and Centaur shown in Figure: 3.2 with exact point locations. Sample full description is also provided in Table: 3.2 WD - XRF was conducted to identify elemental composition of the pistons and cylinder-liners of the Tiger 1.

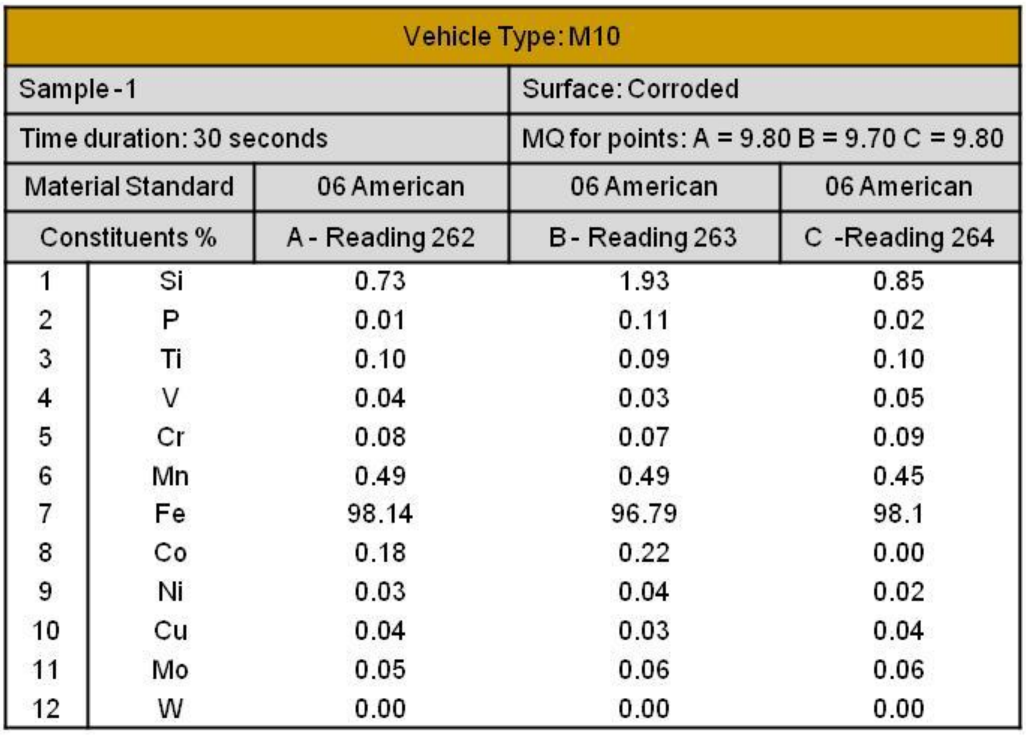
The Materials composition which was originally specified for the pre/during 2nd World War was obtained and the nearest materials standards were indentified.

5.1. Material Characterisation

5.1.1. M10 Tank Destroyer Sample - 1

Table: 5.1 illustrate the XRF results of three points A, B and C on the corroded surface of the M10 military tank. The highest constituent on average was Fe (97.67%), second highest was Si (1.17%) while the lowest recorded was Ni (0.03%) and no trace of W was found.

Table: 5.1 M10 Sample -1 XRF of Corroded Surface at Points A, B and C



Vehicle Type: M10				
Sample -1			Surface: Corroded	
Time duration: 30 seconds			MQ for points: A = 9.80 B = 9.70 C = 9.80	
Material Standard		06 American	06 American	06 American
Constituents %		A - Reading 262	B - Reading 263	C -Reading 264
1	Si	0.73	1.93	0.85
2	P	0.01	0.11	0.02
3	Ti	0.10	0.09	0.10
4	V	0.04	0.03	0.05
5	Cr	0.08	0.07	0.09
6	Mn	0.49	0.49	0.45
7	Fe	98.14	96.79	98.1
8	Co	0.18	0.22	0.00
9	Ni	0.03	0.04	0.02
10	Cu	0.04	0.03	0.04
11	Mo	0.05	0.06	0.06
12	W	0.00	0.00	0.00

Figure: 5.1 illustrate XRF results of location D (cross section) of the same sample. Highest component at the cross section was Fe (99.06%). Si (0.13%) was the second highest with no traces of Ti, V, Co and W.

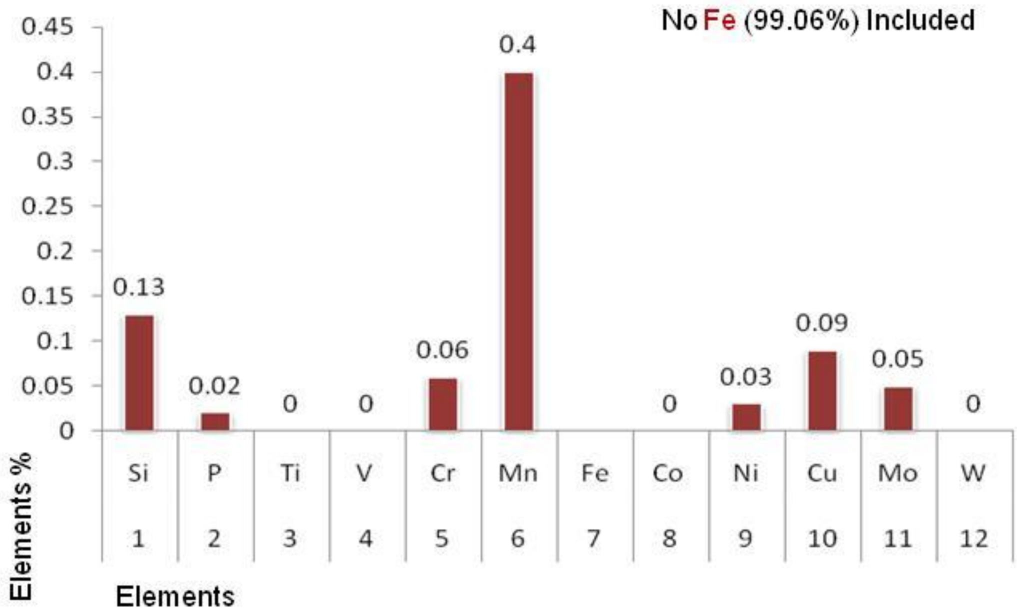
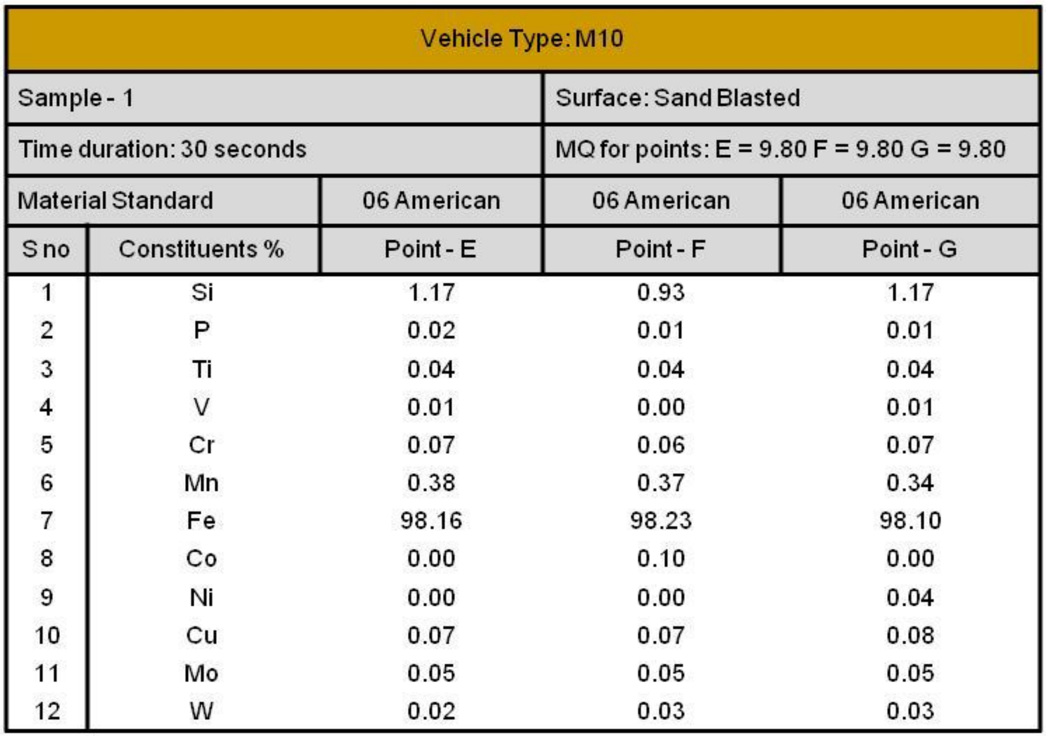


Figure: 5.1 M10 Sample -1 XRF at Cross Section Point D

Table: 5.2 illustrate XRF results of the three points E, F and G at the sandblasted surface. On averages Fe (98.16%) was the highest; Si (1.09%) was the second highest and trace of V (0.01%) was identified.

Table: 5.2 M10 Sample - 1XRF results of Sand Blasted Surface Points E, F and G

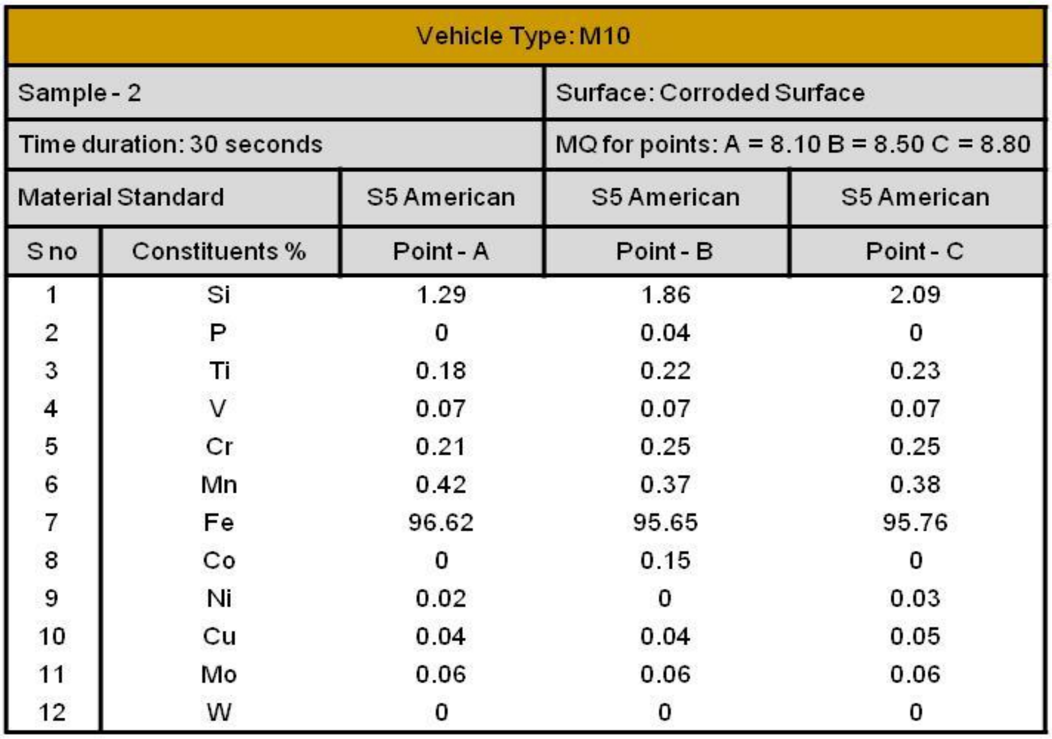


Vehicle Type: M10				
Sample - 1			Surface: Sand Blasted	
Time duration: 30 seconds			MQ for points: E = 9.80 F = 9.80 G = 9.80	
Material Standard		06 American	06 American	06 American
S no	Constituents %	Point - E	Point - F	Point - G
1	Si	1.17	0.93	1.17
2	P	0.02	0.01	0.01
3	Ti	0.04	0.04	0.04
4	V	0.01	0.00	0.01
5	Cr	0.07	0.06	0.07
6	Mn	0.38	0.37	0.34
7	Fe	98.16	98.23	98.10
8	Co	0.00	0.10	0.00
9	Ni	0.00	0.00	0.04
10	Cu	0.07	0.07	0.08
11	Mo	0.05	0.05	0.05
12	W	0.02	0.03	0.03

5.1.2. M10 Tank Destroyer Sample - 2

Table: 5.3 show XRF results for points A, B and C. On average the highest element was Fe (96.01%), and Si (1.746%) was the second highest. The lowest recorded was Ni (0.016%) and no trace of W.

Table: 5.3 M10 Sample - 2 XRF Analysis of Corroded Surface at Points A, B and C



Vehicle Type: M10				
Sample - 2			Surface: Corroded Surface	
Time duration: 30 seconds			MQ for points: A = 8.10 B = 8.50 C = 8.80	
Material Standard		S5 American	S5 American	S5 American
S no	Constituents %	Point - A	Point - B	Point - C
1	Si	1.29	1.86	2.09
2	P	0	0.04	0
3	Ti	0.18	0.22	0.23
4	V	0.07	0.07	0.07
5	Cr	0.21	0.25	0.25
6	Mn	0.42	0.37	0.38
7	Fe	96.62	95.65	95.76
8	Co	0	0.15	0
9	Ni	0.02	0	0.03
10	Cu	0.04	0.04	0.05
11	Mo	0.06	0.06	0.06
12	W	0	0	0

Figure: 5.2 illustrate results of point D at the cross section. Analysis showed Fe (99.40%) the highest constituent, Cu (0.07%) the second highest and Mo (0.05%) the third highest.

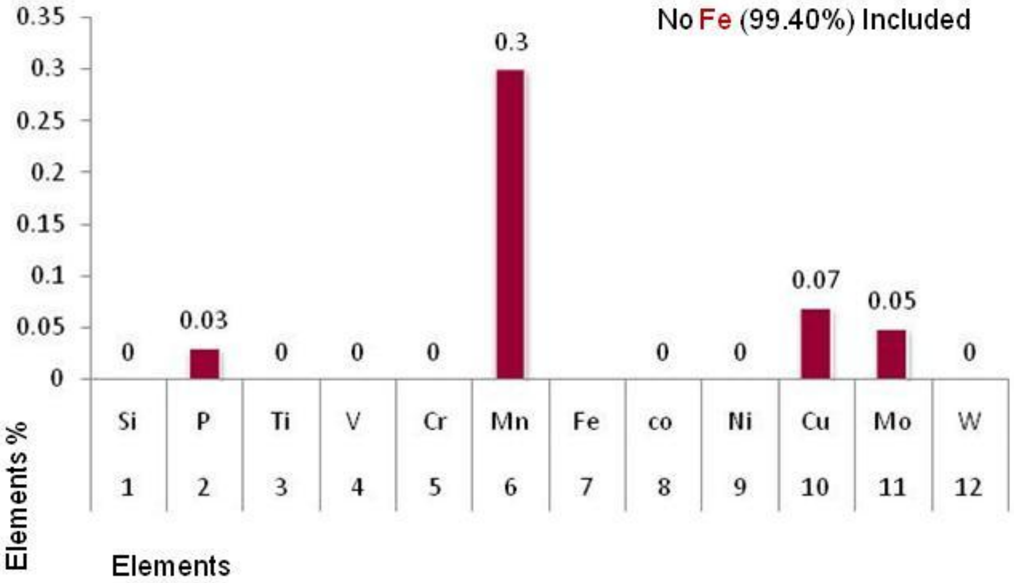
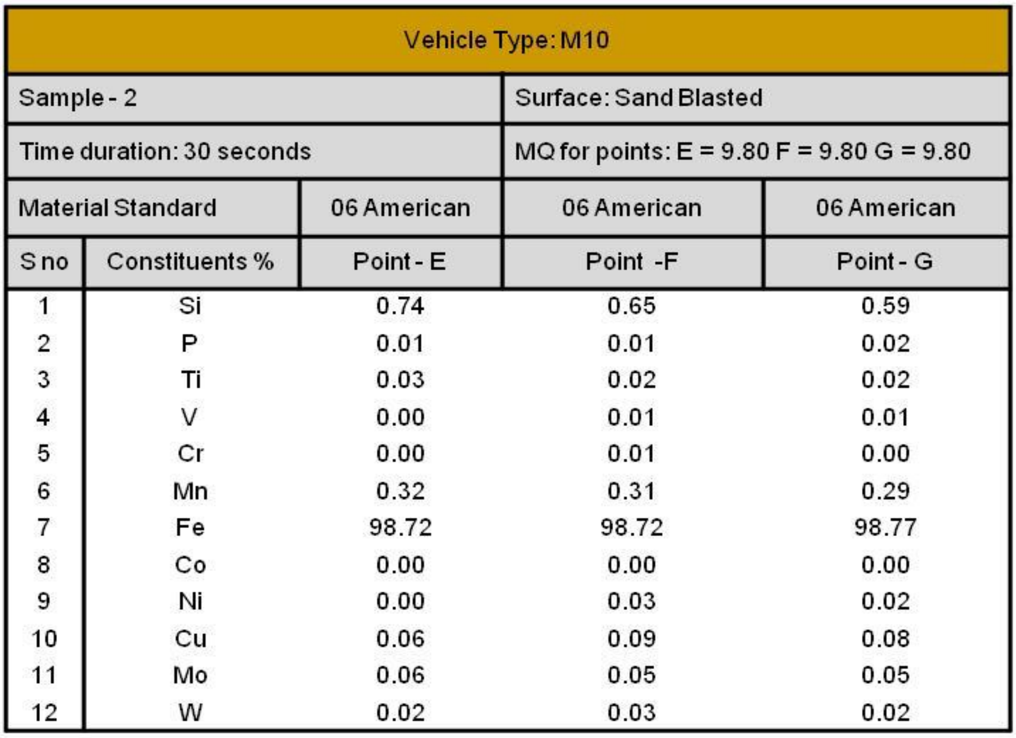


Figure: 5.2 M10 Sample - 2 XRF of Cross Section at Point D

Table: 5.4 show XRF results of the sandblasted surface at three points E, F and G. On average Fe (98.73%) was the highest, Si (0.66%) was the second highest and Mn (0.306%) was the third highest. Traces of W and Mo were detected too.

Table: 5.4 M10 Sample - 2 XRF of Sand Blasted Surface E, F and G

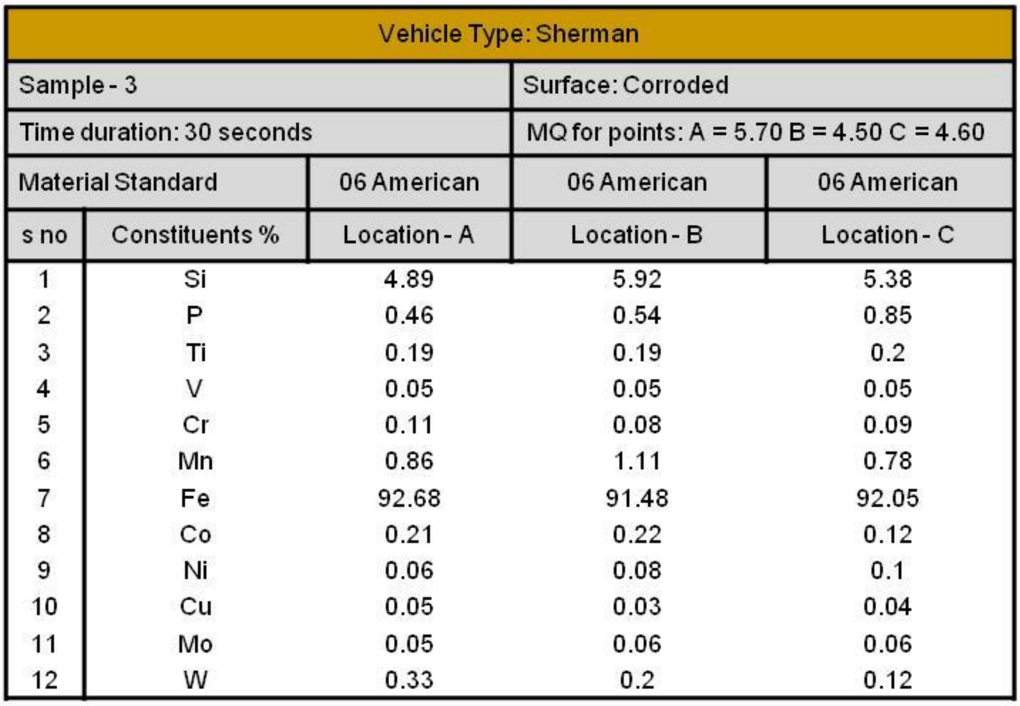


Vehicle Type: M10				
Sample - 2			Surface: Sand Blasted	
Time duration: 30 seconds			MQ for points: E = 9.80 F = 9.80 G = 9.80	
Material Standard		06 American	06 American	06 American
S no	Constituents %	Point - E	Point -F	Point - G
1	Si	0.74	0.65	0.59
2	P	0.01	0.01	0.02
3	Ti	0.03	0.02	0.02
4	V	0.00	0.01	0.01
5	Cr	0.00	0.01	0.00
6	Mn	0.32	0.31	0.29
7	Fe	98.72	98.72	98.77
8	Co	0.00	0.00	0.00
9	Ni	0.00	0.03	0.02
10	Cu	0.06	0.09	0.08
11	Mo	0.06	0.05	0.05
12	W	0.02	0.03	0.02

5.1.3. Sherman Military Tank Sample - 3

Table: 5.5 show results of the points A, B and C on the corroded surface. On averages Fe (92.07%) was the highest, second highest was Si (5.39%), Mn (0.91%) was third and lowest was Cu with trace of 0.04%.

Table: 5.5 Sherman Sample - 3 XRF of Corroded Surface A, B and C



Vehicle Type: Sherman				
Sample - 3			Surface: Corroded	
Time duration: 30 seconds			MQ for points: A = 5.70 B = 4.50 C = 4.60	
Material Standard		06 American	06 American	06 American
s no	Constituents %	Location - A	Location - B	Location - C
1	Si	4.89	5.92	5.38
2	P	0.46	0.54	0.85
3	Ti	0.19	0.19	0.2
4	V	0.05	0.05	0.05
5	Cr	0.11	0.08	0.09
6	Mn	0.86	1.11	0.78
7	Fe	92.68	91.48	92.05
8	Co	0.21	0.22	0.12
9	Ni	0.06	0.08	0.1
10	Cu	0.05	0.03	0.04
11	Mo	0.05	0.06	0.06
12	W	0.33	0.2	0.12

Figure: 5.3 show results of XRF performed at point D at the cross section. Fe (98.30%) was highest, second highest was Si (0.65%) and Mn (0.63%) was third. Traces of Ti, V, Co and Mo were identified.

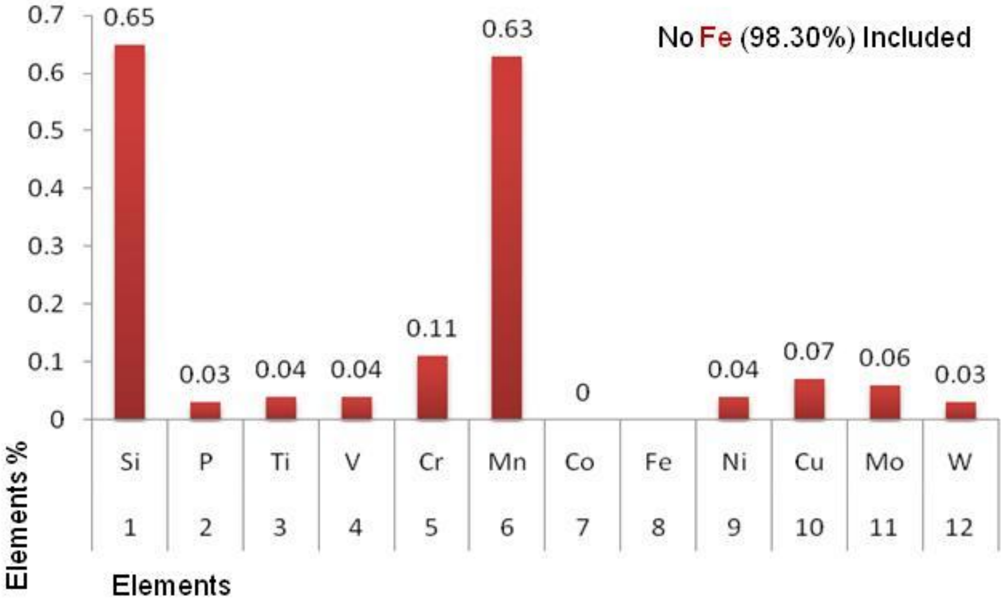
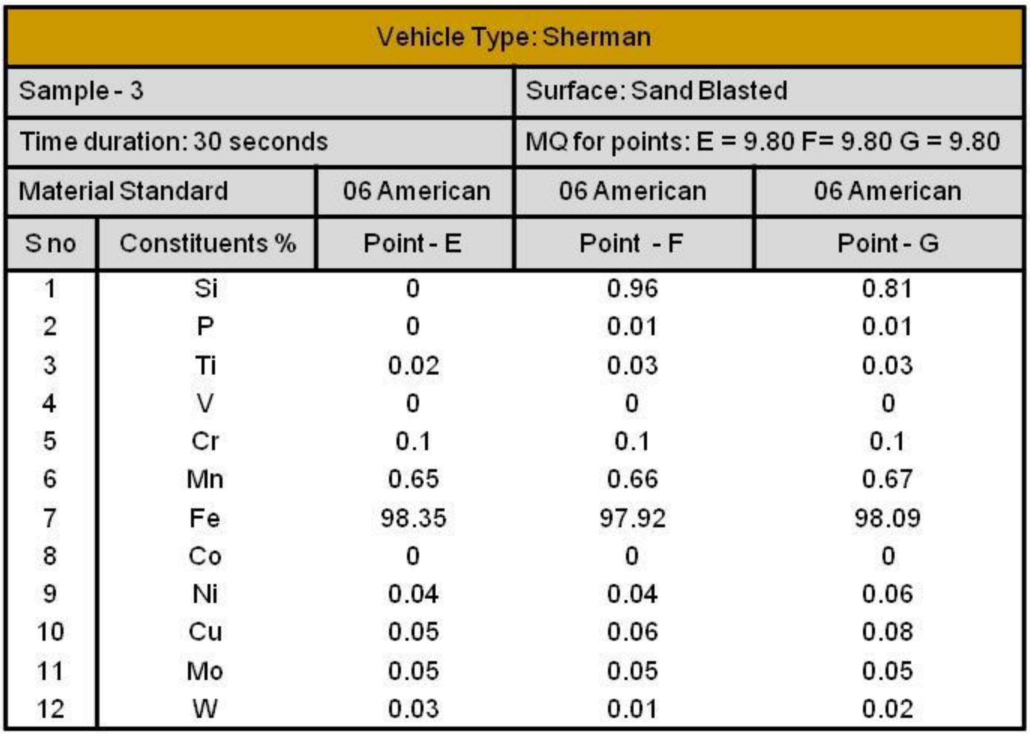


Figure: 5.3 Sherman Sample - 3 XRF of Cross Section at Point D

Table: 5.6 is the results of points E, F and G on the sandblasted surface. On average Fe (98.12%) was highest, Mn (0.66%) second highest and Si (0.59%) third highest. W (0.02%) was lowest and no traces of Co or V were identified.

Table: 5.6 Sherman Sample - 3 XRF of Sand Blasted Surface Points E, F and G

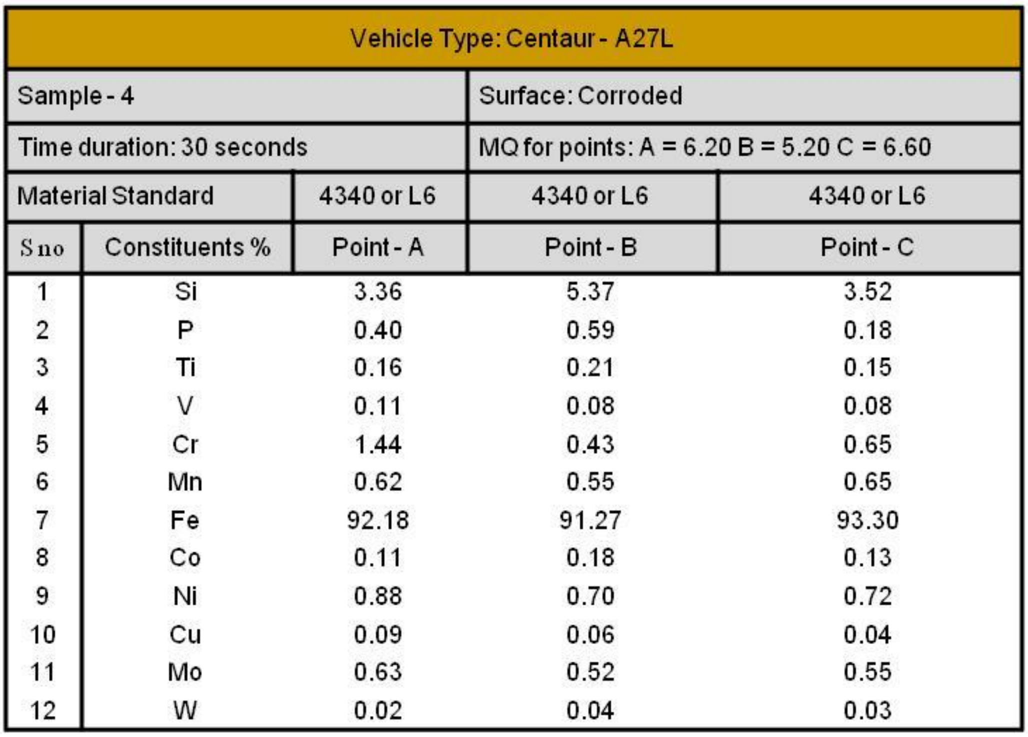


Vehicle Type: Sherman				
Sample - 3			Surface: Sand Blasted	
Time duration: 30 seconds			MQ for points: E = 9.80 F= 9.80 G = 9.80	
Material Standard		06 American	06 American	06 American
S no	Constituents %	Point - E	Point - F	Point - G
1	Si	0	0.96	0.81
2	P	0	0.01	0.01
3	Ti	0.02	0.03	0.03
4	V	0	0	0
5	Cr	0.1	0.1	0.1
6	Mn	0.65	0.66	0.67
7	Fe	98.35	97.92	98.09
8	Co	0	0	0
9	Ni	0.04	0.04	0.06
10	Cu	0.05	0.06	0.08
11	Mo	0.05	0.05	0.05
12	W	0.03	0.01	0.02

5.1.4. Centaur A27L Main Battle Tank Sample - 4

Table: 5.7 illustrate XRF analysis of the three points A, B and C at corroded surface. In this analysis on average Fe (92.25%) was the highest, Si (4.08%) was the second highest while lowest were V (0.09%) and (W 0.03%) respectively.

Table: 5.7 Centaur Sample - 4 XRF Results of Corroded Surface at Points A, B and C



Vehicle Type: Centaur - A27L				
Sample - 4			Surface: Corroded	
Time duration: 30 seconds			MQ for points: A = 6.20 B = 5.20 C = 6.60	
Material Standard		4340 or L6	4340 or L6	4340 or L6
Sno	Constituents %	Point - A	Point - B	Point - C
1	Si	3.36	5.37	3.52
2	P	0.40	0.59	0.18
3	Ti	0.16	0.21	0.15
4	V	0.11	0.08	0.08
5	Cr	1.44	0.43	0.65
6	Mn	0.62	0.55	0.65
7	Fe	92.18	91.27	93.30
8	Co	0.11	0.18	0.13
9	Ni	0.88	0.70	0.72
10	Cu	0.09	0.06	0.04
11	Mo	0.63	0.52	0.55
12	W	0.02	0.04	0.03

Figure: 5.4 show XRF of point D at the cross section. Fe (95.82%) was the highest; Cr (1.83%) was the second highest while P (0.05%) was lowest. No traces of Ti, Co and W were found.

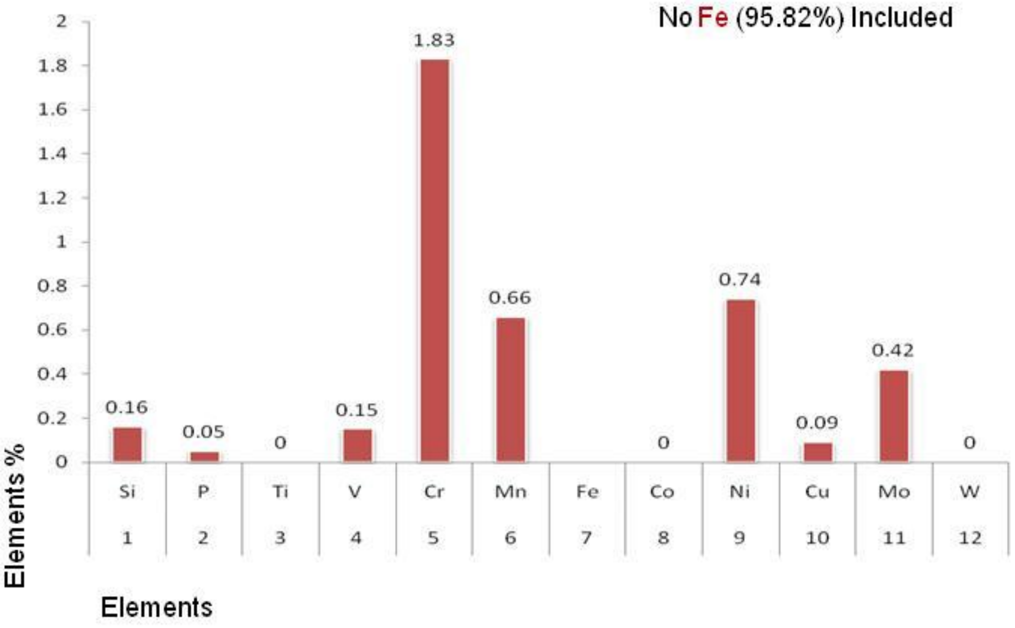
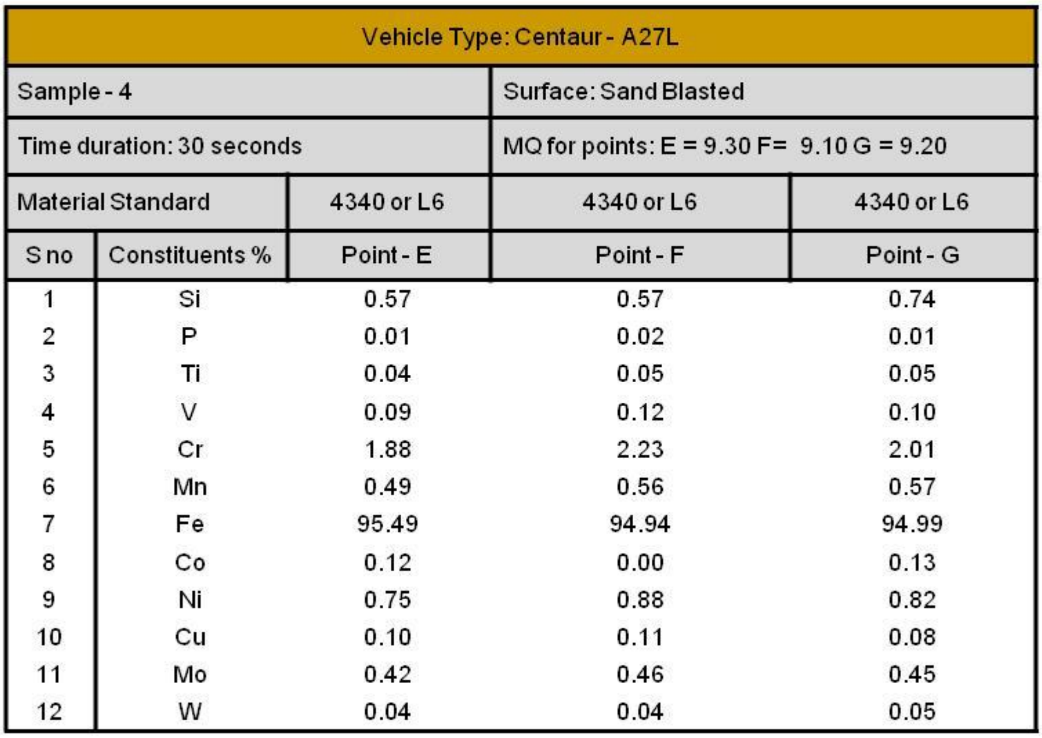


Figure: 5.4 Centaur Sample - 4 XRF of Cross Section at Point D

In Table: 5.8 XRF results of the sandblasted surface at three points E, F and G are given. On average Fe (95.14%) was the highest, Cr (2.04%) was the second highest and lowest was P (0.01%).

Table: 5.8 Centaur Sample - 4 XRF Results of Sand Blasted Surface E, F and G

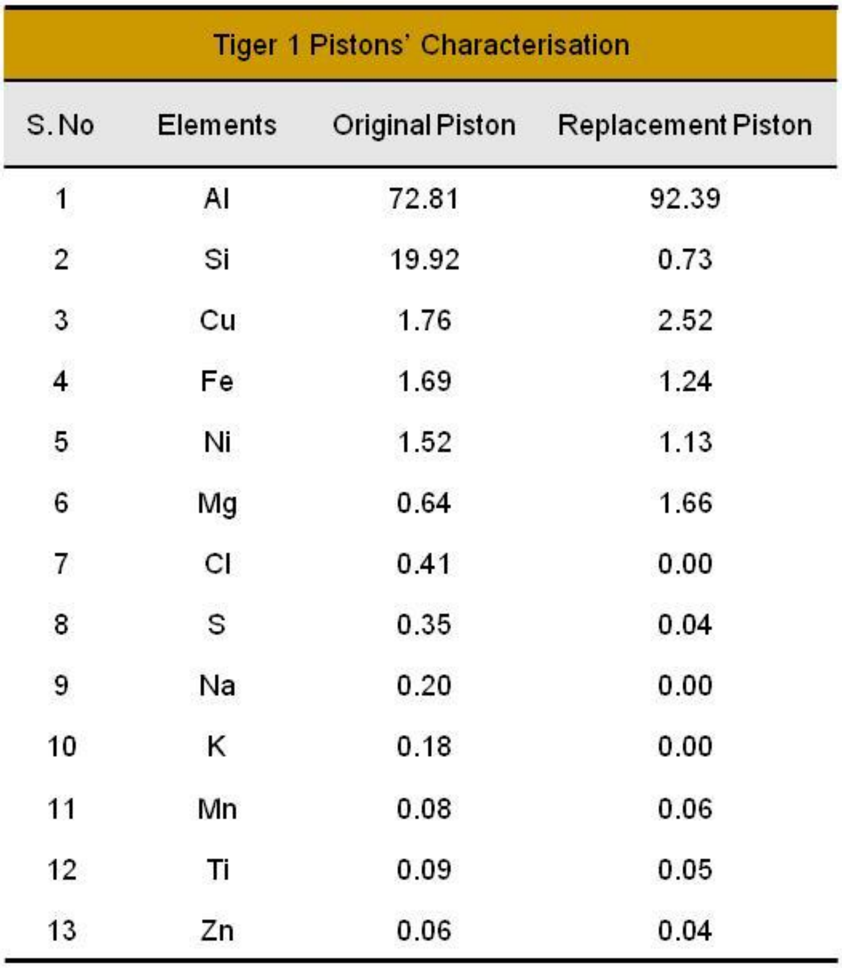


Vehicle Type: Centaur - A27L				
Sample - 4			Surface: Sand Blasted	
Time duration: 30 seconds			MQ for points: E = 9.30 F= 9.10 G = 9.20	
Material Standard		4340 or L6	4340 or L6	4340 or L6
S no	Constituents %	Point - E	Point - F	Point - G
1	Si	0.57	0.57	0.74
2	P	0.01	0.02	0.01
3	Ti	0.04	0.05	0.05
4	V	0.09	0.12	0.10
5	Cr	1.88	2.23	2.01
6	Mn	0.49	0.56	0.57
7	Fe	95.49	94.94	94.99
8	Co	0.12	0.00	0.13
9	Ni	0.75	0.88	0.82
10	Cu	0.10	0.11	0.08
11	Mo	0.42	0.46	0.45
12	W	0.04	0.04	0.05

5.1.5. Tiger 1 Original and Replacement Pistons

Table: 5.9 illustrate elemental identification results of the Tiger’s original and replacement pistons. Results revealed that the original piston was aluminium silicon hyper-eutectic alloy whereas the replacement piston was aluminium copper alloy with very low silicon (Si) content. Zinc (Zn), calcium (Ca), chlorine (Cl) and sulphur (S) as residues, possibly transported as contaminants by the lubricating oil, were also detected in the characterisation.

Table: 5.9 Tiger 1 Original and Replacement Pistons Characterisation Results



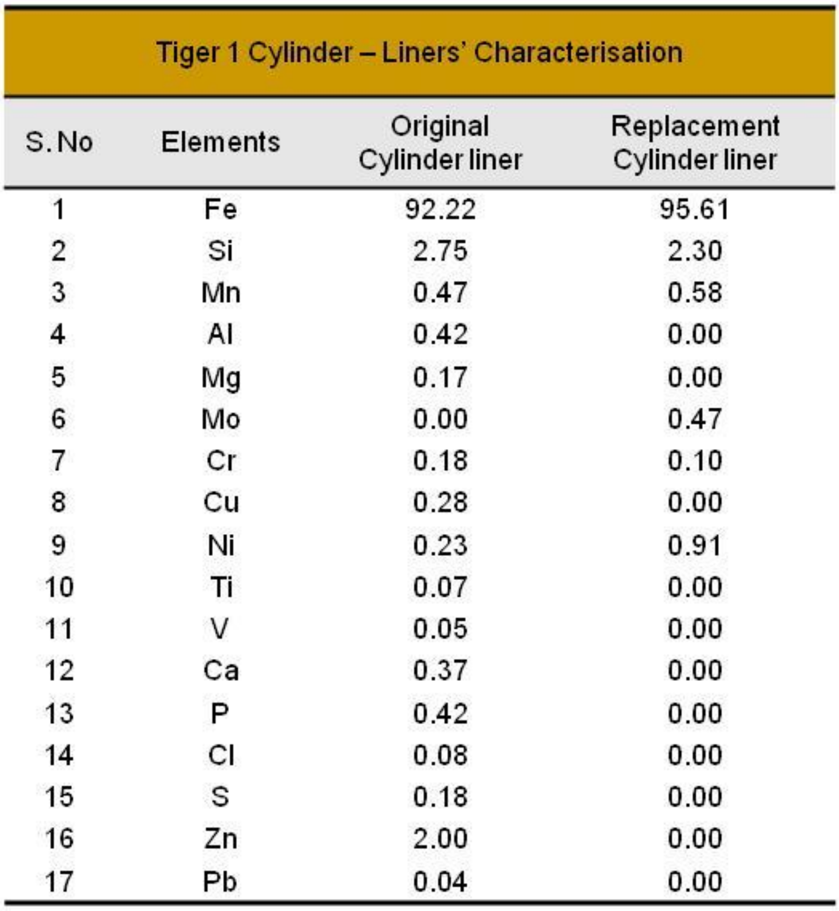
Tiger 1 Pistons' Characterisation

S. No	Elements	Original Piston	Replacement Piston
1	Al	72.81	92.39
2	Si	19.92	0.73
3	Cu	1.76	2.52
4	Fe	1.69	1.24
5	Ni	1.52	1.13
6	Mg	0.64	1.66
7	Cl	0.41	0.00
8	S	0.35	0.04
9	Na	0.20	0.00
10	K	0.18	0.00
11	Mn	0.08	0.06
12	Ti	0.09	0.05
13	Zn	0.06	0.04

5.1.6. Tiger 1 Original and Replacement Cylinder-liners

WD - XRF results to identify elements in both the original and replacement cylinder liners are given in Table: 5.10. Results indicate in both liners Fe as the main element which is indicative of being made of cast-iron, a common alloy for such applications. Identification of elements such as Zn, Ca and S is likely to be a residue of lubricating oil. Characterisations of the replacement cylinder-liner revealed Fe and Si as the main elements.

Table: 5.10 Tiger 1 of Original and Replacement liners WD-XRF Results



Tiger 1 Cylinder – Liners' Characterisation

S.No	Elements	Original Cylinder liner	Replacement Cylinder liner
1	Fe	92.22	95.61
2	Si	2.75	2.30
3	Mn	0.47	0.58
4	Al	0.42	0.00
5	Mg	0.17	0.00
6	Mo	0.00	0.47
7	Cr	0.18	0.10
8	Cu	0.28	0.00
9	Ni	0.23	0.91
10	Ti	0.07	0.00
11	V	0.05	0.00
12	Ca	0.37	0.00
13	P	0.42	0.00
14	Cl	0.08	0.00
15	S	0.18	0.00
16	Zn	2.00	0.00
17	Pb	0.04	0.00

5.2. Conclusions

5.2.1. M10, Sherman and Centaur

The main purpose of the material characterisation was to understand the material which was processed and utilised in the manufacture of the tanks during 2nd World War. Characterisation indicates low C steel for all the samples examined.

Cross section of the Centaur A27L showed Fe the main element with Mn and Cr the highest and approximately matches AISI 4000 series steel. For Sherman M4A1 and M10 the main alloying element was Mn and approximately matches AISI 1000 series steel.

Alloying elements such as Mn, Cr, V, W and Mo, act as hardening agents and improve hardness, ductility and tensile strength [85]. Mo was found in a variation of 0.05% to 0.63%. Mo forms hard and stable carbides and has the sixth highest melting point and for this reason it is used in high strength steel alloys, cast iron and super alloys to enhance harden-ability, strength, toughness and for wear and corrosion resistance [7]. Additionally Mn and P are also used for rust and corrosion prevention.

5.2.2. Tiger 1 Characterisation of Original and Replacement Pistons

Original piston characterisation results are shown in Table: 5.9 and match specifications of RSA - 419 AE, AA 4019 and AA 4048 aluminium alloy. Si percentage is 19.92 and the results indicate that the original piston is hyper-eutectic Al-Si alloy. The classification of Al-Si alloy in three categories (a) hypoeutectic less than 11% Si (b) eutectic 11-13% Si and (c) hyper-eutectic with more than 13% Si has been well reported [86, 87]. Al-Si pistons provide low density, high wear resistance, good strength-to-weight ratio, good thermal conductivity and resistance to corrosion and wear in petrol engines of industrial, aerospace and military applications [88, 89]. Petrol engines operate under severe conditions of high temperatures and gas pressure and therefore for piston material it is necessary to have excellent temperature and mechanical properties in-order to resist changes influenced by elevated temperatures [88, 90]. Other elements such as Ni, Fe, Ti and Mn detected in the characterisation are added for the purpose of improving the tensile properties and strengthening of α-Al matrix [88, 91, 92].

Characterisation results of the replacement piston approximately match specification of Al 2031 and Al 2618-T6 series. According to the results the replacement piston can be classified as hypo-eutectic piston [86, 87]. Eutectic and hyper-eutectic versions possess better properties compared to hypo-eutectic and for this reason the use of hypo-eutectic versions has been phased out in many applications.

The percentage of Si is significantly low at only 0.73 %. Silicon is a very important part of Al-Si piston alloys and hard Si precipitates within the aluminium matrix are directly related to greater strength, scuff, seizure resistance and provide better resistance to sudden temperature fluctuations [93, 94].

5.2.3. Tiger 1 Characterisation of Original and Replacement cylinder-liners

WD - XRF results in Table: 5.10 of the original cylinder-liner approximately meet the specifications of SAE J431, BS 220, UNS F33100 and UNS F34100. Fe is the main element present, so indicating that the liner is of cast iron. The source of elements such as Zn, Ca and S is likely to be a residue of lubricating oil. Characterisations of the replacement cylinder-liner revealed Fe and Si as the main elements.

Phosphorus (P) was detected in the original-liner but not for the replacement. P content generates better properties for wear and scuffing resistance. In addition alloying elements such as chromium (Cr), copper (Cu), molybdenum (Mo), nickel (Ni), titanium (Ti) and vanadium (V) enhances wear resistance when added [10].

Chapter 6 **Corrosion Damage Assessment**

This chapter details results of the corrosion investigation in two parts. In first part ultrasonic scanning was conducted to record material loss due to corrosion in the M10, Sherman, Centaur, BT R 60 and King Tiger. For M10, Sherman and Centaur sample samples shown in Figure: 3.2 were used. Samples for BT – R60 and King Tiger are discussed in the relevant sections. The exact dimension of each sample is also explained in the relevant section. Corrosion mapping revealed significant material loss because of corrosion. In the second part surface corrosion and corrosion propagation (corrosion layer depth) into the sub-surface have been analysed. These analyses identified various cracks, corrosion pits in and other anomalies both on the surfaces as well as in the cross section of the samples.

The novelty of the current research lies in the fact of fully characterising structural materials where information and specifications were not complete or scarce. The current research provides understating of the failure mechanisms due to corrosion and linkages to the materials' characteristics. These results will inform an optimised design solution of controlled environment and preventative measures for the vehicles kept in uncontrolled environments.

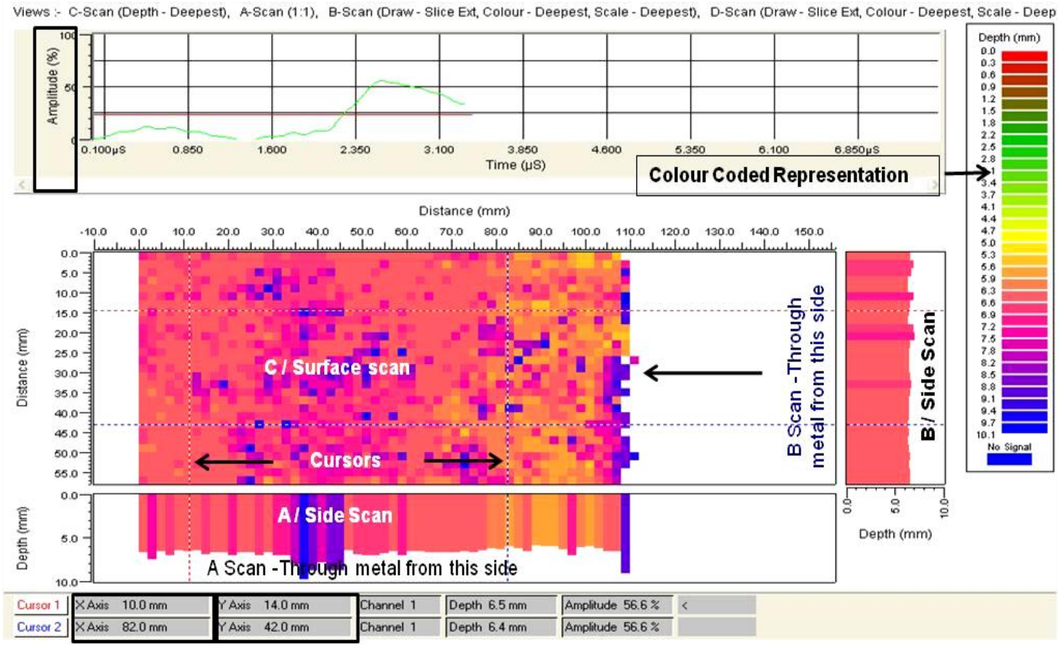
6.1. Ultrasonic Scanning

Ultrasonic scanning was conducted using pulse-echo followed by phased array methods. These are two novel scanning methods to map corrosion in metal structures. Result illustrated remarkable material loss in all the samples. Table: 6.1 provide the ultrasonic scan results for five maximum and minimum remaining thicknesses for the samples from M10, Sherman and Centaur. M10 Sample - 2 did not fulfil the required specification for ultrasonic scanning, thus this method was not performed on it.

6.1.1. M10 Tank Destroyer Sample - 1

First scan was conducted using pulse echo method on the M10 sample-1using a 4 MHz twin crystal transducer with a 10 mm diameter. Hi pass and low pass analogue signal filtre frequencies were set at 0.25 MHz and 10 MHz respectively. Data was collected every 2 mm on a total area of 102 mm length with 6.04 pulses/mm and 94 mm width with 3.58 pulses/mm. Compression waves with a velocity of 5903 m/sec and a probe delay of 7.63 µs were used.

Figure: 6.1 show C – Scan (surface scan) and side views (A and B scan) of data collected from the ultrasonic scan. A colour coded palette with scale starting from maximum 10 mm (blue) and gradually decreasing to 0.00 mm minimum (red) for visual representation of the remaining thicknesses is also given. Two cursors, red and blue, illustrate X and Y co-ordinates and corresponding remaining thicknesses of the particular points.

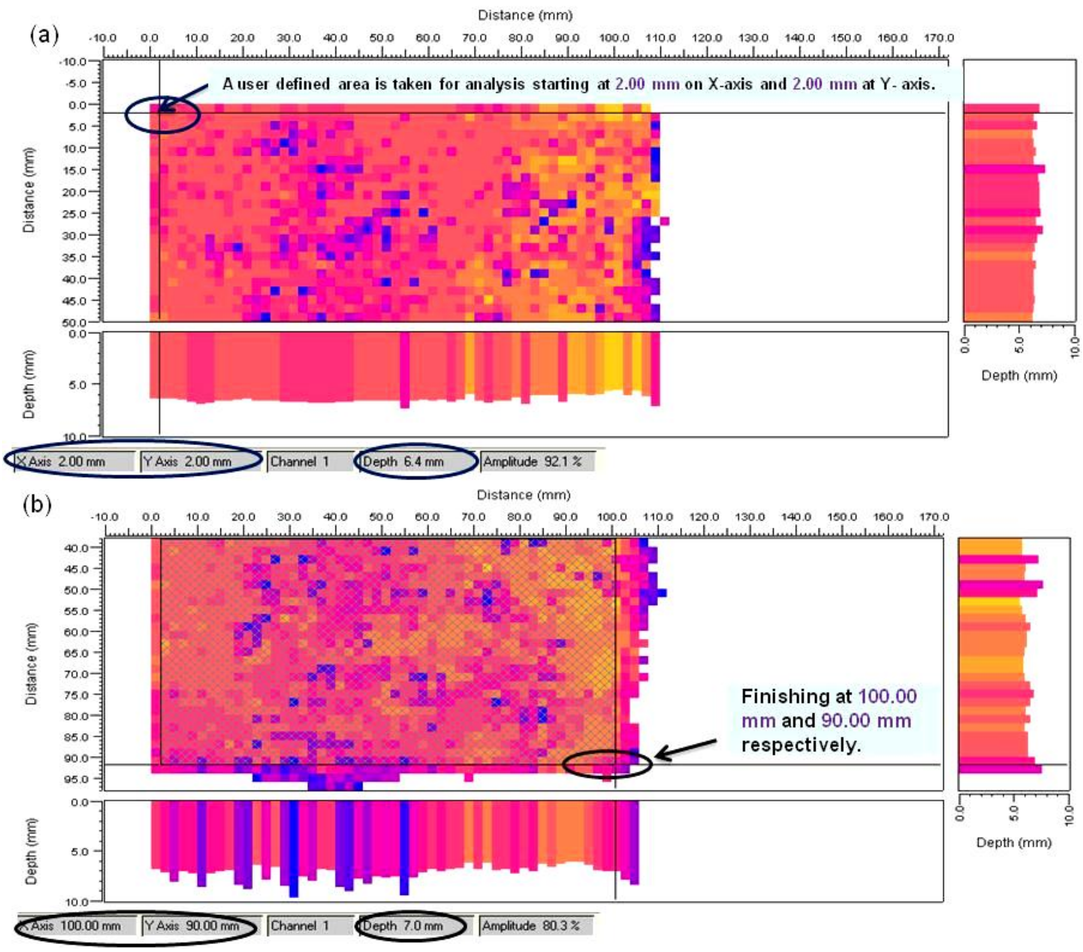


Views :- C-Scan (Depth - Deepest), A-Scan (1:1), B-Scan (Draw - Slice Ext, Colour - Deepest, Scale - Deepest), D-Scan (Draw - Slice Ext, Colour - Deepest, Scale - Deep

Cursor 1	X Axis 10.0 mm	Y Axis 14.0 mm	Channel 1	Depth 6.5 mm	Amplitude 56.6 %	<
Cursor 2	X Axis 82.0 mm	Y Axis 42.0 mm	Channel 1	Depth 6.4 mm	Amplitude 56.6 %	

Figure: 6.1 M10 Sample-1 Ultrasonic Surface Scan

A user defined area shown in Figure: 6.2, was taken for analysis starting at 2 mm on X - axis, 2 mm at Y - axis and finishing at 100 mm and 90 mm respectively. Scans at the edges were ignored to avoid any possible spurious/distorted signals in the analysis.



A user defined area is taken for analysis starting at 2.00 mm on X-axis and 2.00 mm at Y- axis.

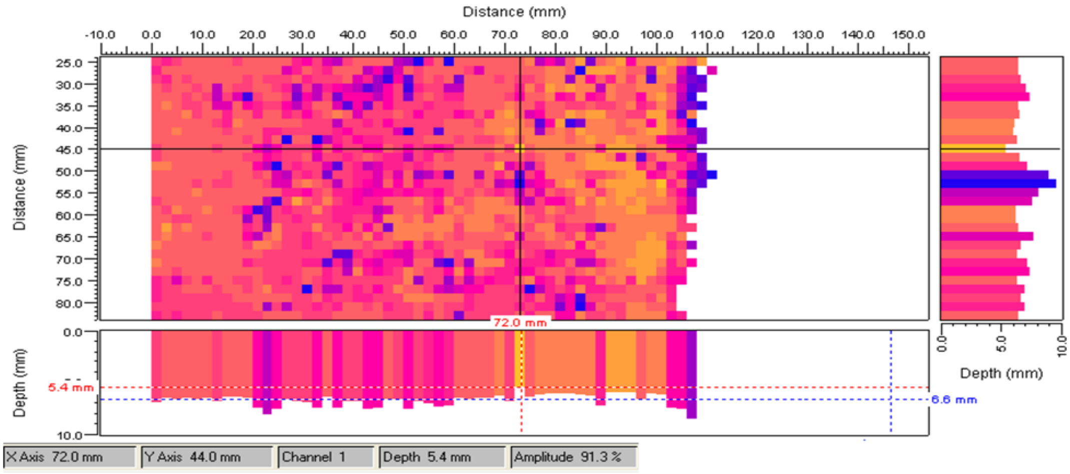
X Axis 2.00 mm | Y Axis 2.00 mm | Channel 1 | Depth 6.4 mm | Amplitude 92.1 %

Finishing at 100.00 mm and 90.00 mm respectively.

X Axis 100.00 mm | Y Axis 90.00 mm | Channel 1 | Depth 7.0 mm | Amplitude 80.3 %

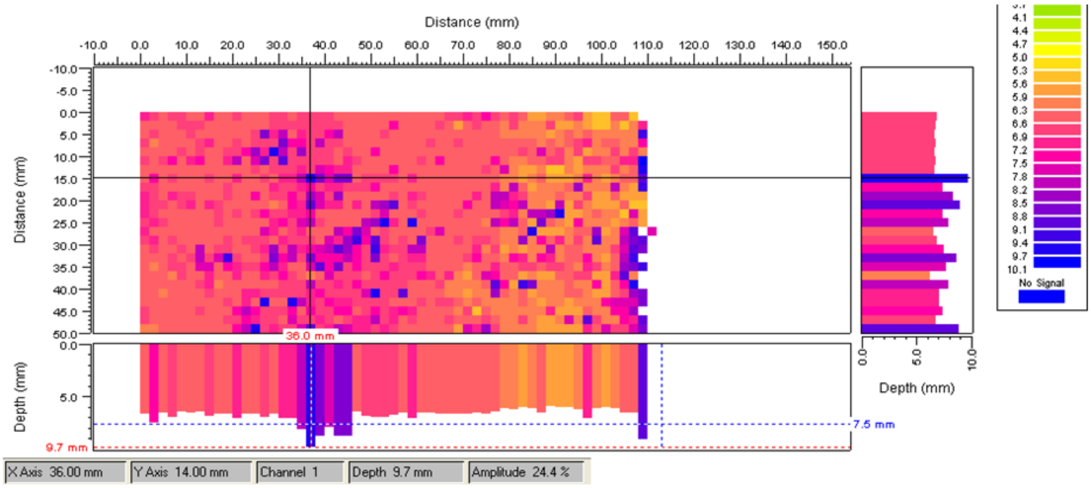
Figure: 6.2 M10 Sample - 1 Ultrasonic Surface Analysis

Figure: 6.3 demonstrates a severe material loss in the sample, recording a minimum thickness of 5.40 mm at horizontal position of 72 mm and vertical position of 44 mm while the maximum remaining thickness is 9.70 mm at horizontal position of 36 mm and vertical position of 14 mm shown in Figure: 6.4. The thickness of 9.70 mm has been recorded at six different points. The second lowest depth recorded is 5.60 mm at horizontal position of 98 mm and vertical position of 2 mm, the remaining thickness of 5.60 mm is recorded at three different points in the scan. The third lowest recorded remaining thickness is 5.70 mm at a horizontal position of 92 mm and vertical position of 12 mm and has been recorded at five different points.



X Axis 72.0 mm | Y Axis 44.0 mm | Channel 1 | Depth 5.4 mm | Amplitude 91.3 %

Figure: 6.3 M10 sample-1 PE Scan illustrate Minimum Thickness



X Axis 36.00 mm | Y Axis 14.00 mm | Channel 1 | Depth 9.7 mm | Amplitude 24.4 %

Figure: 6.4 M10 Sample - 1 PE Scan show Maximum Thickness

The phased array scan was performed using a 4 MHz probe. Hi pass and low pass analogue signal filtre frequencies were set at 0.25 MHz and 10 MHz respectively. Analyses were conducted every 1 mm using compression waves at a velocity of 5903 m/sec and a probe delay of 7.06 µs. Figure: 6.5 show the signal amplitude in A-scan, side view in B-scan, and depth and surface position in C-scan.

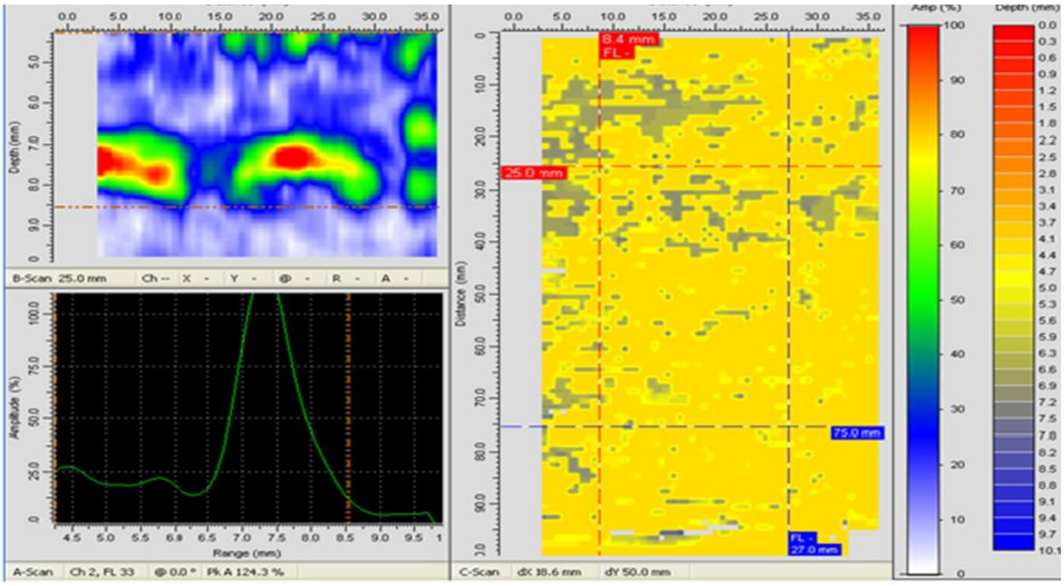


Figure: 6.5 M10 Sample - 1 PA Scan

6.1.2. Sherman Military Tank Sample - 3

Pulse echo scanning was conducted on the Sherman M4A1 with a probe of 4 MHz twin crystal and 10 mm diameter using 0.25 MHz Hi pass filtre and 10 MHz low pass filtre frequencies with a probe delay of 7.63 µS. Compression waves with a velocity of 5903 M/sec are used to scan a total area of 174 mm length with 6.040 pulses/mm and 68 mm width with 3.58 pulses/mm mapping material loss every 2 mm on the sample. Figure: 6.6 show end views and c-scan of the sample with implementation of colour coding, red for 0 mm and green for 10 mm. Cursors show x-y locations and corresponding depths of particular points on the sample.

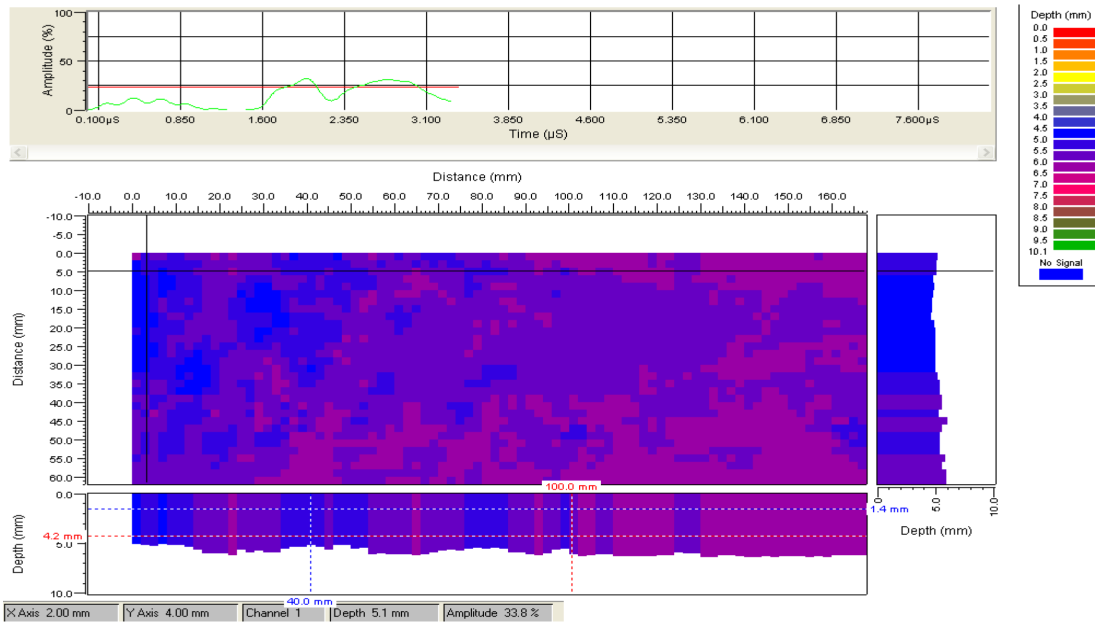
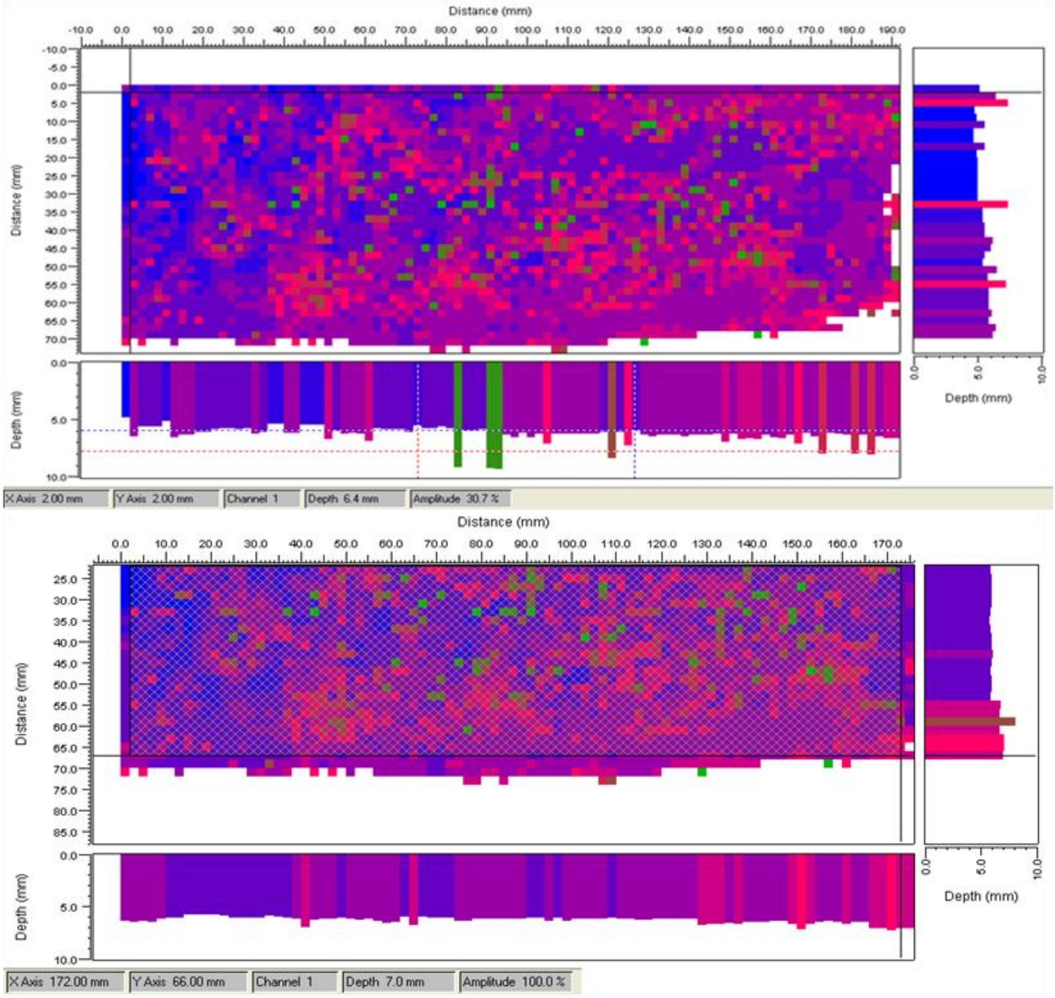


Figure: 6.6 Sherman Sample - 3 PE Scan

User defined area was taken to find maximum and minimum thicknesses starting at 2 mm on X-axis, 2 mm on Y-axis shown in Figure: 6.7 and finishing at 172 mm on x-axis and 66 mm at y-axis respectively. Scan at edges of the samples was ignored to avoid any possible distorted in signals in the analysis.



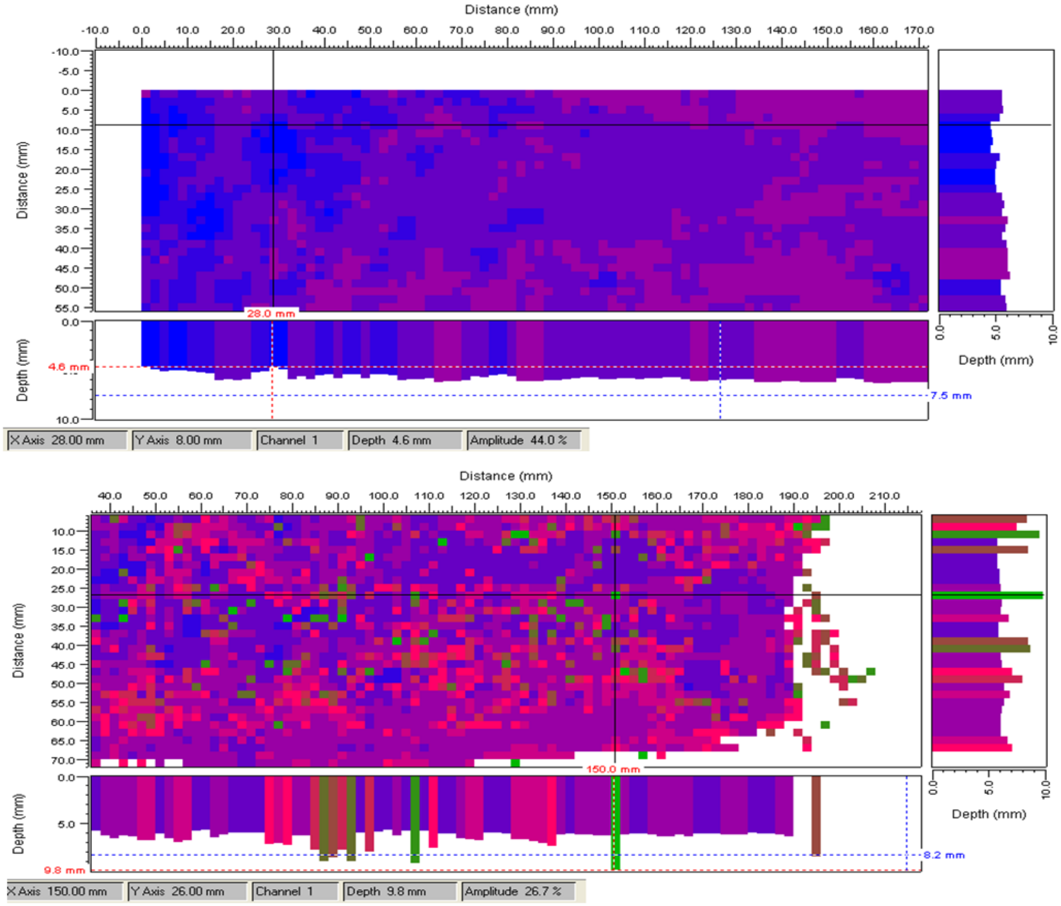
X Axis 2.00 mm | Y Axis 2.00 mm | Channel 1 | Depth 6.4 mm | Amplitude 30.7 %

X Axis 172.00 mm | Y Axis 66.00 mm | Channel 1 | Depth 7.0 mm | Amplitude 100.0 %

Figure: 6.7 Sherman Sample - 3 User Defined Area Start and Finishing Points

Scan detected maximum remaining thickness of 9.80 mm at horizontal position of 150 mm and vertical position of 26 mm with a drastic loss in material to a minimum of 4.60 mm at horizontal position of 28 mm and vertical position of 8 mm illustrated in

Figure: 6.8. The maximum thickness of 9.8 mm is recorded at two different points. Second lowest thickness was 4.7 mm and was detected at seven different positions. Third lowest thickness of 4.8 mm was recorded at six various points and the remaining thickness of 4.9 mm was recorded at four different points. The minimum remaining thickness of 4.6 mm is recorded at three different points.



X Axis 28.00 mm | Y Axis 8.00 mm | Channel 1 | Depth 4.6 mm | Amplitude 44.0 %

X Axis 150.00 mm | Y Axis 26.00 mm | Channel 1 | Depth 9.8 mm | Amplitude 26.7 %

Figure: 6.8 Sherman Sample - 3 PE Scan of Minimum and Maximum Thicknesses

The Phased array scan was performed using a 4 MHz probe. The Hi pass and low pass analogue signal filtre frequencies were set at 0.25 MHz and 10 MHz respectively. Data was collected every 1 mm using compression waves at a velocity of 5903 m/sec and a probe delay of 7.06 µs. Figure: 6.9 show the amplitude and range in the A-Scan, depth and signal amplitude as a side view in B-Scan, and depth & surface position in C-Scan.

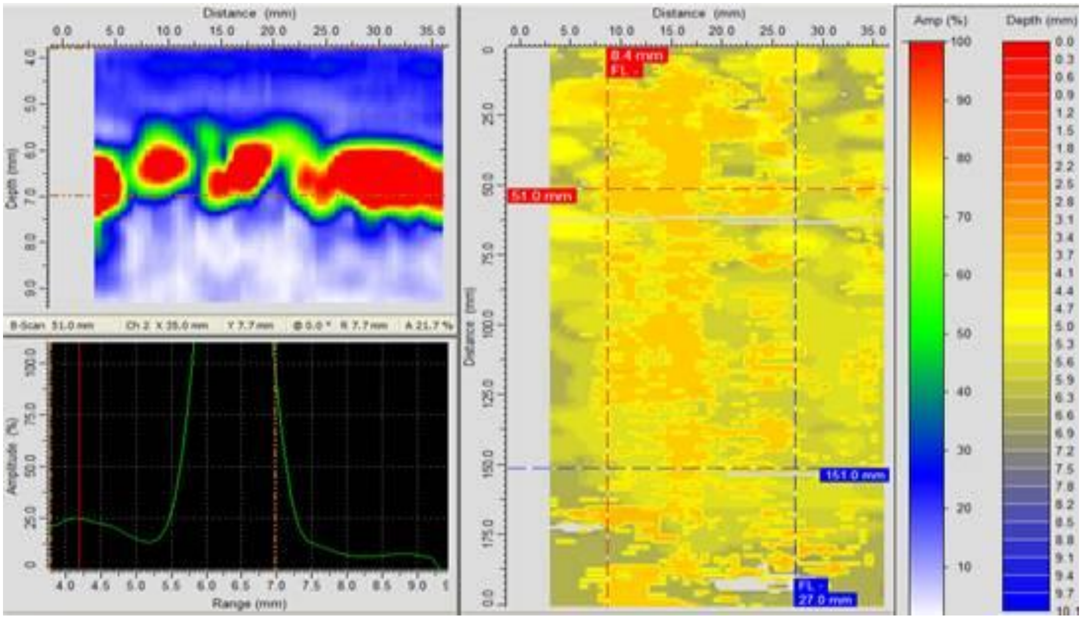
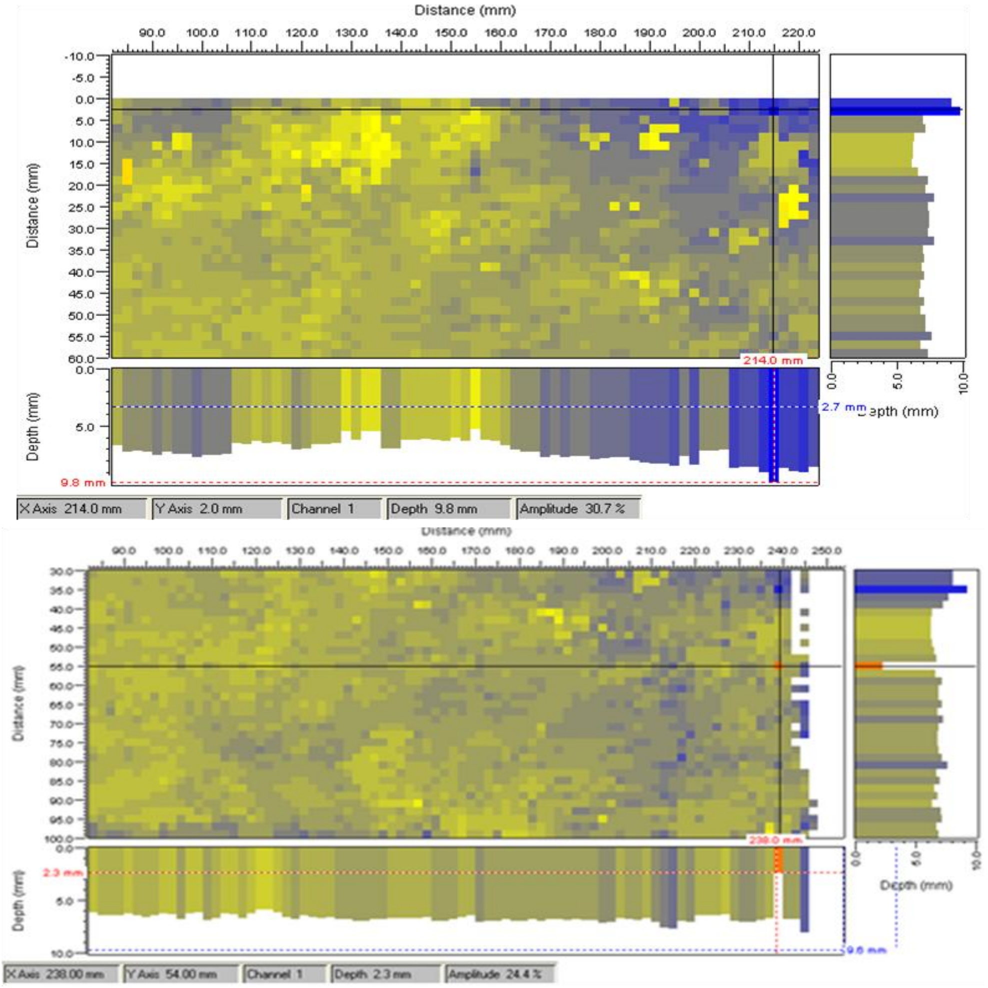


Figure: 6.9 Sherman Sample - 3 PA Scan

6.1.3. Centaur A27L Main Battle Tank Sample - 4

PE and PA ultrasonic scanning was conducted on Centaur A27L (MBT) using same operating and working settings described above for M10 and Sherman.

A user defined area was taken for finding the minimum and maximum thicknesses starting at 2 mm on x-axis, 2 mm on y-axis and finishing at 240 mm on x-axis and 96 mm at Y-axis respectively to avoid any possible distorted signals at the edges. Maximum thickness of 9.80 mm at horizontal position of 214 mm and vertical position of 2 mm with a drastic material loss to a minimum of 2.30 mm at horizontal position of 238 mm and vertical position of 54 mm shown in Figure: 6.10 was detected. The second lowest depth was 3.6 mm at horizontal position of 14 mm and vertical position of 8.00 mm on the sample and the third lowest depth recorded was 3.8 mm at horizontal position of 10 mm and vertical position of 4 mm. The remaining thickness of 3.6 mm was detected at two and 3.8 mm was detected at five various points.

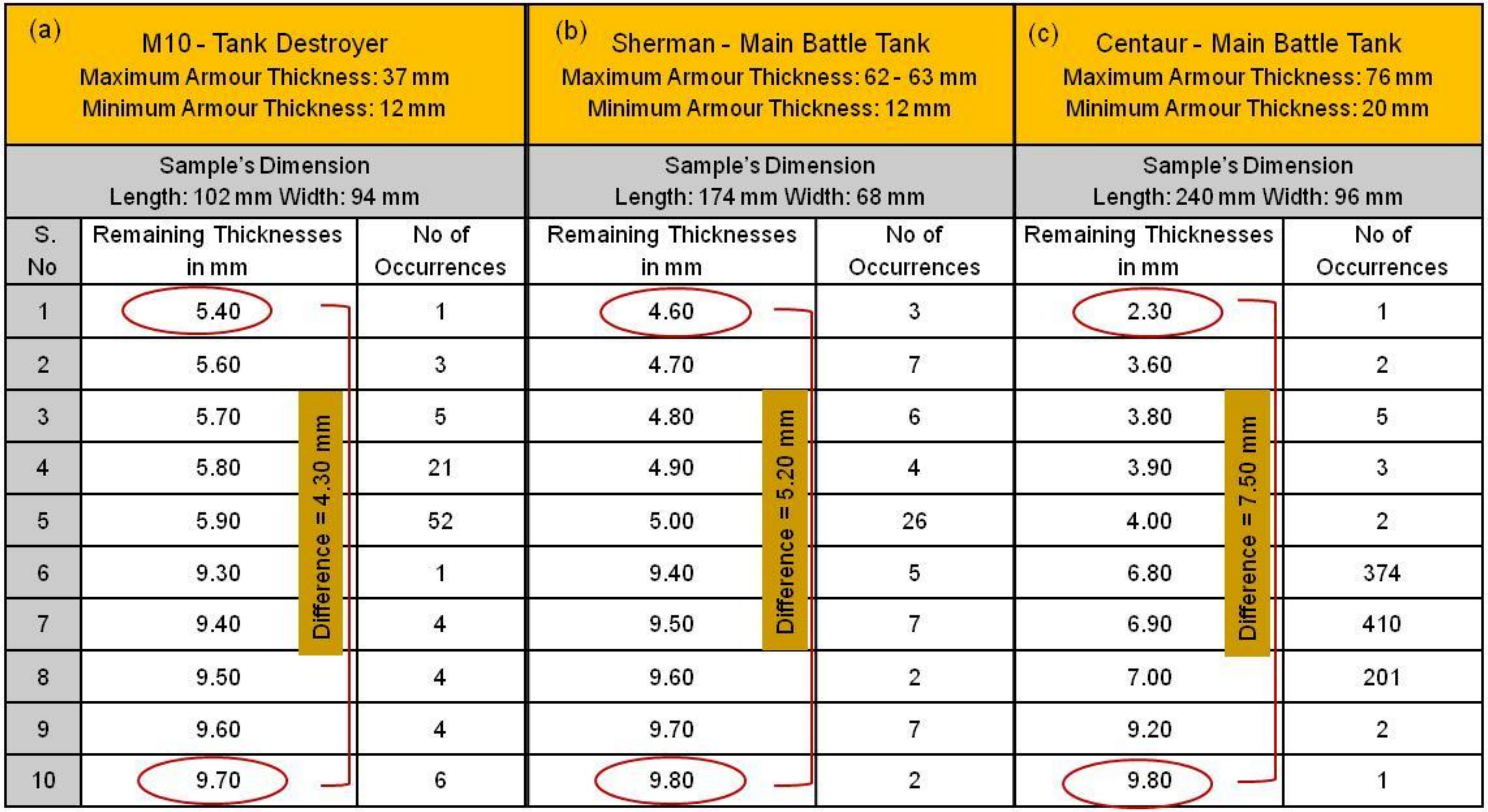


X Axis 214.0 mm | Y Axis 2.0 mm | Channel 1 | Depth 9.8 mm | Amplitude 30.7 %

X Axis 238.00 mm | Y Axis 54.00 mm | Channel 1 | Depth 2.3 mm | Amplitude 24.4 %

Figure: 6.10 Centaur Sample - 4 PE Scan of Maximum and Minimum Thicknesses

Table: 6.1 Surface Thickness' Profile of 5 Lowest and Highest Points



	(a) M10 - Tank Destroyer Maximum Armour Thickness: 37 mm Minimum Armour Thickness: 12 mm		(b) Sherman - Main Battle Tank Maximum Armour Thickness: 62 - 63 mm Minimum Armour Thickness: 12 mm		(c) Centaur - Main Battle Tank Maximum Armour Thickness: 76 mm Minimum Armour Thickness: 20 mm	
	Sample's Dimension Length: 102 mm Width: 94 mm		Sample's Dimension Length: 174 mm Width: 68 mm		Sample's Dimension Length: 240 mm Width: 96 mm	
S. No	Remaining Thicknesses in mm	No of Occurrences	Remaining Thicknesses in mm	No of Occurrences	Remaining Thicknesses in mm	No of Occurrences
1	5.40	1	4.60	3	2.30	1
2	5.60	3	4.70	7	3.60	2
3	5.70	5	4.80	6	3.80	5
4	5.80	21	4.90	4	3.90	3
5	5.90	52	5.00	26	4.00	2
6	9.30	1	9.40	5	6.80	374
7	9.40	4	9.50	7	6.90	410
8	9.50	4	9.60	2	7.00	201
9	9.60	4	9.70	7	9.20	2
10	9.70	6	9.80	2	9.80	1

6.1.4. Russian BT R – 60 Armoured Personal Carrier Sample – 5

Sample from the Russian BT – R 60 was analysed using PE method of ultrasonic scanning on the same equipment settings. Figure: 6.11 illustrate the image of the sample and the corresponding ultrasonic scan.

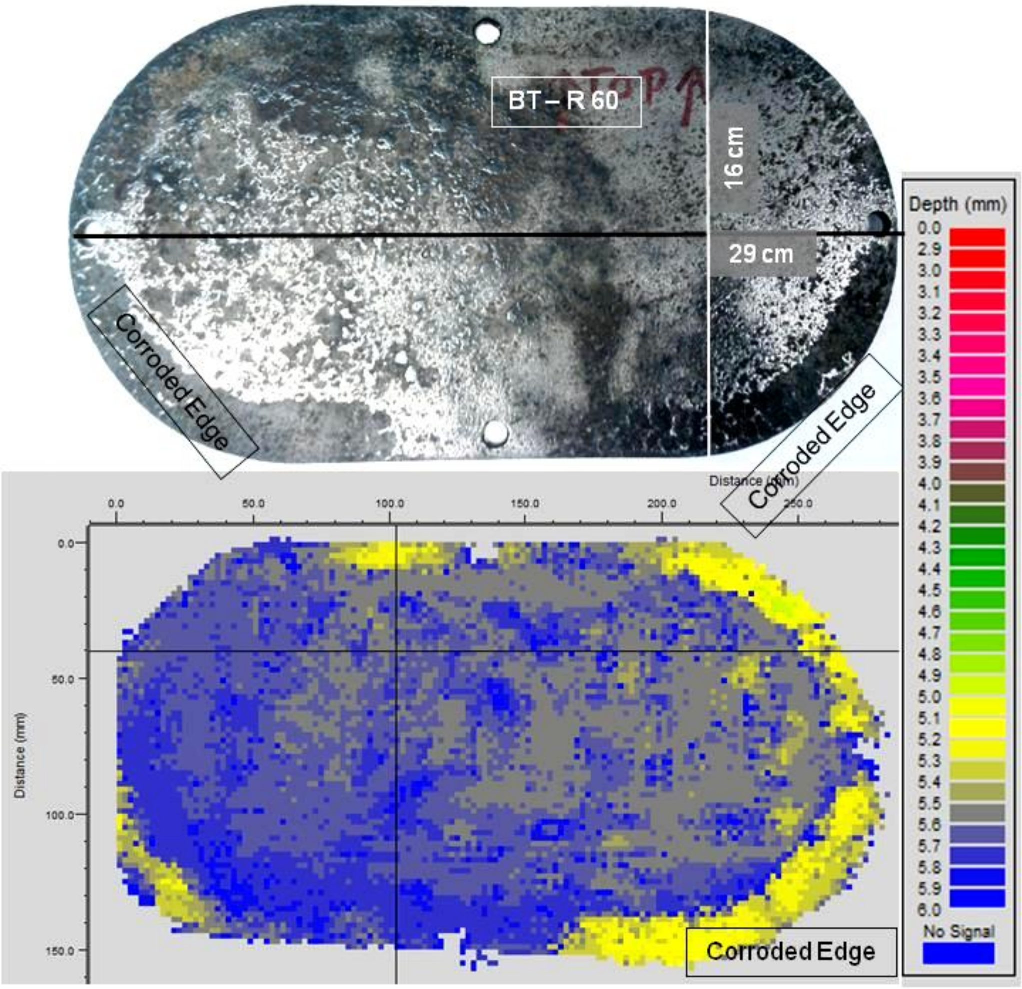
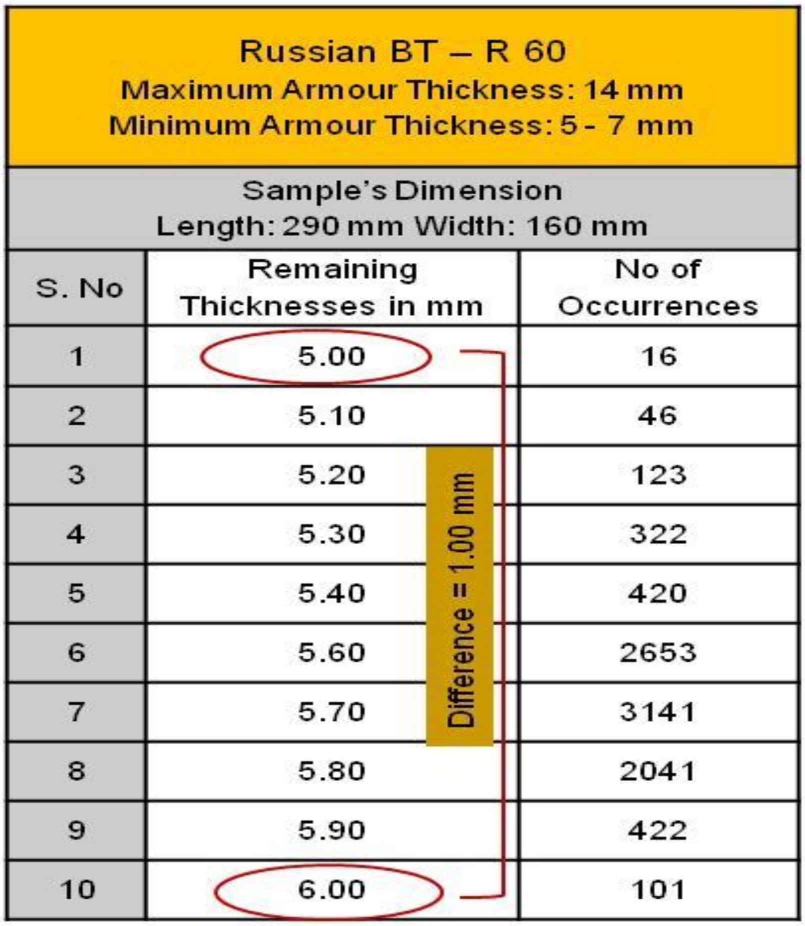


Figure: 6.11 BT R - 60 Sample's Image and Ultrasonic Scan

Corrosion mapping results of five lowest and highest remaining thicknesses' are provided in Table: 6.2. A difference of 1mm material loss was recorded on the sample selected for the corrosion mapping between the maximum and minimum remaining thicknesses. A consistent decrease in the component thickness was observed.

Table: 6.2 BT R - 60 Samples' Scan Results for 5 Highest and Lowest Thicknesses



Russian BT – R 60
Maximum Armour Thickness: 14 mm
Minimum Armour Thickness: 5 - 7 mm

Sample's Dimension
Length: 290 mm Width: 160 mm

S. No	Remaining Thicknesses in mm	No of Occurrences
1	5.00	16
2	5.10	46
3	5.20	123
4	5.30	322
5	5.40	420
6	5.60	2653
7	5.70	3141
8	5.80	2041
9	5.90	422
10	6.00	101

6.1.5. King Tiger Sample – 6

Sample from the King Tiger shown in Figure: 6.12 was one of the most difficult for the ultrasonic scanning. Sample's surface was uneven, had welded threaded rods and holes.

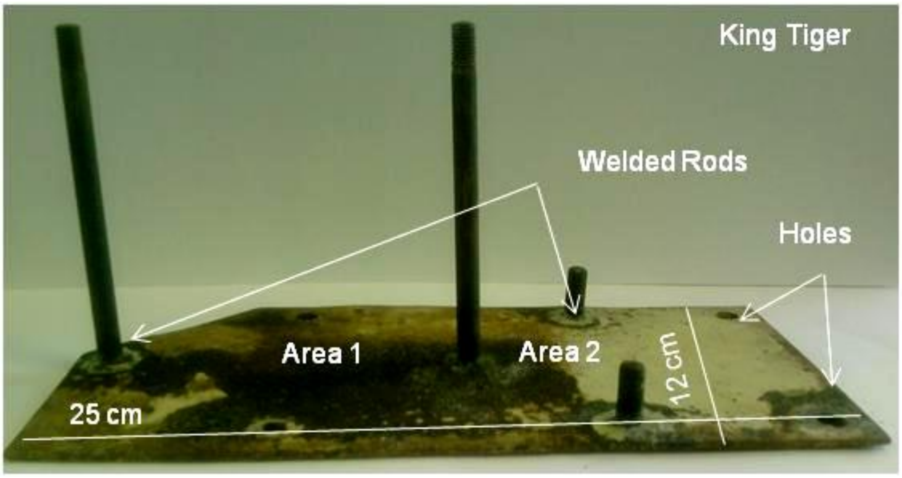


Figure: 6.12 King Tiger Sample collected for Ultrasonic Scan

Ultrasonic scan was conducted through PE method using a twin crystal probe of 10 mm diameter. The surface scan of the sample is shown in Figure: 6.13. Surface of the sample was not even and the welds at the bottom of the rods were raised and occupying areas which were thick from the rest of the samples' surface. The raised welds provided higher thicknesses in the scan so for that reason data of the two areas 1 and 2 was obtained shown in Figure: 6.13.

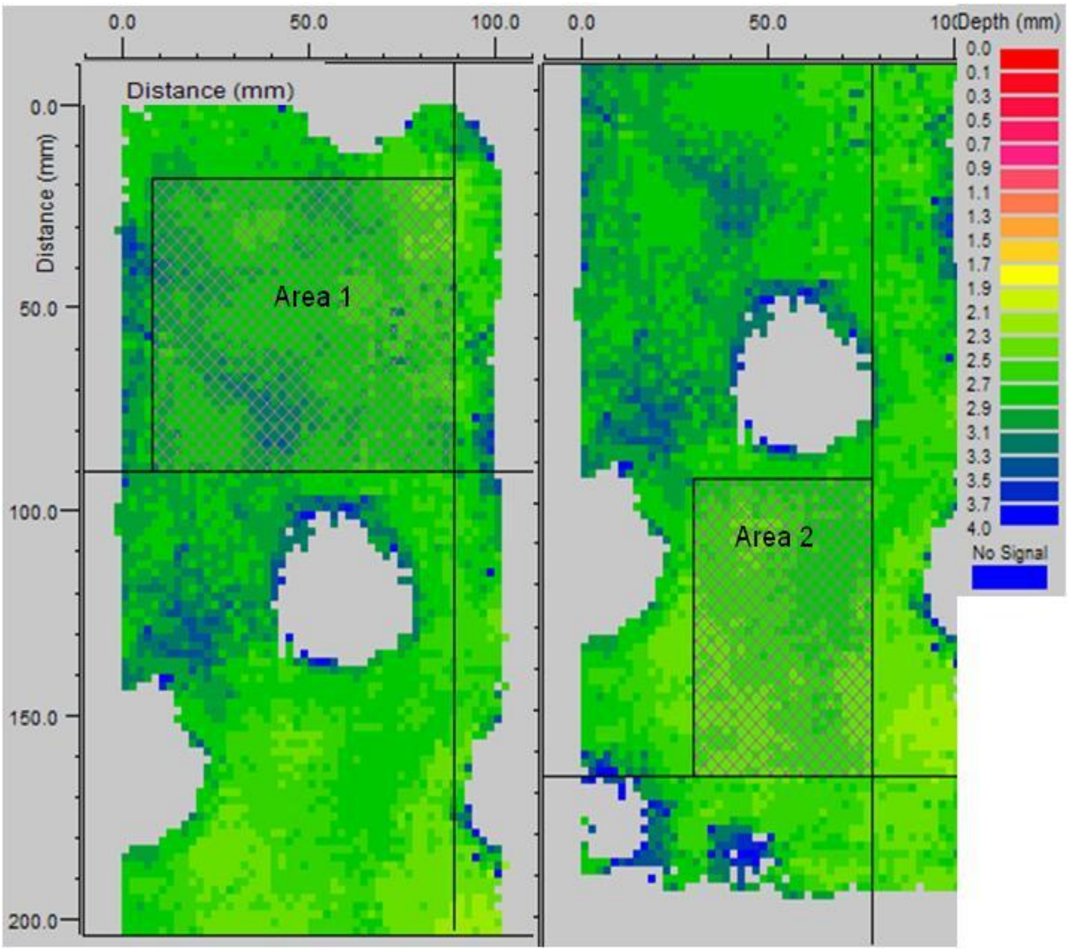
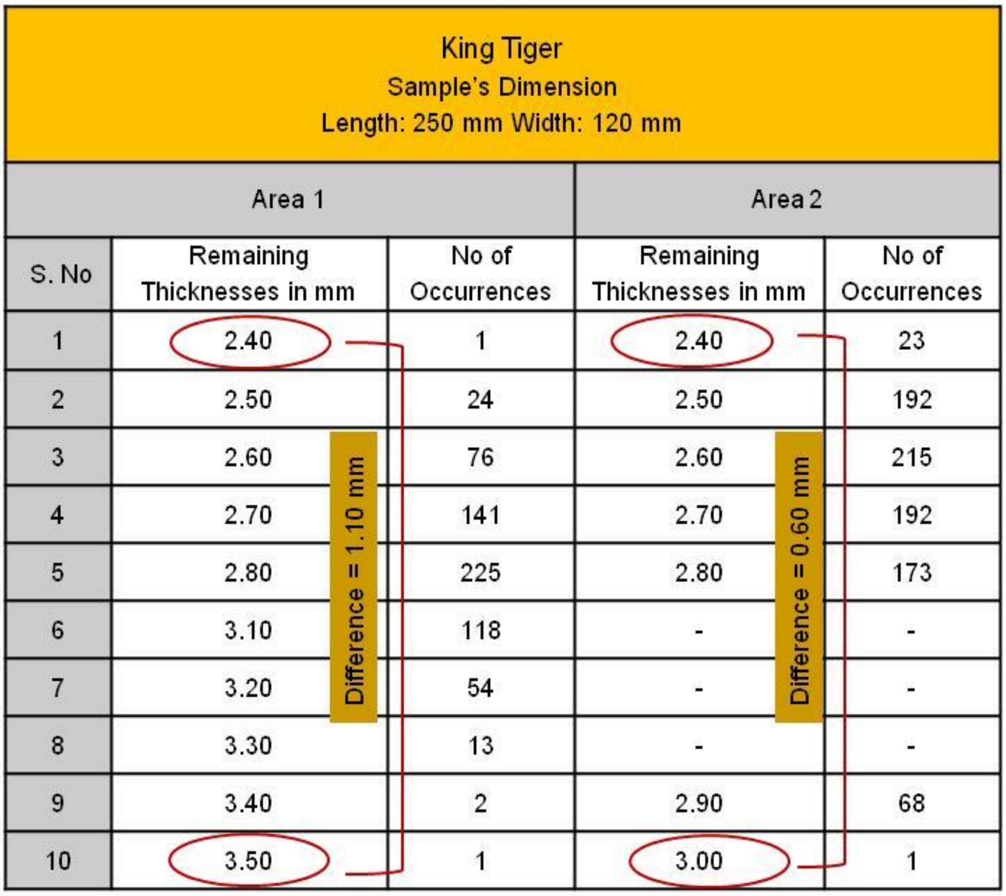


Figure: 6.13 King Tiger Surface Scan

Table: 6.3 illustrate scan results for area 1 and 2 respectively. The x and y coordinates for Area -1 were starting at x = 8, y = 18 and finishing at x = 88 and y = 90. The minimum thickness detected at Area -1 was 2.40 mm at position x = 84 and y = 18 and was recorded once. Maximum thickness recorded at Area - 1 was 3.50 mm at position x = 38 and y = 72, this was also detected only once.

Area - 2, x and y coordinates started at x = 30, y = 144 and finished at x = 78 and y = 216 respectively. Area - 2 analyses showed minimum thickness of 2.40 mm, 23 times and maximum thickness of 3.00 mm, 1 time in the scan. Both Area 1 and 2 exhibit a gradual degradation of the material loss through corrosion.

Table: 6.3 King Tiger Samples' Scan Results for 5 Highest and Lowest Thicknesses



King Tiger
Sample's Dimension
Length: 250 mm Width: 120 mm

	Area 1		Area 2	
S. No	Remaining Thicknesses in mm	No of Occurrences	Remaining Thicknesses in mm	No of Occurrences
1	2.40	1	2.40	23
2	2.50	24	2.50	192
3	2.60	76	2.60	215
4	2.70	141	2.70	192
5	2.80	225	2.80	173
6	3.10	118	-	-
7	3.20	54	-	-
8	3.30	13	-	-
9	3.40	2	2.90	68
10	3.50	1	3.00	1

6.2. Surface and Sub-surface Corrosion Analyses

Surface and sub-surface corrosion analyses were performed using novel methods of SEM and EDS. Samples from the M10, Sherman and Centaur shown in Figure: 3.2 were sectioned and mounted in Bakelite. Analyses revealed corrosion morphology on the surfaces, sub-surface defects of cracks and corrosion pits.

6.2.1. M10 Corroded Surface Sample - 1

Figure: 6.14 shows SEM micrograph of the corroded surface. EDS was conducted at three points represented as spectrum 1, 2 and 3.

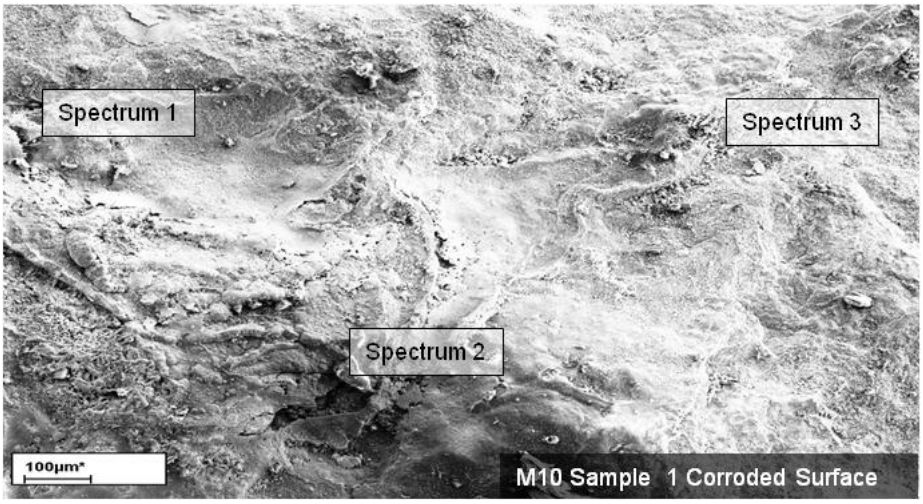


Figure: 6.14 M10 Sample - 1 EDS Points Analysis

Results of three spectra (EDS points) are provided in Table: 6.4. At all the three spectra Fe was significantly oxidised. At spectrum 2 corrosion enhancing contaminant Cl was recorded. High ratio of Si could be attributed to the working environment of the M10. The identification of Al could be attributed to Al based paints and coatings applied on the M10 surfaces.

Table: 6.4 M10 Sample-1 EDS Results (wt %) at CS

Spectrum	O	Al	Si	Cl	Fe
1	41.49	2.42	1.54	0.00	54.53
2	42.14	1.68	1.02	1.47	53.67
3	42.98	2.32	1.43	0.59	52.66

6.2.2. M10 Cross Section Sample - 1

Cross section of the sample was examined that revealed corrosion propagation of approximately 250 µm into the sub-surface shown in Figure: 6.15 (a). In the cross section slag defects shown in Figure: 6.15 (b) and (c) were also identified. Results of two EDS spectra 1 in the slag and 2 near the slag shown in Figure: 6.15 (c) are given in Table: 6.5. Spectrum 1 showed significant amount of S together with Si and O causing Fe oxidation to 68.22 wt %. Spectrum 2 however showed Fe (98.98 wt %) with only manganese (Mn).

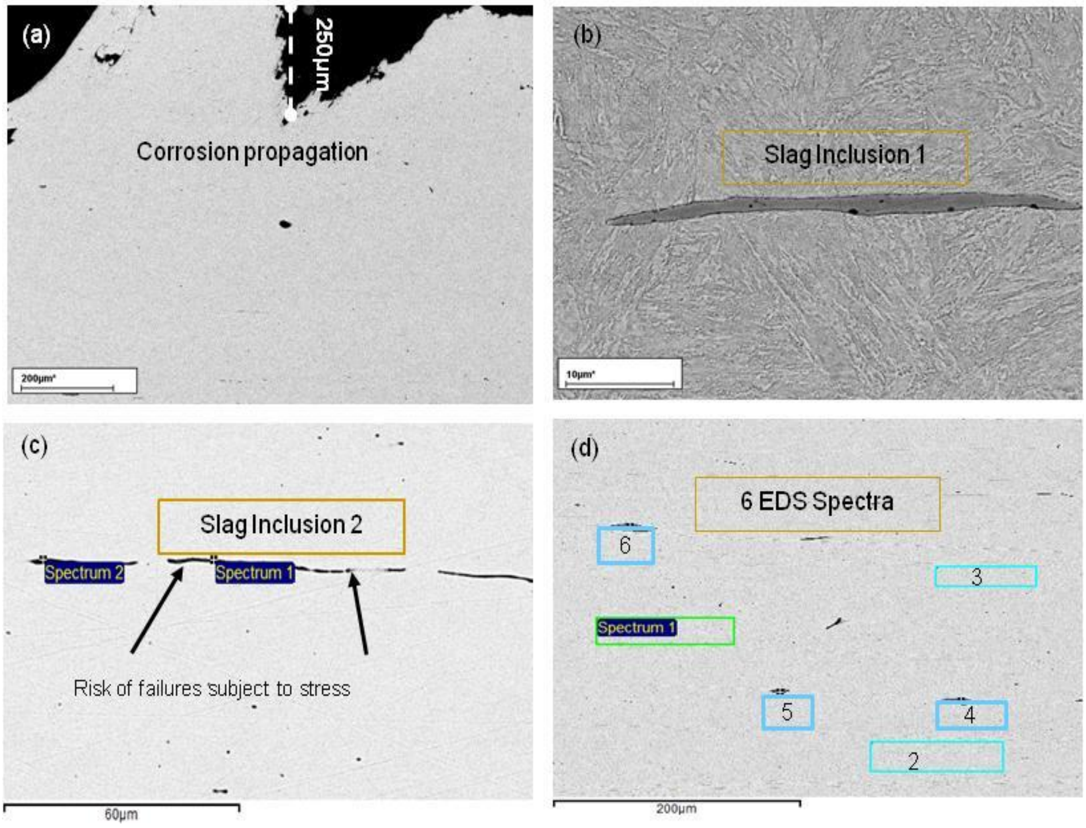


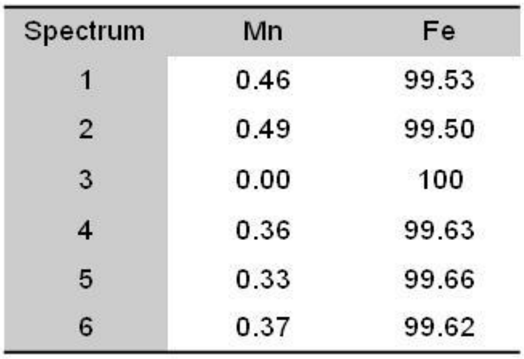
Figure: 6.15 M10 (a) Corrosion propagation (b) Slag Inclusion 1 (c) Slag Inclusion 2 (d) Six EDS Spectra at Bulk Metal

Table: 6.5 M10 Sample - 1 EDS Results (wt %) at Slag Inclusion - 2

Spectrum	O	Si	S	Mn	Fe
1	7.32	2.13	4.76	17.57	68.22
2	0.00	0.00	0.00	1.02	98.98

In the cross section at the bulk metal where no corrosion has reached yet, six spectra were measured shown in Figure: 6.15 (d). Results given in Table: 6.6 revealed Fe above 99 wt % with Mn less than 0.50 wt %.

Table: 6.6 M10 Sample - 1 EDS results (wt %) at Cross Section



Spectrum	Mn	Fe
1	0.46	99.53
2	0.49	99.50
3	0.00	100
4	0.36	99.63
5	0.33	99.66
6	0.37	99.62

Slag (Figure: 6.15 b-c) is a by-product of metal oxide and silica (SiO_2) and tend to promote crack propagation starting from the slag vein and result fatigue failures under stress in operating conditions, which could be assumed safe for the working components [95]. Such defects are not favourable in heavy duty mechanical structures. The detection of S at spectrum 1 in Table: 6.5 in the vicinity of the grain boundaries can compromise physical as well as structural properties of the materials [96, 97]. This type of defect will usually give rise to Mode I failure, the opening crack propagation mode, when subjected to tensile loading. When the stress intensity factor (*K*) reaches a critical value, crack propagation will take place. The stress intensity factor (*K*) (material fracture toughness) is used in fracture mechanics to predict “Stress intensity” or the state of the stress near the crack tip resulted as a consequence of residual stress or load. It depends on type of materials, materials processing, rate of loading, state of stress and temperatures. Such material inherit defects affect this value, hence making component susceptible to mechanical failures when subjected to loading [98].

Internal environment of the museum can be considered free from atmospheric pollution still corrosion stimulating contaminants such as chlorine (Cl) and sulphur (S) were detected on the tanks surfaces. These contaminants mutually with environmental fluctuations could lead to atmospheric corrosion in the museum [19]. S arises from the steel making process and can have detrimental effects if not controlled [19]. To avoid FeS, Mn is added to steel to form MnS which is thermodynamically stable [99, 100]. However MnS exposed to (Cl^{-}) initiate pitting corrosion [101, 102]. The origin of Cl is unknown; its presence on the surfaces of the tanks will play an important role in corrosion.

On the corroding surface (Table: 6.4) Al was also recorded. However in analysis at the cross section (Figure: 6.15 d), no Al was identified. Presence of the Al at three spectra on the corroding surface could be classified as residues from Al based paints protection applied during or after M10s’ service life.

6.2.3. Sherman Corroded Surface Sample - 3

A SEM micrograph of the corroded surface is shown in Figure: 6.16. SEM micrograph demonstrates severe corrosion and flaking of the corrosion residue from the surface. In addition cracks of various lengths were identified. Corrosion on this surface was active and the surface protections were completely failed. Three (EDS point) spectra were measured and their results are given in Table: 6.7.

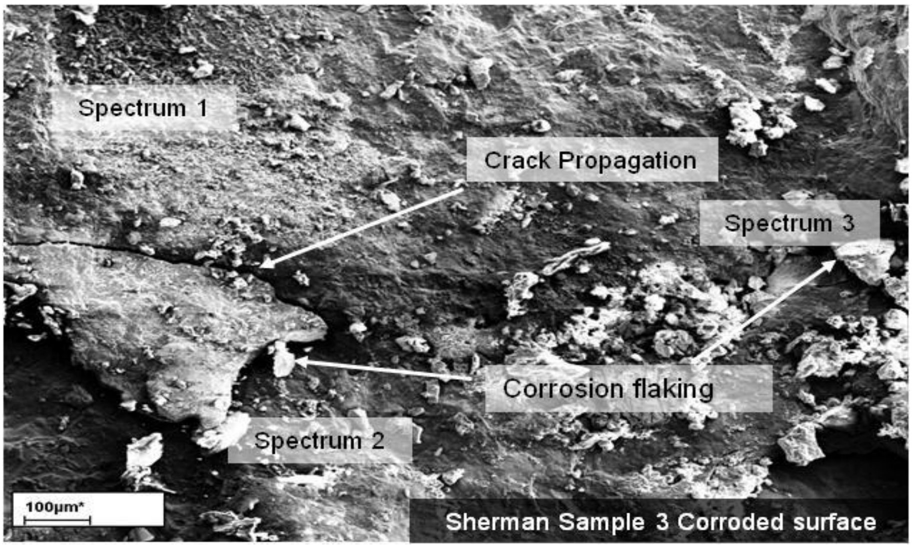
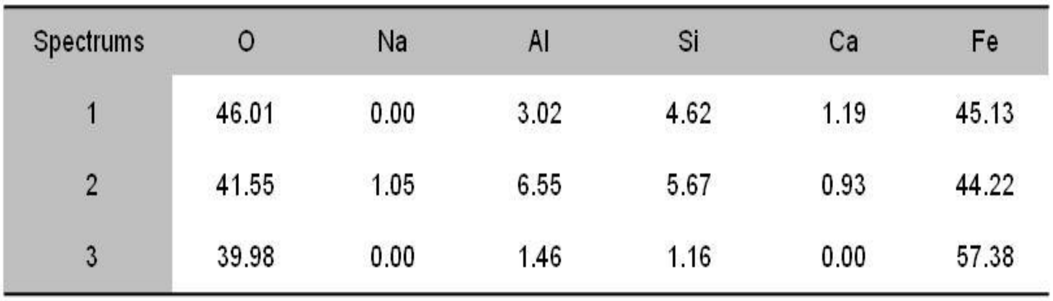


Figure: 6.16 Sherman Sample - 3 EDS Spectra Location at Corroded Surface

On the corroding surface all three spectra, of which results are shown in Table: 6.7, indicated corrosion products comprised of iron oxides. In spectrum 1, the high proportion of O (46.01wt %), nearly equal to Fe (45.13wt %) can be attributed to iron corrosion products. The traces of elemental form of Fe in non-corroded base metal are also likely.

Higher percentage of Si could be considered as contaminant from working environment of the vehicle. Spectrum 2 has Na and Ca and show adverse effect of higher oxidation of Fe compare to spectrum 3 where no Na or Ca was present.

Table: 6.7 Sherman Sample-3 EDS results (wt %) at Corroded Surface



Spectrums	O	Na	Al	Si	Ca	Fe
1	46.01	0.00	3.02	4.62	1.19	45.13
2	41.55	1.05	6.55	5.67	0.93	44.22
3	39.98	0.00	1.46	1.16	0.00	57.38

6.2.4. Sherman Cross Section Sample - 3

Further investigations were conducted to obtain corrosion propagation/corrosion layer depth to sub-surface level, shown in Figure: 6.17. The surface was affected to a depth of almost 110 µm into the bulk metal, where sub-surface cracks were also identified. Corrosion was investigated at the cross section of the corroding edge, labelled as spectrum

1, shown in Figure: 6.17 (a), and about 100 µm below the point of corrosion layer, labelled as spectrum 2, shown in Figure: 6.17 (b). EDS results are given for both spectra in Table 6.8.

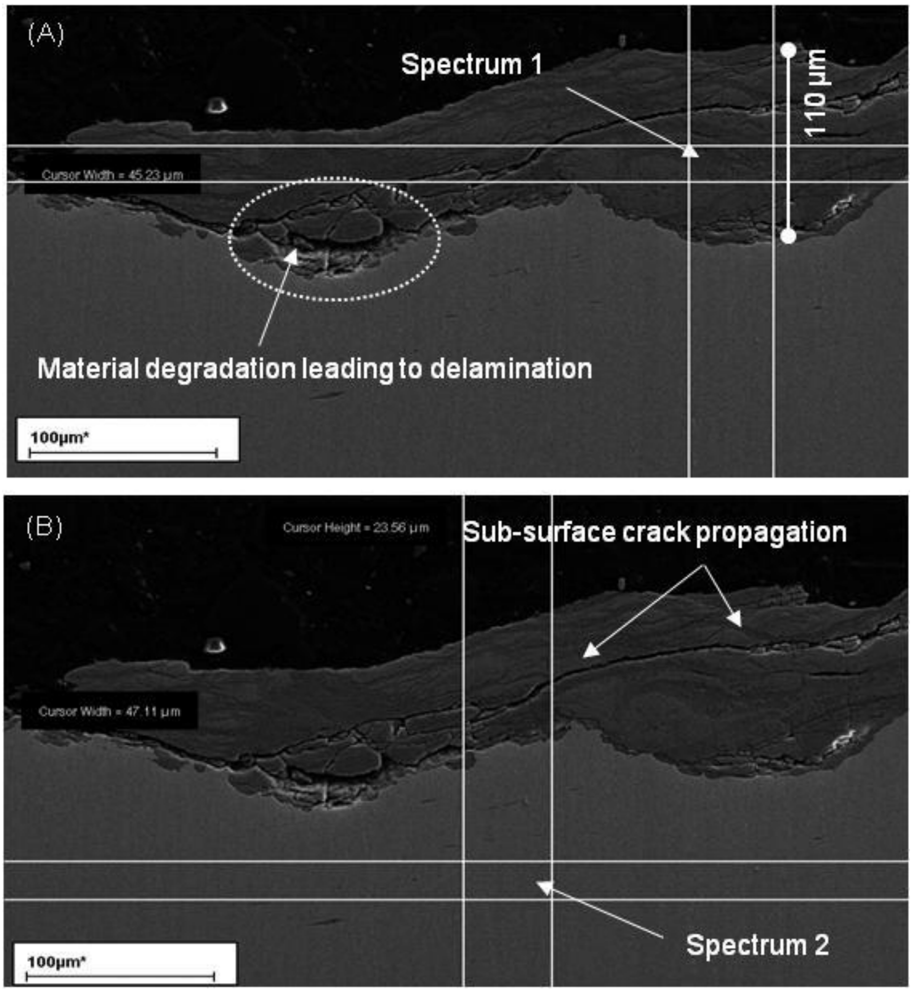


Figure: 6.17 Sherman Sample - 3 (A) Corrosion Layer Depth and Spectrum - 1(B) Crack Propagation and Spectrum - 2

Table 6.8 Sherman- EDS Spectra Results (wt %)

Spectrum	O	Ca	Mn	Fe
1	38.30	0.40	0.45	60.84
2	0	0	0.58	99.41

The presence of high amount of oxygen and a trace of Ca at spectrum 1 show that drastic corrosion has occurred. Oxygen is the signature for iron oxide (FeO) corrosion product formation, and Ca is known to be present in atmospheric salt deposits as well as sea salt [103, 104]. At spectrum 2 where no corrosion has propagated yet, only Fe (99.41wt %) and Mn (0.58wt %) were detected.

Figure: 6.17 demonstrate corrosion on the Sherman resulting in cracks and delamination of the material. Such surfaces when exposed to stresses will become one possible cause of structural failure [105], these are referred to as both mechanical and corrosion induced stresses.

Sulphide inclusions were identified in the cross section from the Sherman, shown in Figure: 6.18. Three EDS points analyses were conducted 1, 3 in the sulphide inclusion and 2 at the bulk metal. Results for these three spectra are given in Table: 6.9.

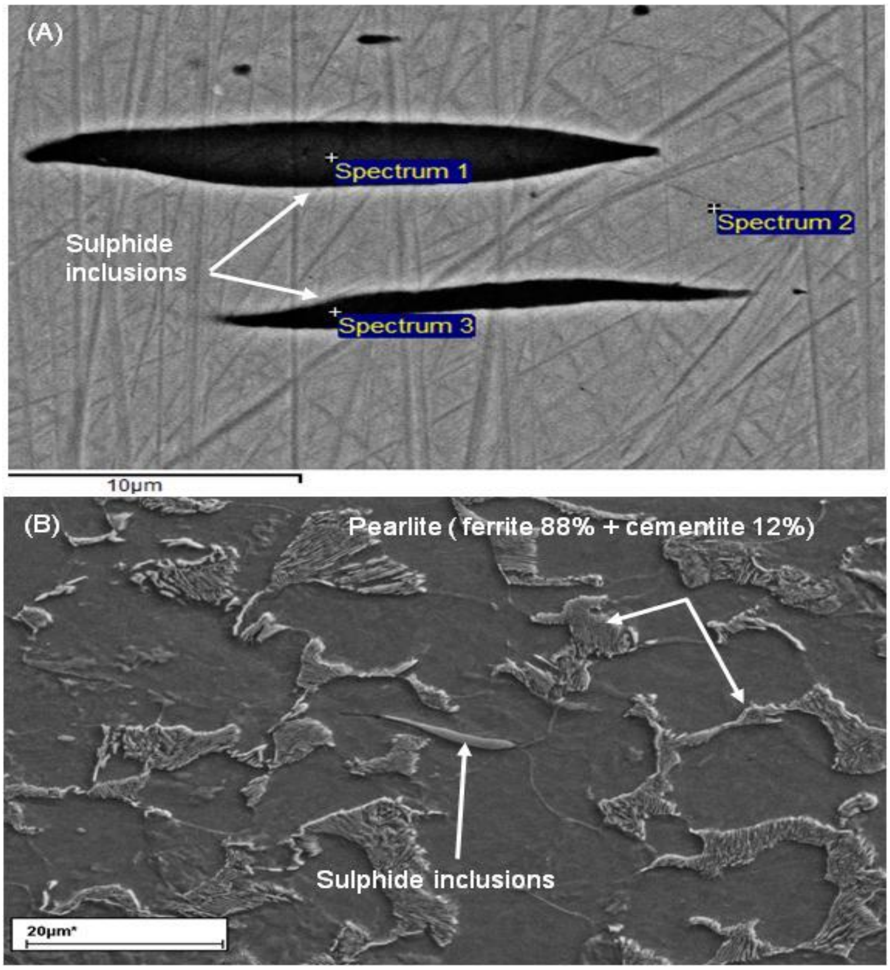
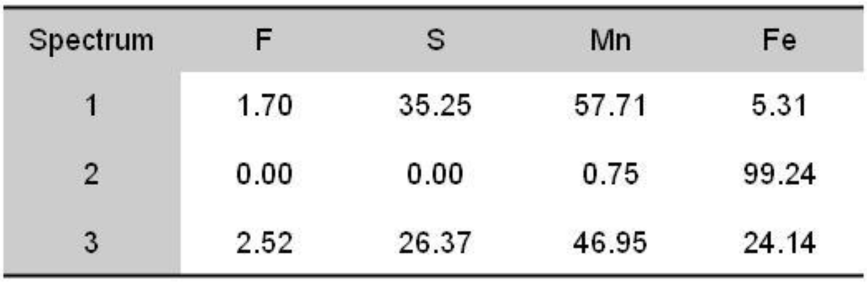


Figure: 6.18 Sherman Sample - 3 (A) Sulphide Inclusion (B) Grain Structure

Spectrum 1 results showed Fe only 5.31wt% with a high amount of sulphur S, other elements found at spectrum 1 was Mn and Fluorine F. Spectrum 2, which was conducted at the metal, demonstrated only Fe and Mn. Spectrum 3 was conducted at the second inclusion and showed Fe with S, Mn and F.

Table: 6.9 Sherman EDS Results (wt %) at Sulphide Inclusions



Spectrum	F	S	Mn	Fe
1	1.70	35.25	57.71	5.31
2	0.00	0.00	0.75	99.24
3	2.52	26.37	46.95	24.14

Sulphur in the Sherman originates from the steel making process and Mn is an alloying agent [19], being added to steel to avoid FeS formation and to form MnS for the purpose of segregating S. MnS has higher melting point and is chemically stable, and also during hot rolling prevents the formation of FeS along the grain boundaries [99, 100]. MnS inclusions tend to provide better machining, increased wear resistance of the components and reduced costs during product manufacturing [106]. However MnS inclusions cause the initiation of corrosive pits in bulk metal, such as carbon steel and low carbon steel [102]. In addition, combined with corrosive environments, these inclusions result in accelerated pit formation and deterioration of the overall corrosion resistance of the metals [102, 107, 108].

6.2.5. Centaur Corroded Surface Sample - 4

Corrosion was investigated at the corroding surface. At this surface coatings were effectively failed and corrosion was active. Figure: 6.19 illustrate SEM micrograph of the corroding surface, where surface disintegration is noticeable. Three EDS spectra 1, 2 and 3 were measured at this surface to identify corrosion products. Results of three spectra are given in Table: 6.10.

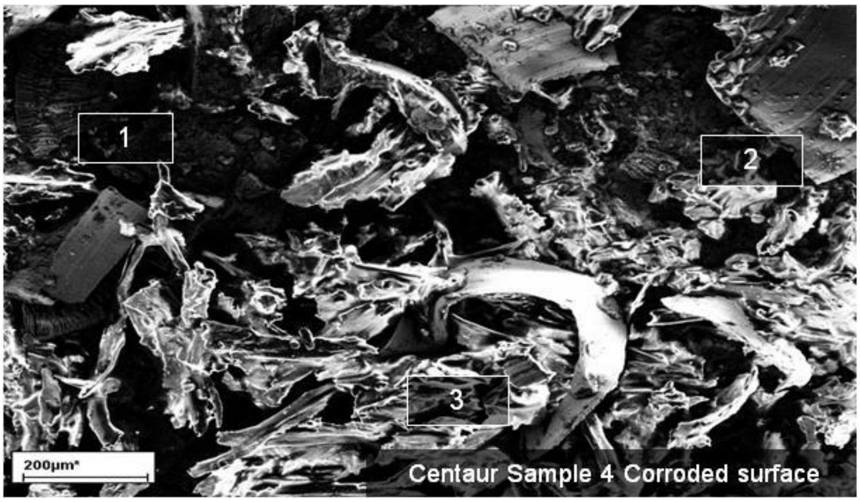


Figure: 6.19 Centaur Sample - 4 SEM Micrograph of CS and EDS Points

Results from Table: 6.10 are examples of extreme Fe corrosion, where Fe oxidation is prevalent at more or less the same rate. Other elements are in high concentrations at the surface due to the build-up of corrosion and atmospheric deposits over time. Spectrum 1 indicated a high amount of corrosion product due the high concentration of oxygen that was directly related to the oxidation of Fe. Fe, initially expected to be in the high 90’s for weight percentage, was corroded to 56.25 wt %, other elements detected were Al and Si. Results from spectrum 2 illustrated the highest Fe corrosion among all the three spectra. Fe was recorded the highest in spectrum 3 with Si, Al and O.

Table: 6.10 Centaur EDS Point Analysis at CS

Spectrum	O	Al	Si	Fe
1	36.58	3.97	3.18	56.25
2	36.88	22.34	5.04	35.72
3	28.06	2.15	4.09	65.67

6.2.6. Centaur Cross Section Sample - 4

Cross sectional analyses were conducted at sample - 4. Sub-surface corrosion propagation was recorded 50 µm deep. 50 µm is a noticeable propagation when viewed in the context of Table: 6.1 where a material thickness of 7.50 mm has already been lost due to corrosion between two the lowest and highest points of 2.30 mm and 9.80 mm respectively. In addition cracks propagation and corrosion pits were also identified 100 µm deep shown in Figure: 6.20.

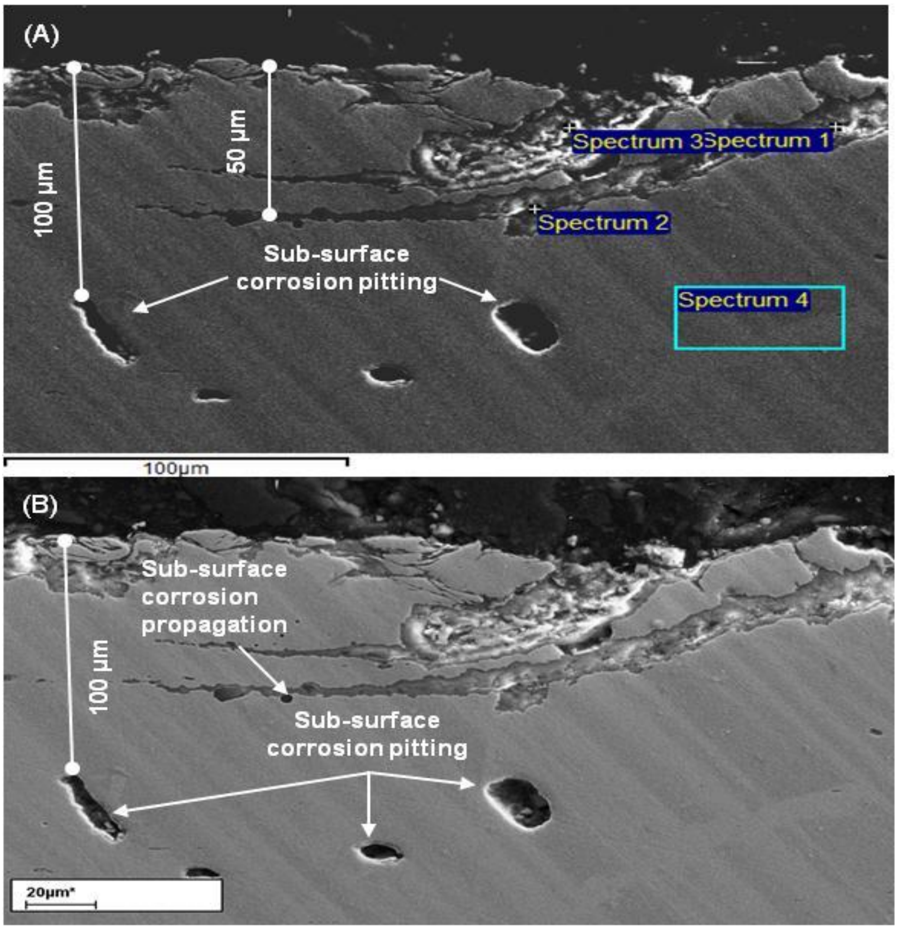


Figure: 6.20 Centaur Sample - 4 (A) EDS Spectra Locations (B) Corrosion Propagation and Sub-Surface Pits

Four spectra 1, 2, 3 and 4 were measured. 1, 2 and 3 were at the corroded section while 4th was conducted at the bulk metal where no corrosion was occurring. These results are given in Table: 6.11. At these spectra nine elements were recorded. Spectra 1, 2 and 3 are of the corrosion product layer, which clearly show the high amount of oxygen versus elemental iron. In the crack represented as spectrum 2 in Figure: 6.20(A), Fe is oxidised to 18.75 wt %. O, Ca, and S are present in considerable amounts and will form a localised zone of corrosion to propagate any cracks preferentially across the bulk metal grain boundaries leading to delamination of the surface material. Spectrum 4 was at the bulk metal (where corrosion had not reached yet), taken approximately 50 µm below the interface of the corrosion product layer and reveals the alloying elements only.

Table: 6.11 Centaur Sample - 4 EDS Results (wt %) at Corroded Edge and Cross Section

Spectrum	O	Al	Si	S	Ca	Cr	Mn	Fe	Ni
1	40.39	0.29	3.39	0.40	1.71	1.30	2.00	49.88	0.60
2	39.86	1.05	14.12	0.29	0.47	1.35	24.06	18.75	0.00
3	41.14	0.00	0.57	0.76	1.85	5.52	0.68	47.94	1.50
4	0.00	0.00	0.41	0.00	0.00	1.87	0.46	96.50	0.74

Si originates from alloying elements but higher percentage at spectra 1 and 2 possibly have been accumulated from the environment. The presence of Al seems to be a residue from the passivation treatment (Al based paints/coats) applied during/after Centaur service life, because no Al has been identified at the bulk metal (spectrum 4) where no corrosion was occurring. As such, the presence of Ca at spectra 1, 2 and 3 also seems to be a residue because no Ca was detected at the bulk metal at spectrum 4.

Sub-surface crack was also identified at the cross section analysis of the Centaur illustrated in Figure: 6.21. Spectra were taken at the bulk area surrounding the crack and at the crack and the results are given in Table: 6.12. At spectra 1 and 2 only the alloying elements were identified and no O or Al was detected. But in the crack, O and Al were detected. Under the influence of static or dynamic loading this crack might propagate resulting in partial or complete failure of the component.

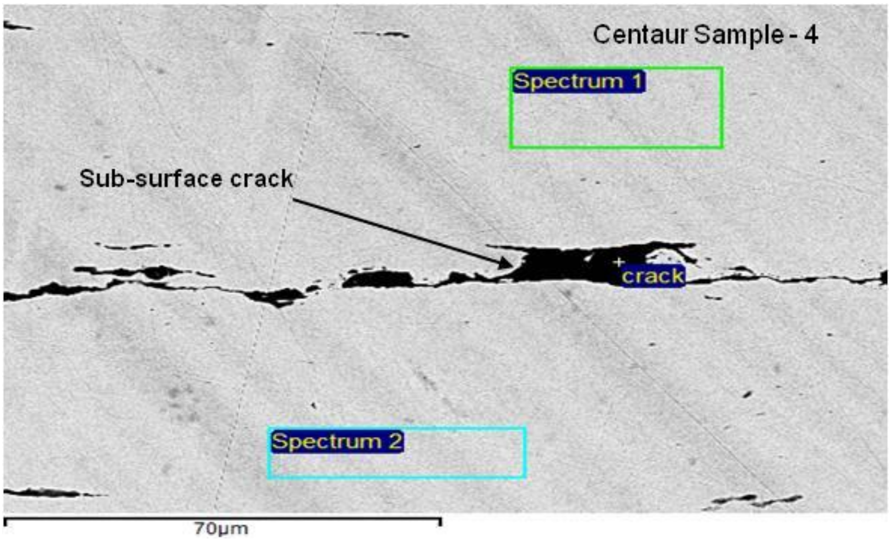
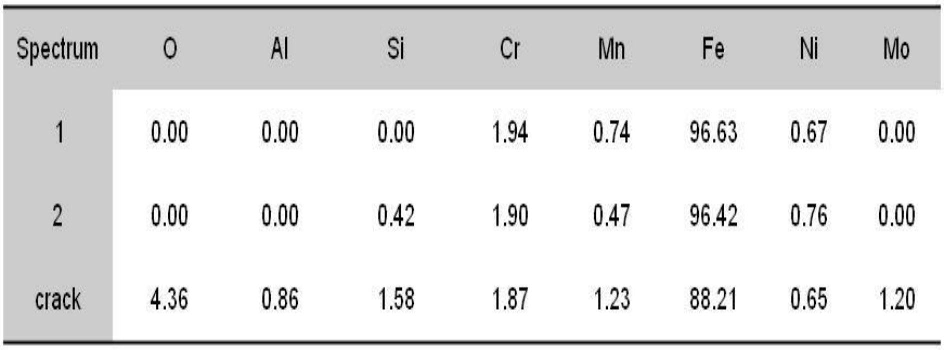


Figure: 6.21 Centaur Sample- 4 (A) EDS Points Locations at Crack and Near Crack

Table: 6.12 Centaur EDS Spectra Results (wt %) Near and at the Crack



Spectrum	O	Al	Si	Cr	Mn	Fe	Ni	Mo
1	0.00	0.00	0.00	1.94	0.74	96.63	0.67	0.00
2	0.00	0.00	0.42	1.90	0.47	96.42	0.76	0.00
crack	4.36	0.86	1.58	1.87	1.23	88.21	0.65	1.20

Figure: 6.20 illustrate localised form of corrosion pits associated with surface corrosion. Pits were widespread and their formation into cracks/cavities can be observed in Figure: 6.22 [20].

The formation of pits in two phases, (a) meta-stable and (c) stable pits has been extensively reported [12, 23, 31-34]. In the initial stage, due to non-linear coupling between the dissolution of the metal and the electrolyte composition, the formation of the pit takes place, (a) after which the pit may propagate for a short period and then die-down (meta-stable pit) or (b) it may continue propagating indefinitely, known as stable pit, depending on the local fluctuations in the hydrodynamic boundary layer [12, 27, 31, 32, 100].

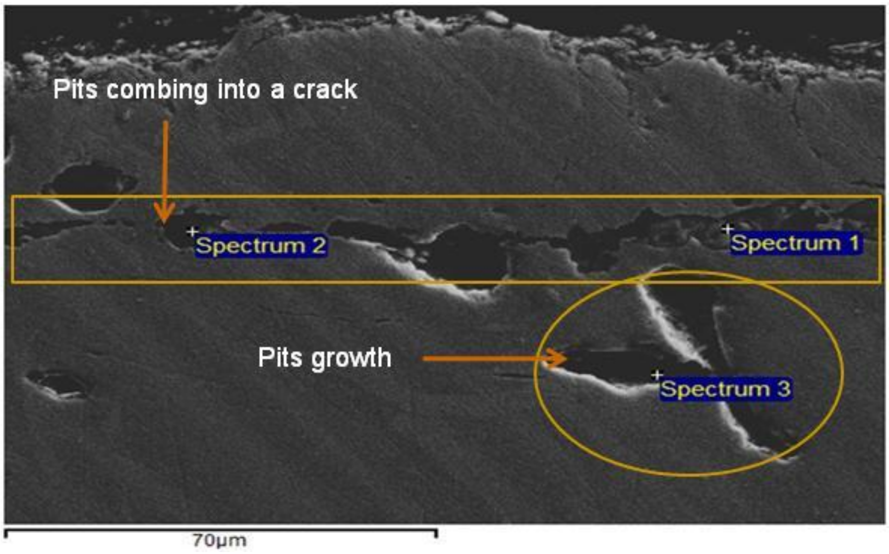


Figure: 6.22 Centaur Formation of Crack due to Corrosion Pits

The Centaur is exposed to rain, sea winds and temperature fluctuations etc. Consequently, with time, the sizes of the pits (Figure: 6.20 and Figure: 6.22) are expected to increase sidewise as well as in depth depending on (a) pitting potential (b) re-passivation potential (c) inhibition potential and their properties [35, 36]. A corrosive environment, under fatigue loads and the localised pitting in the Centaur could lead to the formation of large cavities and could become one possible form of structural failure even though considerable material remains on the surfaces [20, 37,38]. Furthermore in its current environment, corrosion pits in the Centaur will continue their electrochemical reactions and cause inter-subgranular corrosion, resulting in stress corrosion cracking (SCC) when exposed to stresses [38, 39]. Climatic effects such as oxygen, water and salts are able to promote surface corrosion [19, 37] and can penetrate into the subsurface layers through cracks (Figure: 6.21) delivering rapid corrosion.

6.2.6.1 White Light Interferometry

White Light Interferometry (WLI) was conducted on corrosion pits which were identified in Centaur cross section. In this section few pits were selected and their lengths and depths were measured. Figure: 6.23 illustrate the 3D measurement conducted on corrosion pits. Figure: 6.23 (a-b), show the surface structure of the pit, (c) demonstrate same pit in 3D format and (d) show the length (77.09 µm) of the same pit.

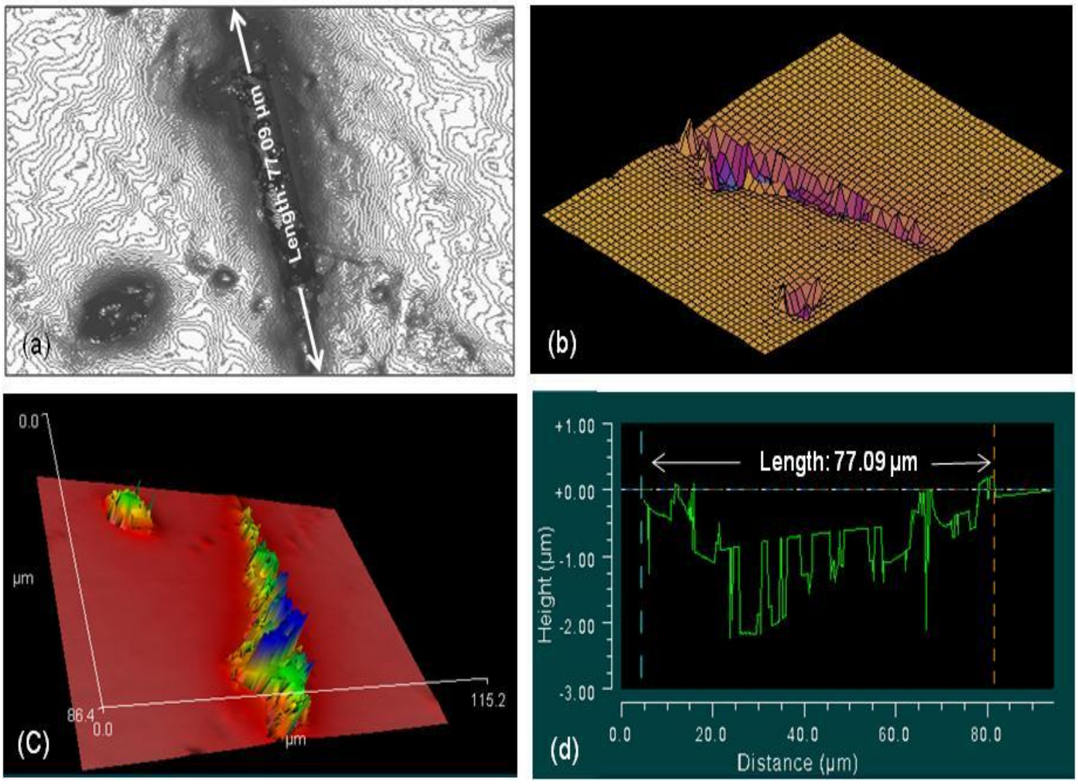


Figure: 6.23 Centaur 3D Profile of Corrosion Pits

WLI was conducted on some more corrosion pits shown in Figure: 6.24 below. Figure: 6.24 (a) show geometry of the corrosion pit and (b) illustrate the length (381 µm) and depth (2.79 µm) of the same pit. Figure: 6.24 (c) illustrate a different pit with length (34.40 µm) and (d) show some more corrosion pits with different geometrical profiles.

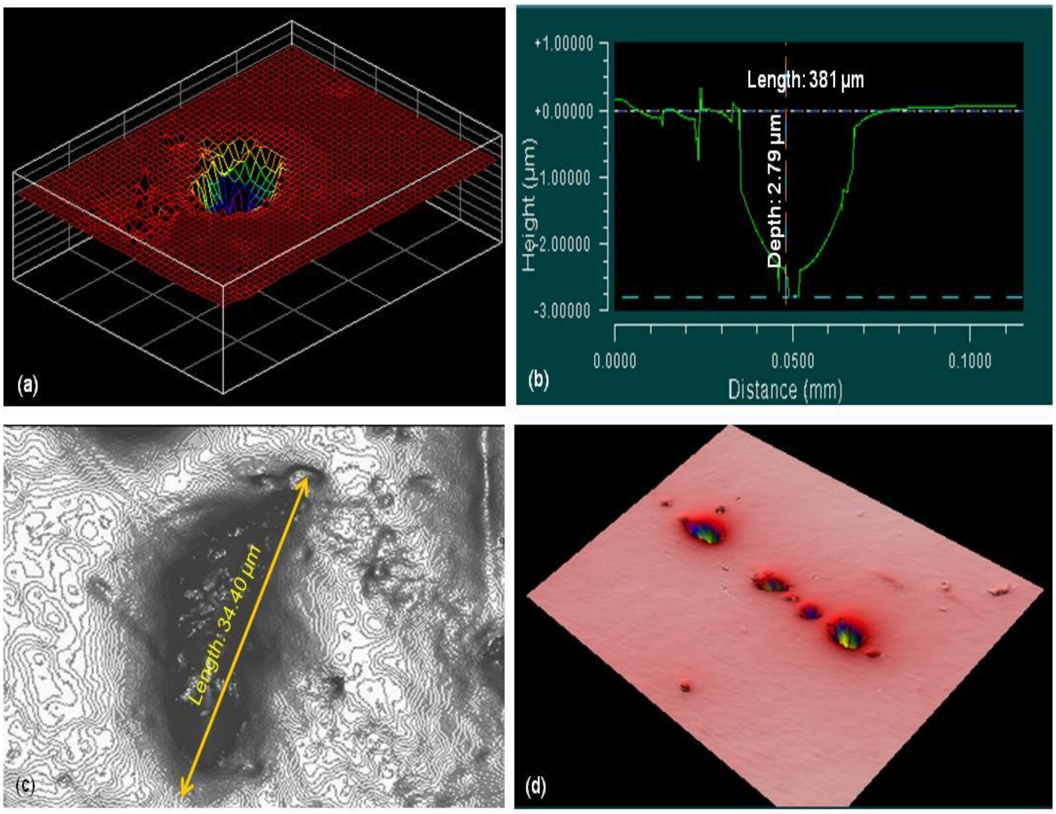


Figure: 6.24 Centaur Corrosion Pits Measurement

All these corrosion pits in above figures indicate complex geometrical profiles with noticeable lengths and depths. These pits if they were to continue to grow will play a vital role in the degradation of the concerned component in particular and the whole structure in general.

6.3. Conclusions

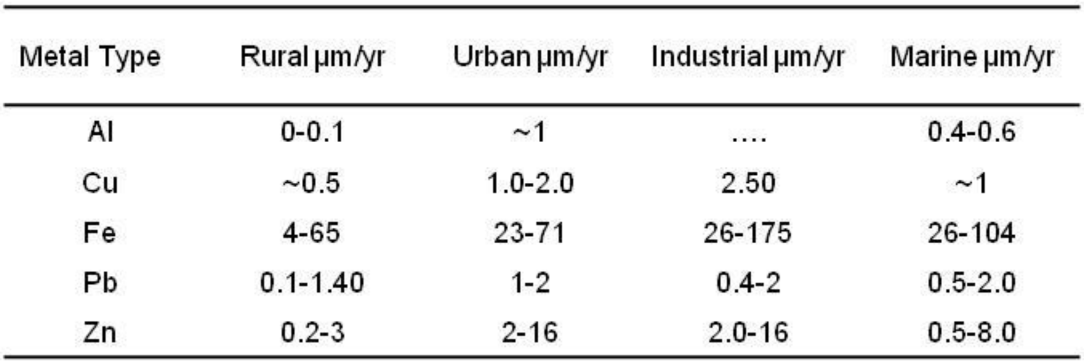
6.3.1. Ultrasonic Scanning

In this section of the experimental research a benchmark of corrosion damage has been achieved in five tanks in different environments. Results showed considerable loss of material in all samples. Table: 6.1 illustrate the five lowest and highest remaining thicknesses of the samples for the M10, Sherman and Centaur. The M10 showed a loss of 4.30 mm, Sherman 5.20 mm and Centaur shows a critical loss of 7.50 mm between the highest and lowest points. BT R - 60 comparatively a new vehicle has shown material loss of 1.00 mm between two points. Two areas of same sample from the King Tiger revealed material loss of 1.10 mm and 0.60 mm respectively. All samples display a steady material loss and indicate the severity of corrosion degradation.

During their service life these military vehicles had been exposed to intense environments and as a consequence the test samples unveil material loss. During production the range of armour thickness for the M10 was between 37.00 mm and 12.00 mm, for Sherman 62-63 mm to 12 mm and for Centaur it was 76.00 mm maximum and 20.00 mm minimum respectively [62, 63]. However in this research the highest value detected in the ultrasonic scan is regarded as the reference point for maximum thickness because of various modifications and upgrades of these vehicles during their service life and hence it is beyond the scope of this research to follow any such modifications.

Table: 6.13 shows the typical corrosion rates for Fe, Cu, Al, Pb and Zn [6, 109, 110]. Fe has shown the most material loss in the four environments provided and therefore protective measures are needed to slowdown the existing corrosion mechanism.

Table: 6.13 Typical Corrosion Rates of Common Metals in Various Environments



Metal Type	Rural μm/yr	Urban μm/yr	Industrial μm/yr	Marine μm/yr
Al	0-0.1	~1	....	0.4-0.6
Cu	~0.5	1.0-2.0	2.50	~1
Fe	4-65	23-71	26-175	26-104
Pb	0.1-1.40	1-2	0.4-2	0.5-2.0
Zn	0.2-3	2-16	2.0-16	0.5-8.0

An empirical model may be proposed predict the life expectancy programme for the tanks which are exposed to uncontrolled environment based upon the results for the remaining thicknesses of the samples.

6.3.2. Surface and Sub-surface Corrosion Analyses

Surface and sub-surface corrosion analyses provided existing corrosion morphology on the surfaces, depth of the corrosion layer and corrosion layer composition. Also surface and sub-surface defects both manufacturing and the ones which were accumulated through material degradation were identified.

A tank has a complex shape, geometric profile and is comprised of many components where dirt, moisture and other atmospheric contaminants can easily be deposited. Accumulation of Cl is expected in many crevices of the M10 and Cl influenced localised corrosion is likely to happen in many parts of its structure [19, 111, 112].

Internal environment of the museum can be considered free from atmospheric pollution. Nevertheless corrosion stimulating contaminants such as chlorine (Cl) and sulphur (S) were detected on the tanks surfaces. These contaminants mutually with environmental fluctuations could lead to atmospheric corrosion and will result in serious corrosion problems in the M10 inside the museum [8, 19, 113].

Tanks which are exposed to the outside environment from time to time can accumulate contaminants on their surfaces. In the likelihood of inadequate or no treatment of the affected surfaces; atmospheric corrosion will occur even when these tanks are stationary inside the museum.

Being outdoor Centaur-A27L is exposed to temperature fluctuation, humidity variation, rain water and local condition of acidity, all these factors together with the time of wetness and the extent of the chemical reaction on the metal surface will establish the corrosion rate [8]. Pits formation and its growth in the Centaur can be classified as severe and will continue to deteriorate rapidly because of pitting.

Chapter 7 Simulated Environmental Corrosion Testing

In this chapter environments both inside The Tank Museum and outside of the museum have been analysed. The term indoor environment refers to the controlled environment inside the museum and the outdoor environment refers to the uncontrolled environment that exists naturally in Bovington, United Kingdom. Based upon this data, research experiments were designed to understand corrosion behaviour under simulated environmental tests taking into account the comfort of the museum visitors.

7.1. Environment in Bovington United Kingdom

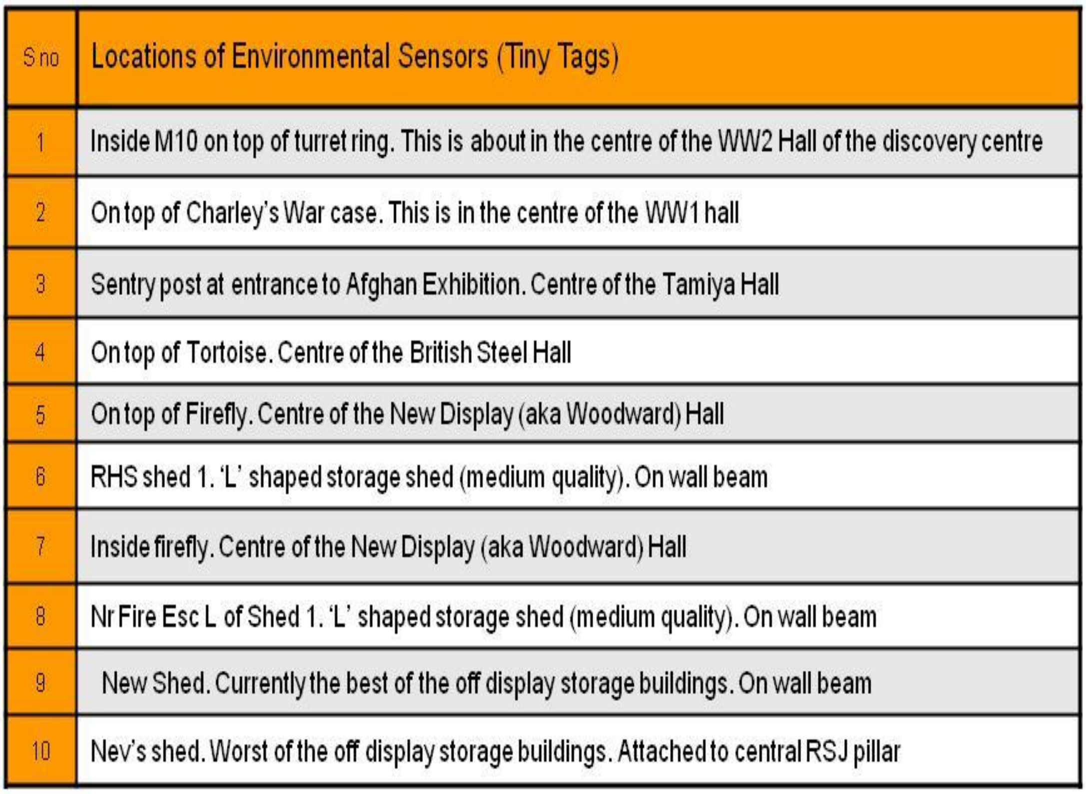
Bovington is in Dorset County in the south-western coast of England and is located approximately 9km north of the Atlantic Ocean/English channel. There is significant precipitation in Bovington, where fog, rain, and/or snow are reported, on average, for 18 days of each month [114]. The relative humidity averages around 80% for most of the year, however peaks of 100% and lows of 40-60% range occurs [115]. Average high and low temperature for around 30 years (1981-2010) were 14.03°C and 8.11°C respectively, whereas daily average fluctuations between 7° to 22°C in summers and 2° to 12°C in winter were observed [114, 116].

There are 30 Acid and Aerosols Monitoring Network (AGANet) sites in the United Kingdom [117]. At Bovington there is no such monitoring centre. Therefore AGANet site at Goonhilly Downs situated in the lizard Peninsula in Cornwall, England (south-western-most coast approximately 6km north of the English Channel), was used to understand the average deposition of salts and pollutants, an area of similar distance as of Bovington from the same marine environment. Average salts and pollutants recorded between 2006 and 2009 were; chlorides at 4.0 µg/m^3, sulphur dioxide at 0.080 µg/m^3, sulphites at 1.00 µg/m^3, nitrates at 3.00 µg/m^3, sodium at 2.00 µg/m^3, and both calcium and magnesium at 0.00 µg/m^3[117]. Sulphur dioxide and sulphite levels are shown to be relatively low, though they are only indirectly related to the effects of sulphur dioxide on corrosion but the actual amount of hydrated sulphur dioxide deposited on metal surfaces is important. The actual amount of sulphur deposited on the outdoor tanks will be less than the amount found in the aerosols. The atmospheric chloride concentration is considerably low, as expected for a normal rural area.

7.2. Environment in The Tank Museum

The Tank Museum Bovington has an area of 15,412 m^2. The lighting source is natural daylight combined with fluorescent lighting, which emits a low amount of UV light. Temperature is kept between (18-25°C) in winters, but is not controlled in the summer. The buildings where the tanks are housed are not humidity controlled apart from being enclosed and protected from direct atmospheric moisture. Recording of temperatures (T) and relative humidity (RH) have started in October 2011 in five different locations and another five were added early 2012 in the museum. Table: 7.1 gives location of the sensors for the purpose of recording temperature and humidity.

Table: 7.1 Location of Environmental Sensors in the Museum



S no	Locations of Environmental Sensors (Tiny Tags)
1	Inside M10 on top of turret ring. This is about in the centre of the WW2 Hall of the discovery centre
2	On top of Charley's War case. This is in the centre of the WW1 hall
3	Sentry post at entrance to Afghan Exhibition. Centre of the Tamiya Hall
4	On top of Tortoise. Centre of the British Steel Hall
5	On top of Firefly. Centre of the New Display (aka Woodward) Hall
6	RHS shed 1. 'L' shaped storage shed (medium quality). On wall beam
7	Inside firefly. Centre of the New Display (aka Woodward) Hall
8	Nr Fire Esc L of Shed 1. 'L' shaped storage shed (medium quality). On wall beam
9	New Shed. Currently the best of the off display storage buildings. On wall beam
10	Nev's shed. Worst of the off display storage buildings. Attached to central RSJ pillar

The recent monitoring, over a period of four months indicate temperature fluctuations from 17°C to 20°C and daily range of RH was reported to be as low as 40% and as high as 80%. Each out of 10 locations detected conditions where RH reached above 70% at various intervals of time during 24 hours. There is plenty of evidence of condensation inside some of the buildings in the museum where water regularly runs off the tanks. On the contrary this occurrence is less prevalent in tanks which are kept in locations in the museum where better ventilation is observed.

7.3. Simulated Environmental Test

In this section results from the simulated and accelerated corrosion test are provided. Results showed corrosion build-up on all samples after exposure. These results will help show magnitude of corrosion and its behaviour in the tanks which display failures in their paint systems. Accumulated corrosion on the samples had extremely complex morphology, and therefore state-of the-art image analysis techniques were performed to measure those areas. Figure: 7.1illustrate the complex structure of the accumulated corrosion on samples from the Sherman and Centaur.

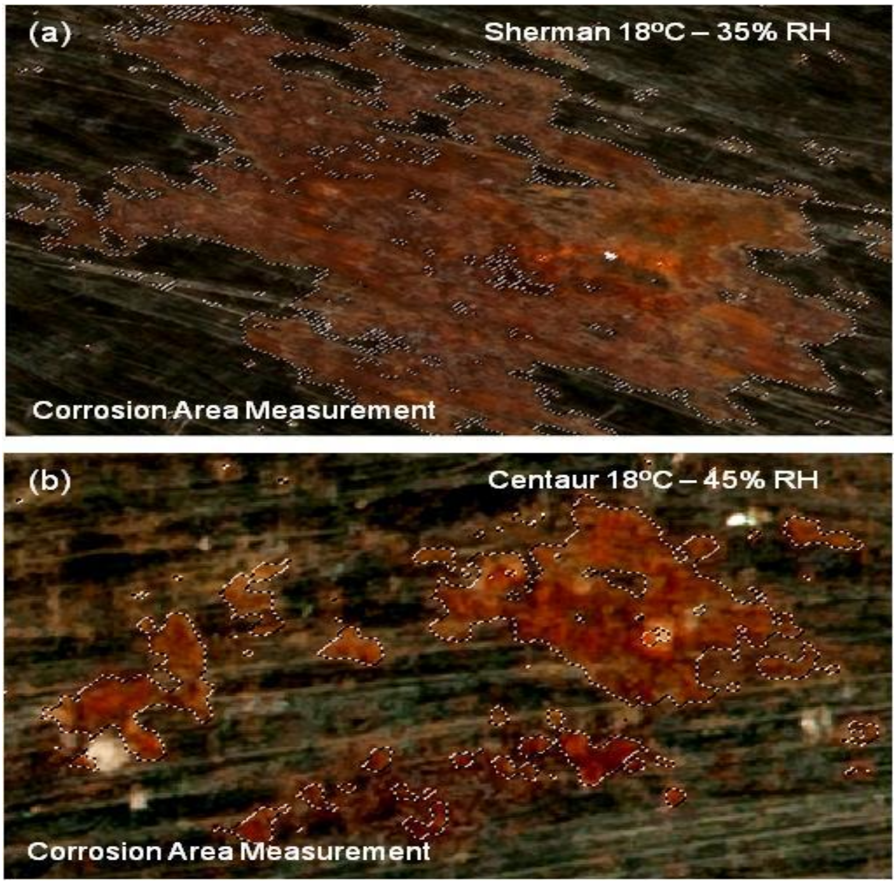


Figure: 7.1 Corrosion Area Measurement

7.3.1. M10 - Simulated Environmental Test Results

Corrosion build-up after exposure to SET was observed on all the samples from M10. Sample 4 which was exposed to 18°C and 55%RH showed the highest percentage of corrosion. Table: 7.2 provide area of the sample, test conditions and total percentage of the accumulated corrosion on each sample.

Table: 7.2 M10 - Environmental Conditions and Accumulated Corrosion

Wolverine - M10 Tank destroyer						
Sample no	Temperature (°C)	Relative Humidity (%)	Exposure Time (Hours)	Samples' Area (mm^2)	Corrosion Area (mm^2)	% Corrosion
1	5	40	125	542.69	2.95	0.54%
2	25	40	125	527.05	1.07	0.20%
3	18	35	125	519.14	0.14	0.03%
4	18	55	125	533.99	5.40	1.01%

Analyses were conducted to obtain the morphology of the accumulated corrosion on sample 4 which was exposed to 18ºC and 55% RH. In Figure:

7.2(a), EDS area mapping illustrate the concentration of Fe (red) and O (blue) at sample 4. Corrosion products were characterised shown in Figure: 7.2(c) where Fe (88.27 wt % and O (11.73 wt %) were recorded.

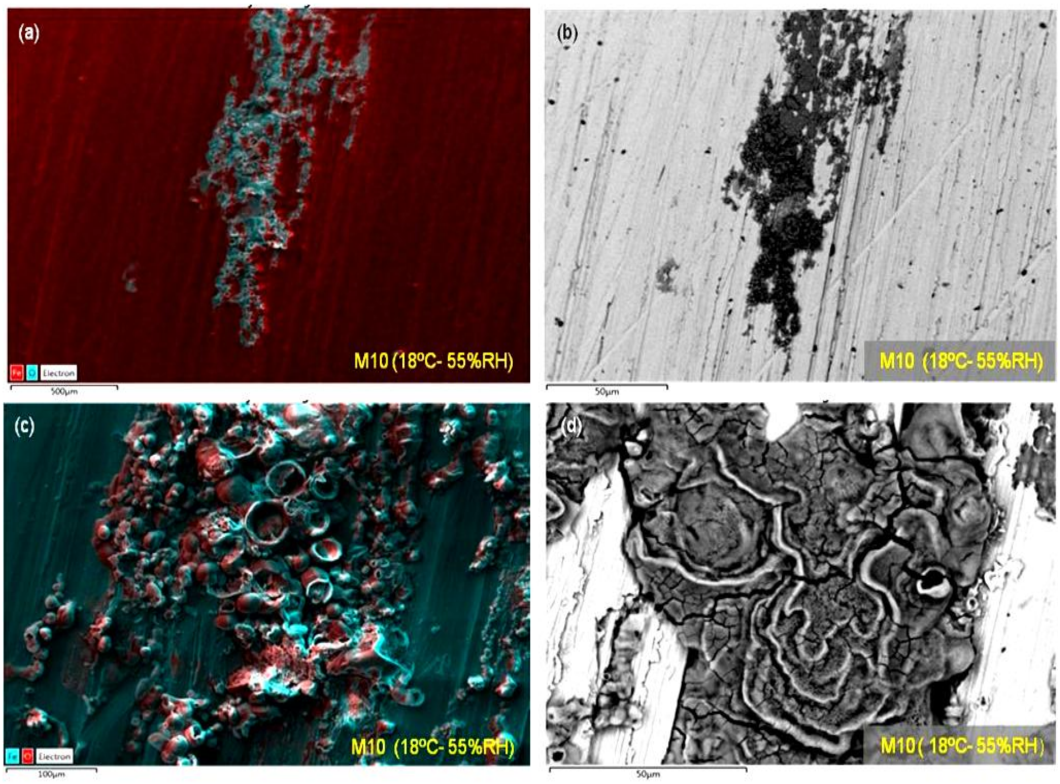


Figure: 7.2 M10 - Corrosion Morphology Results after Simulated Environmental Tests

7.3.2. Sherman - Simulated Environmental Tests Results

Sherman exposure to SET showed same behaviour in-terms of corrosion accumulation shown in Table: 7.3. Sample - 4 which was exposed to 18ºC and 55%RH has showed the most corrosion build up after 125 hours.

Table: 7.3 Sherman – Environmental Conditions and Accumulated Corrosion

Sherman M4A1						
Sample no	Temperature (°C)	Relative Humidity (%)	Exposure Time (Hours)	Sample's Area (mm²)	Corrosion Area (mm²)	% Corrosion
1	5	40	125	797.18	14.03	1.76%
2	25	40	125	857.22	18.98	2.21%
3	18	35	125	1017.23	61.58	6.05%
4	18	55	125	896.04	56.70	6.33%

Corrosion morphology was studied on samples 2 and 4 which were exposed to18ºC - 35%RH and 18ºC - 55%RH respectively. Sample 4 has the most build up of corrosion among all the samples. Corrosion build-up after SET illustrates complex morphologies on both samples shown in Figure: 7.3.

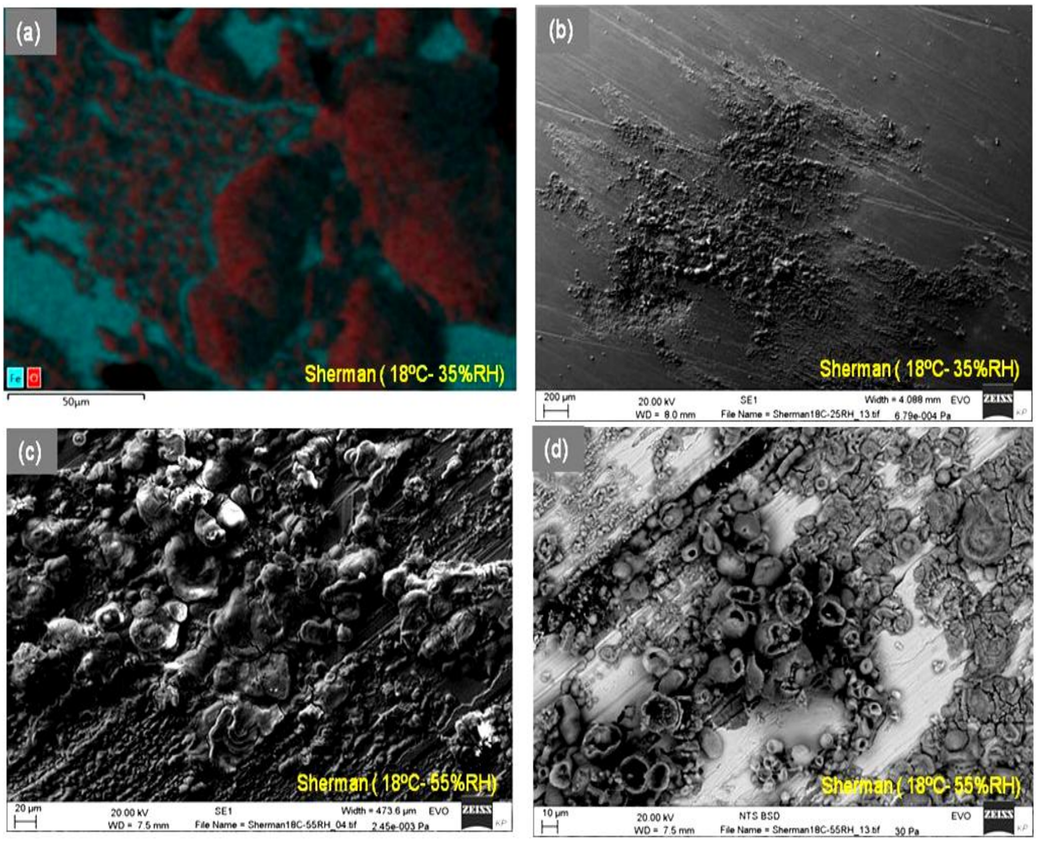


Figure: 7.3 Sherman - Corrosion Morphology Results after Simulated Environmental Tests

Figure: 7.3 (a) shows concentration of Fe (blue) and O (red). Figure: 7.3 (c) and (d) are from the sample 4 illustrating the morphology of corrosion. Figure: 7.4 of the Sherman illustrate build-up of a typical oxide layer on steel and have characteristics of lepidocrocite (γ-FeOOH) and goethite (γ- Fe_2O_3) of rust layer for a non- polluted environment [112, 118-120]. These layers have various types of cracks, pores, have poor adherence and will flake away from the surfaces depending on localised corrosion [120, 121]. This type of rust layer cannot result as a passivation and therefore electrolyte and corrosive contaminants can reach the steel substrate [112, 122, 123].

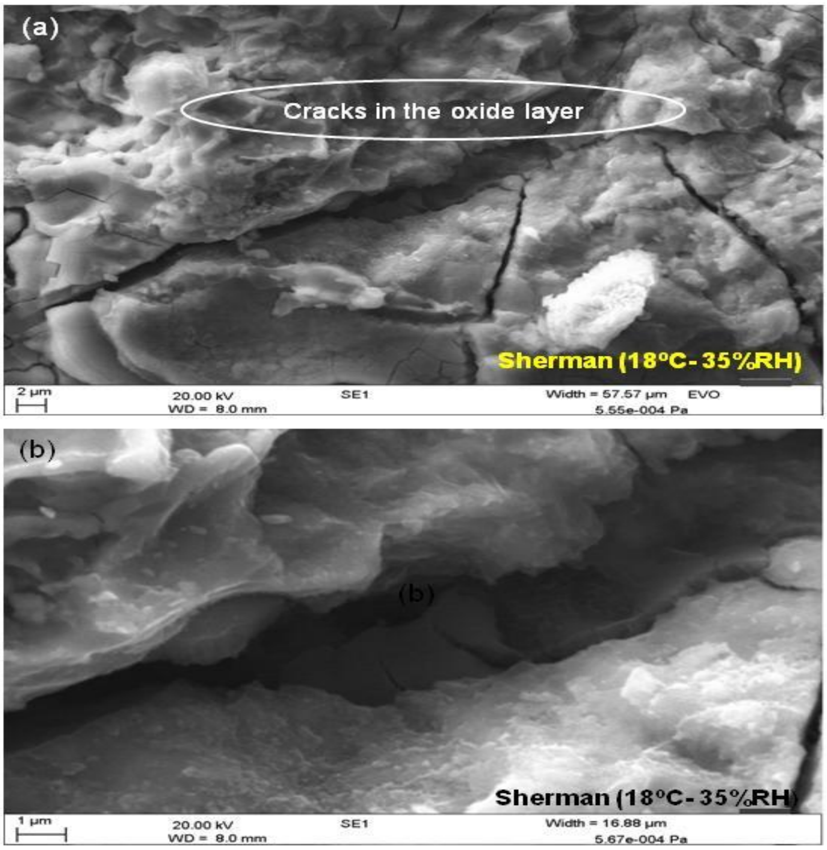


Figure: 7.4 Sherman Corrosion Morphology of Rust Layer with Visible Cracks

7.3.3. Centaur - Simulated Environmental Tests Results

Samples from the Centaur exposed to SET illustrated same behaviour as of that the M10 and Sherman. Results are given in Table: 7.4. Sample 4 which was exposed to 18°C and 55%RH, accumulated higher percentage of corrosion than the other samples.

Table: 7.4 Centaur - Environmental Conditions and Accumulated Corrosion

Centaur A27L MBT						
Sample No	Temperature (°C)	Relative Humidity (%)	Exposure Time (Hours)	Sample's Area (mm²)	Corrosion Area (mm²)	% Corrosion
1	5	40	125	570.14	0.24	0.04%
2	25	40	125	547.39	1.18	0.22%
3	18	35	125	521.43	0.12	0.02%
4	18	55	125	487.82	1.65	0.34%

7.4. Prohesion (ASTM G85 A5) Corrosion Test

Corrosion problems are primarily associated with failures in the surface protection/coating. Failures in the coating were also a common occurrence in the museum vehicles. Figure: 7.5 demonstrate surface protection breakdown in the Challenger I.

Figure: 7.5 Challenger I Surface Protection Breakdown

The Tank Museum deploys Red-oxide (colour red) as primer shown in Figure: 7.6, and Air Drying Alkyd (colour green) as coat on the tanks surfaces.

Figure: 7.6 M 60 A3 - Application of Red-Oxide Primer

Failure of surface protection (air drying alkyd - colour green) was observed in the Centurion shown in Figure: 7.7. Coating failure was followed by corrosion attack in the Centurion shown in Figure: 7.7 (b).

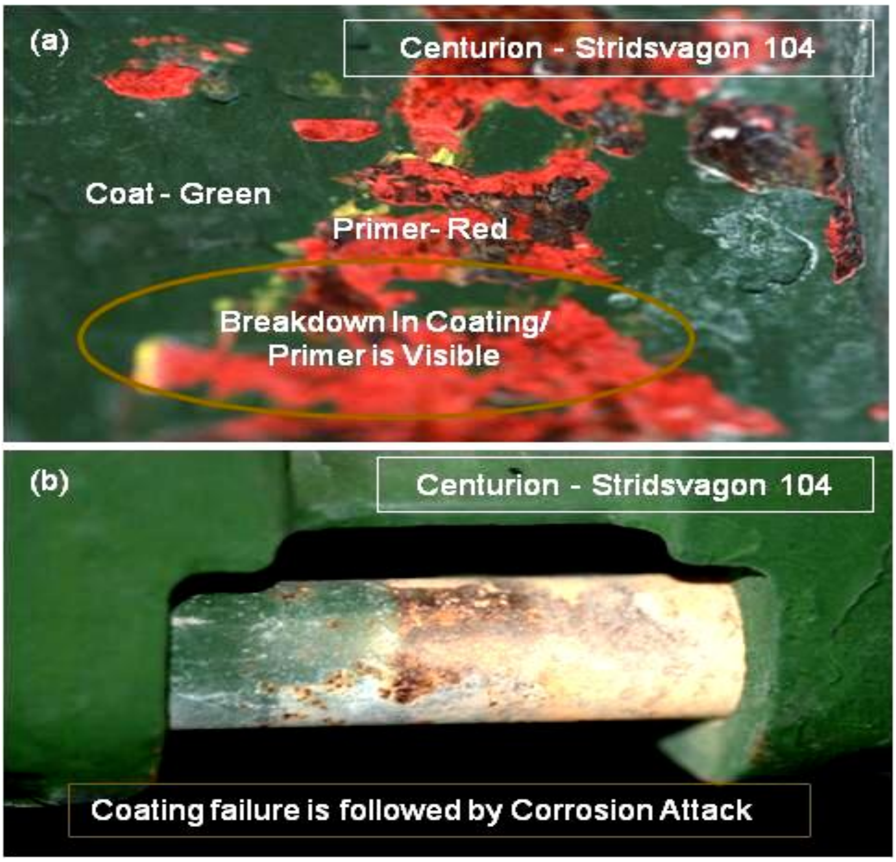


Figure: 7.7 Centurion Breakdown of Protection

Both primer and coat in practice in the museum were exposed to ASTM G 85 A - 5 an accelerated corrosion test, in order to obtain their ability to withstand extreme environment.

7.4.1. Bare Samples

Samples without any protection from the M10, Sherman and Centaur were exposed to the ASTM G 85 A – 5 for 48 hours only. The material did not exhibit any ability to resist corrosion and accumulated 100% corrosion in just 48 hours of exposure to the test. Figure: 7.8 illustrate the optical and SEM micrograph of accumulated corrosion.

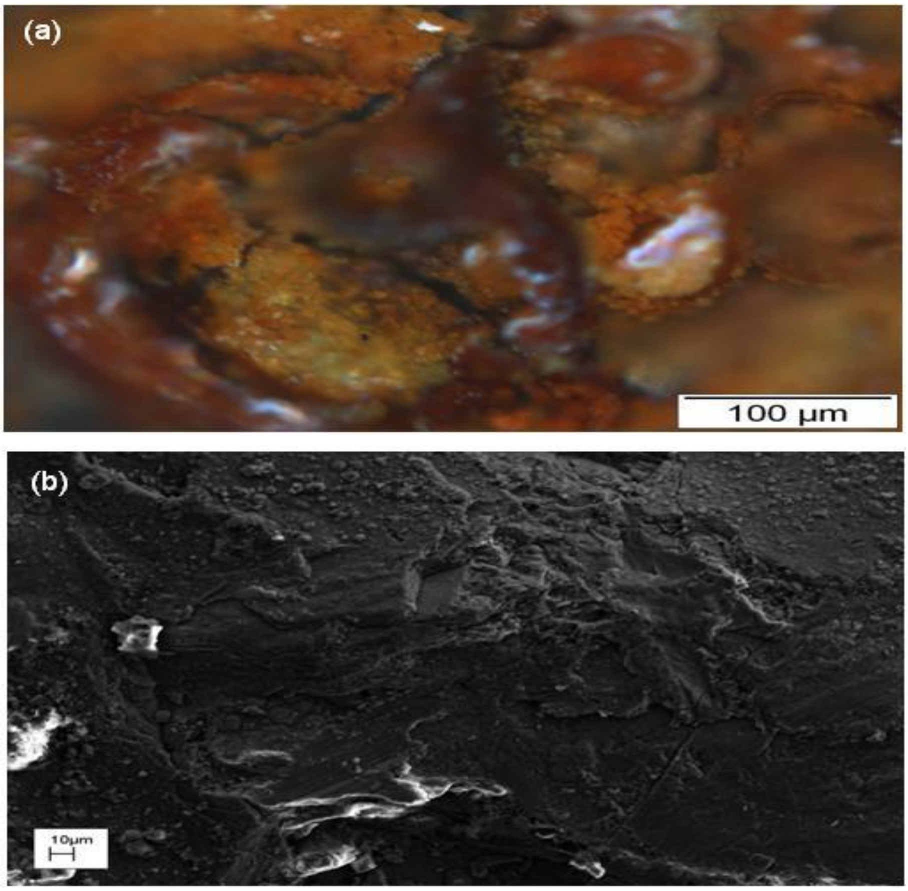


Figure: 7.8 M10 - (a) Optical and (b) SEM Micrograph of Corrosion Morphology

7.4.2. Coated Samples

Samples were painted in primer red-oxide and coat air drying alkyd. They were exposed to dilute cyclic salt fog/dry test for 264 hours in total shown in Table: 3.5. The overall performance of primer red-oxide was better and no significant signs of failure were observed. However air drying alkyd coat started to fail after 192nd hour of exposure. Figure: 7.9 illustrate the initiation of the breakdown in the form of pores in the coat after 192nd hour of exposure to the test.

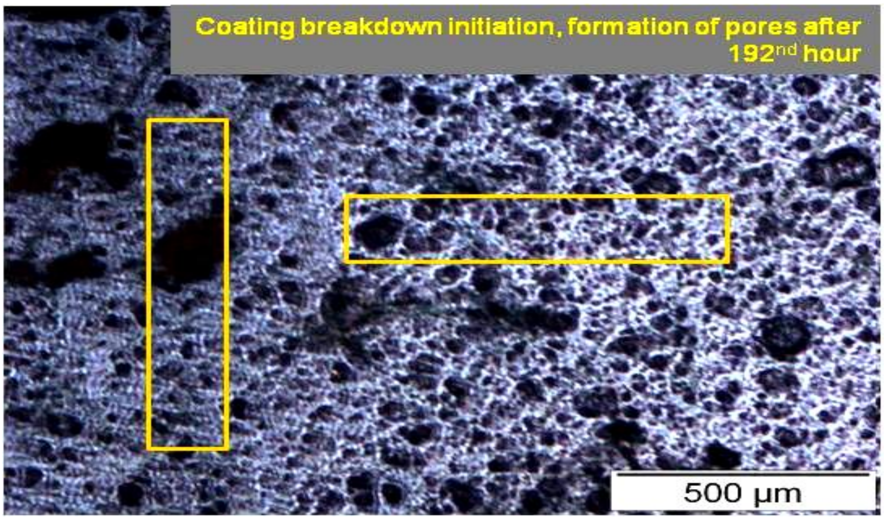


Figure: 7.9 Initiation of Breakdown in the Coat

One section of the same sample demonstrated surface corrosion build-up shown in Figure: 7.10 (a), after the complete breakdown of the coating. Two areas 1 still under protection and 2 under corrosion attack are visible.

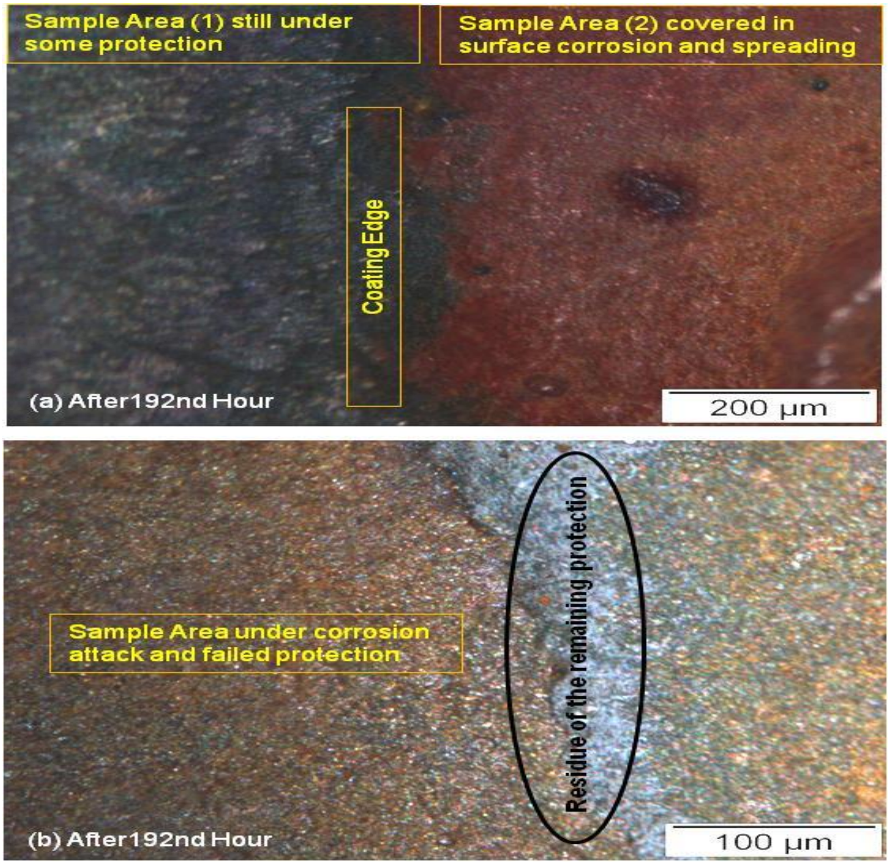


Figure: 7.10 Coating Failure during Exposure to Prohesion Test

Significant degradation of the coating was observed after 264th hour of exposure. Figure: 7.11 also illustrate areas of small corrosion deposits on its surface.

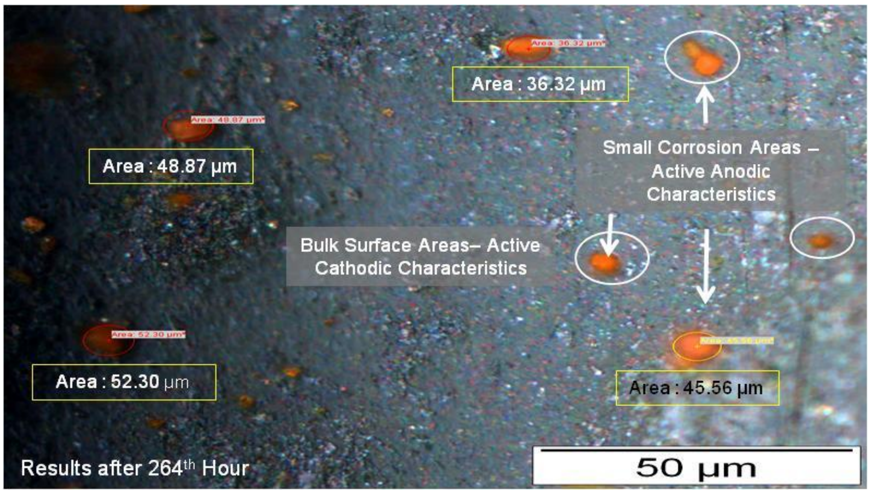


Figure: 7.11 Failure of the Coating after 264 Hours

Under such condition small areas of corrosion deposits will have the tendency to spread sidewise and occupy larger surface. Such small corrosion areas have active anodic characteristics compare to the passive bulk area which act as cathode causing severe pitting [21].

7.5. Conclusions

7.5.1. Simulated Environmental Corrosion Tests

All four samples from each tank showed some degree of corrosion accumulation after 125 hours of exposure. The purpose of the simulated environmental corrosion testing was to quantify corrosion build-up on the tanks surfaces, when they are kept in a controlled environment taking into account the comfort of the visitors.

Temperature increase result in accelerated diffusion rate and corrosion, however temperature rise under constant humidity evaporates the electrolytic layer created by dew/rain and creates dry conditions [82, 122]. Results of sample 4 could be attributed to such conditions where temperatures was not high enough to evaporate the moisture layer (RH 55%) and provided extended period of wetness for the electrochemical process to continue. Conversely in the case of other samples dry atmospheres may have been achieved and hence rate of corrosion was slow. Carbon steel is not able to form a protective layer against corrosion except when the atmosphere is clean and dry. The atmosphere in the museum could be expected to be free of atmospheric pollutants however surfaces of the tanks are contaminated and humidity reaches above 80%. This will result corrosive electrolytic layer on the surfaces because of hygroscopic salts i.e. chlorides and sulphates, accordingly rapid corrosion will occur in the tanks' components and on the surfaces [82]. Also the role of oxygen is important as an oxidant element in atmospheric corrosion, water layer formed on metallic surfaces determines oxygen diffusion towards the surfaces and reaction products [22].

During EDS (Table: 6.4) chlorine was also identified on the sample from the M10. The evaporation of the spray due to sea winds result chloride deposition on in the form of droplets or crystals on surfaces. Coal burning incinerators de-icers, bleaching plants and dust-binders on roads may also emit chlorides. Rusting of the metals can occur at low humidity such as 35% in the presence of chlorides. Steel rusts with higher rate when exposed to continuous spray of salt [19, 82]. Figure: 7.12 illustrate formation of the typical oxide-layer on a metal surface. Through these pores and cracks chlorine can reach the substrate and may provide paths of fast diffusion.

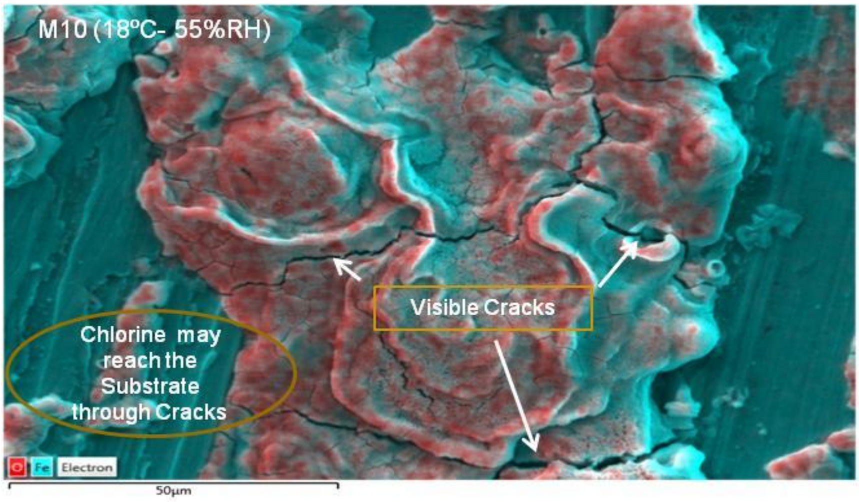


Figure: 7.12 M10 EDS Layered Micrograph, O (red) and Fe (blue) Concentrations

Chlorine has the ability to diffuse through this type of oxide layer reaching the steel surface resulting in metal chlorides and escalated corrosion. Oxygen potential is very low at the metal-scale interface because oxygen (O_2) produces metal oxides and its consumption is more. The diffusion of gases through metal-scale determines the corrosion rate [111, 124].

Dew is an important factor causing corrosion of metals in indoor environments. Dew formation on surfaces is dependent on temperatures and humidity and stay longer on the metal surfaces resulting atmospheric corrosion. Its formation depends on the relative humidity and changes of the temperature. Dew does not wash the surface therefore the concentration of the pollutants is relatively high and could be more aggressive compare to rain. Also if surfaces and/or indoor environment are polluted then the atmospheric corrosion would be significant which could also decrease the critical relative humidity. For unpolluted environment rate of corrosion is less significant when the relative humidity is below 75%. However in The Tank Museum Bovington RH values reach 80% and 100% at certain times shown in Figure: 7.13. Higher value of RH together with temperatures greater than 0°C would lead to longer TOW causing faster corrosion of the components/surfaces which have failed protection, exposed and are polluted [19, 125, 126].

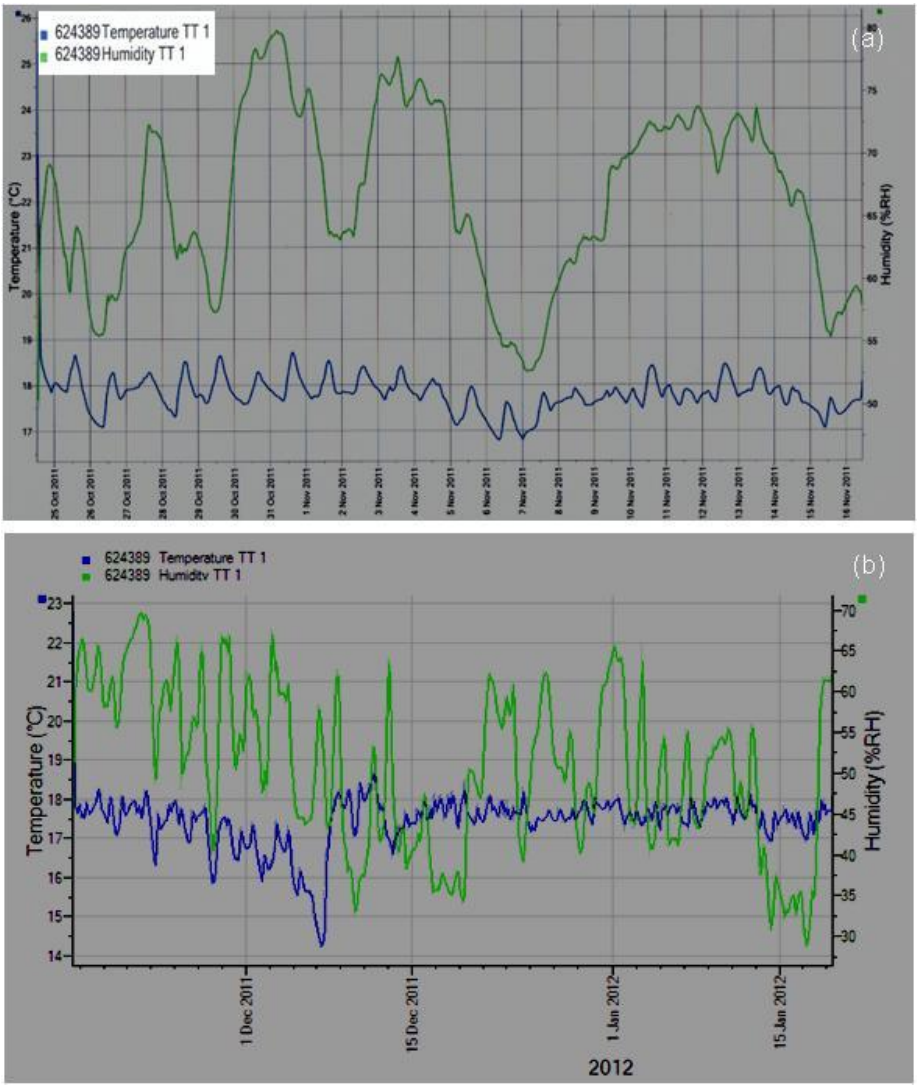


Figure: 7.13 Temperature vs. RH in WW2 hall

During atmospheric exposure of any material, a repeated and endless cycle of wetting and drying occurs. This is caused by precipitation, heat and wind drying the wetted surfaces, adsorption and deposition of pollutants. The electrochemical mechanism developed by the continuous wet-dry cycles in this natural environment, via condensation, precipitation, heat and wind would play a significant role in the corrosion of the tanks [121, 127]. Once the paint barrier is damaged and the underlying carbon steel substrate is exposed to the environment, the activity of the corrosion reactions would be almost continuous. The oxidation of the metal is known to occur in an accelerated manner during wet conditions. Furthermore the highest rate of corrosion takes place just before drying starts i.e. when the liquid layer is thin (before evaporation) and the oxygen transport through the electrolyte film is maximum [19, 128].

7.5.2. Prohesion (ASTM G85 A5) Corrosion Tests

Cyclic Salt Fog/Dry Corrosion Tests revealed 100% corrosion accumulation on the samples which were exposed to this test without any coating in 48 hours. Materials showed no ability to resist corrosion under extreme environments. Bovington is around 9 km from the coastline; winds from the sea are able to deposit salt aerosols on the tanks surfaces outside the museum [82, 129]. In addition sea winds can access the museum through doors and any windows left open. Salt particles deposited act as nuclei to start corrosion, becomes hygroscopic and increases the duration of surface wetness. Sea wind delivered chlorides also have significant role in corrosion and the phenomenon of corrosion can sustain at humidity as low as 35% [19, 130, 131]. It is therefore of extreme importance that surface which are exposed must be protected through adequate protection system.

Chapter 8 **Tribological Considerations**

Wear is one of the major factors to influence the structural integrity of The Tank Museum vehicles which operate regularly or intermittently. In this chapter the piston-liner assembly wear is reported from the Tiger 1. This was the real-time wear evaluation which occurred in pistons and cylinder-liners. Piston's design for both original and replacement pistons are also reported and wear assessment was conducted taking into account materials' composition.

8.1. Tiger 1 Piston Design

Original piston and cylinder-liner from the Maybach HL 210P45 engine were collected from The Tank Museum Bovington. This engine was disassembled to analyse various types of tribological failures. Replacement pistons and cylinder-liners that had been run in the engine for two hours were also obtained.

The original piston (130P15) is shown in Figure: 8.1. The original design for the piston was completely circular with two compression rings and two secondary compression/oil scraper rings. There were also two additional scraper rings at the bottom of the piston.

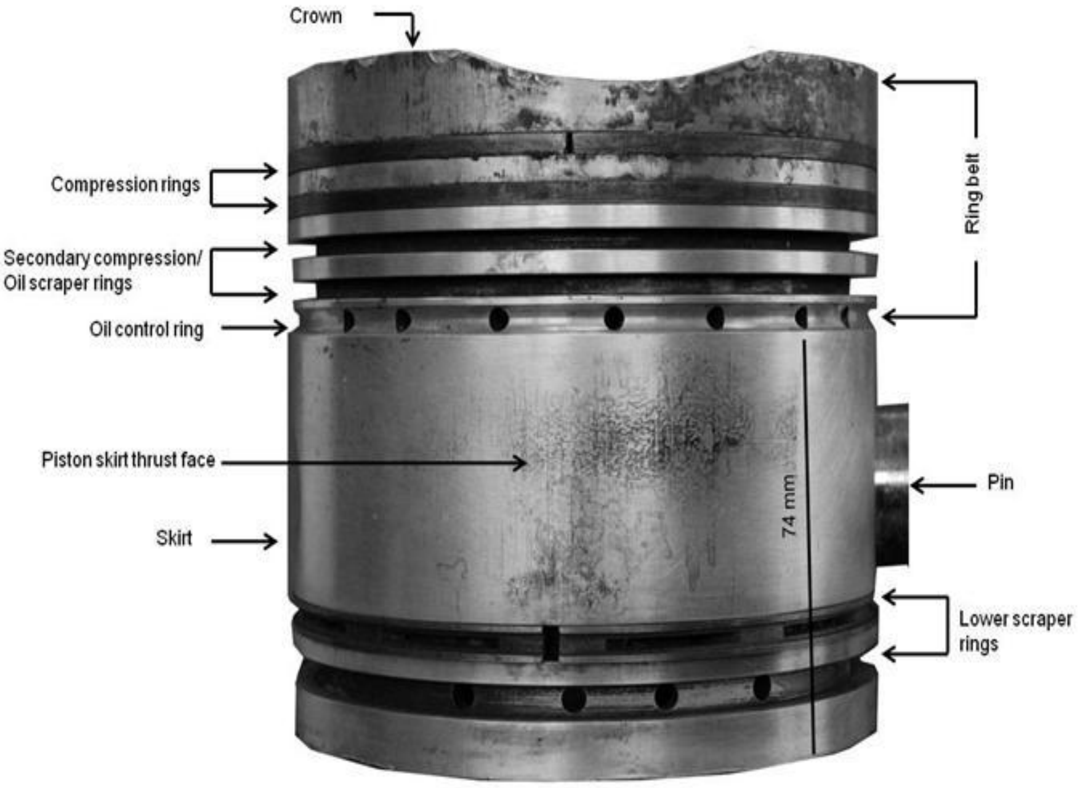


Figure: 8.1Tiger 1 Original Piston (130P15) – Marginal wear

The design of the replacement piston has been modified as shown in Figure: 8.2. First the fourth compression/scraper ring was omitted. Secondly, an additional rectangular profile was included at both ends of the piston-pin, and lastly, the bottom oil scarper rings were omitted. The modifications in design and the material's chemical characteristics of the replacement piston resulted in catastrophic failures.

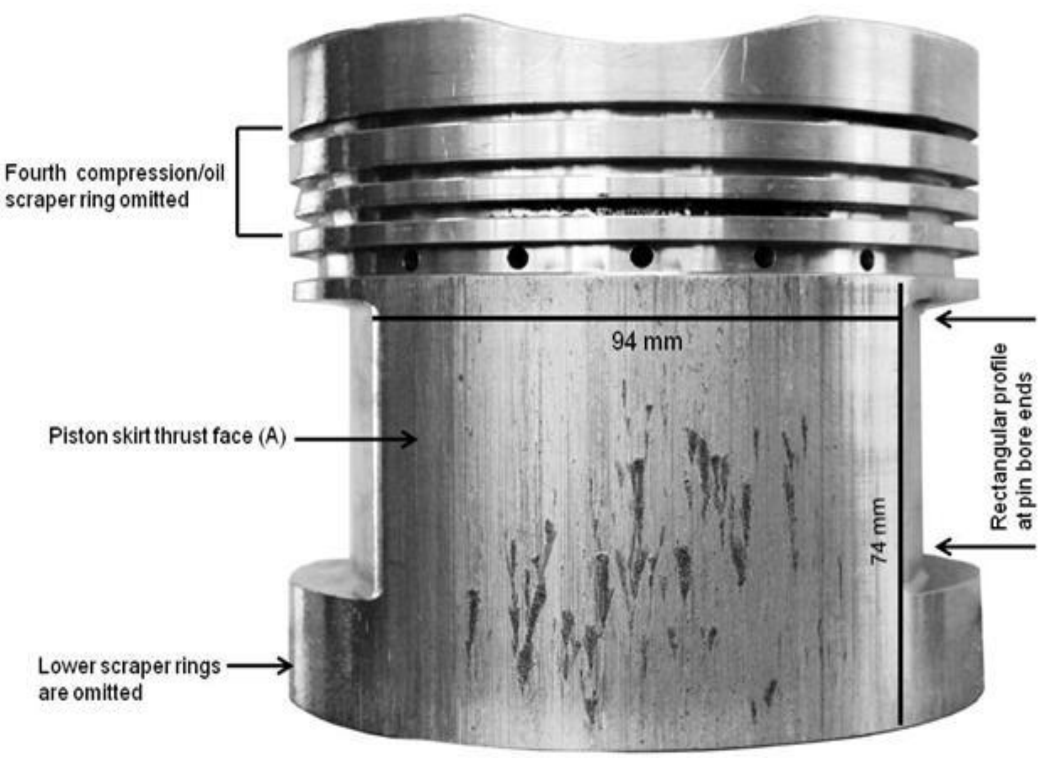


Figure: 8.2 Tiger Replacement Piston Extreme Scuffing

8.2. Wear Assessment

The original piston and original cylinder-liner were operative during the 2nd World War in the Maybach HL 210P45 engine. The exact hours of operation of the engine piston-liner assembly are unknown. Taking into account the harsh mechanical and environmental conditions under which the Tiger 1 engine operated piston performed extremely well. The original piston can be classified as hyper-eutectic Al-Si alloy and its performance can be attributed to materials' composition. Surface morphology of the original piston-skirt-thrust-face is shown in Figure: 8.3, where negligible wear was observed compared to the severe operating conditions under which it performed.

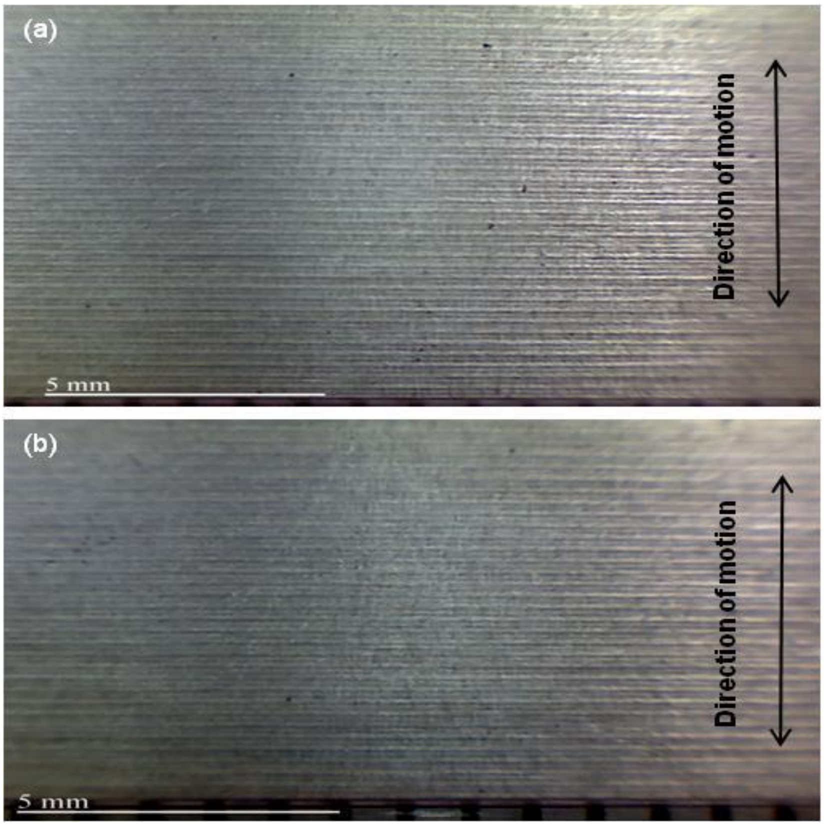


Figure: 8.3 Original Piston Skirt - Thrust - Face Horizontal Lines Show Original Machining Marks

Replacement piston and cylinder-liner were used as substitutes and were obtained for this research after failure in two hours of operation in the actual engine. The replacement piston has a very low Si (0.73 wt %) content. Si produces good thermal and wear characteristics. One of the major reasons of failure of the replacement piston was its susceptibility to thermal expansion under the influence of temperature, which resulted small/no piston-to-wall clearance. Thermal expansion under elevated temperature has lead to a direct contact between piston-skirt and the cylinder-liner. The result of this contact between piston-skirt and cylinder-liner was observed as sliding/adhesive wear shown in Figure: 8.4.

Adhesive wear can be explained using adhesion theory of friction. When surfaces come into contact under loads welding occurs at the contacting asperities and during relative motion shear develops. The presence of any contaminants during relative motion between the surfaces can strongly influence the shear strength. The resultant developed shear in one of the surfaces can cause transfer of material from one surface to the other [83, 132]. This phenomenon of a materials' removal from the surfaces was observed in the replacement piston and cylinder-liner.

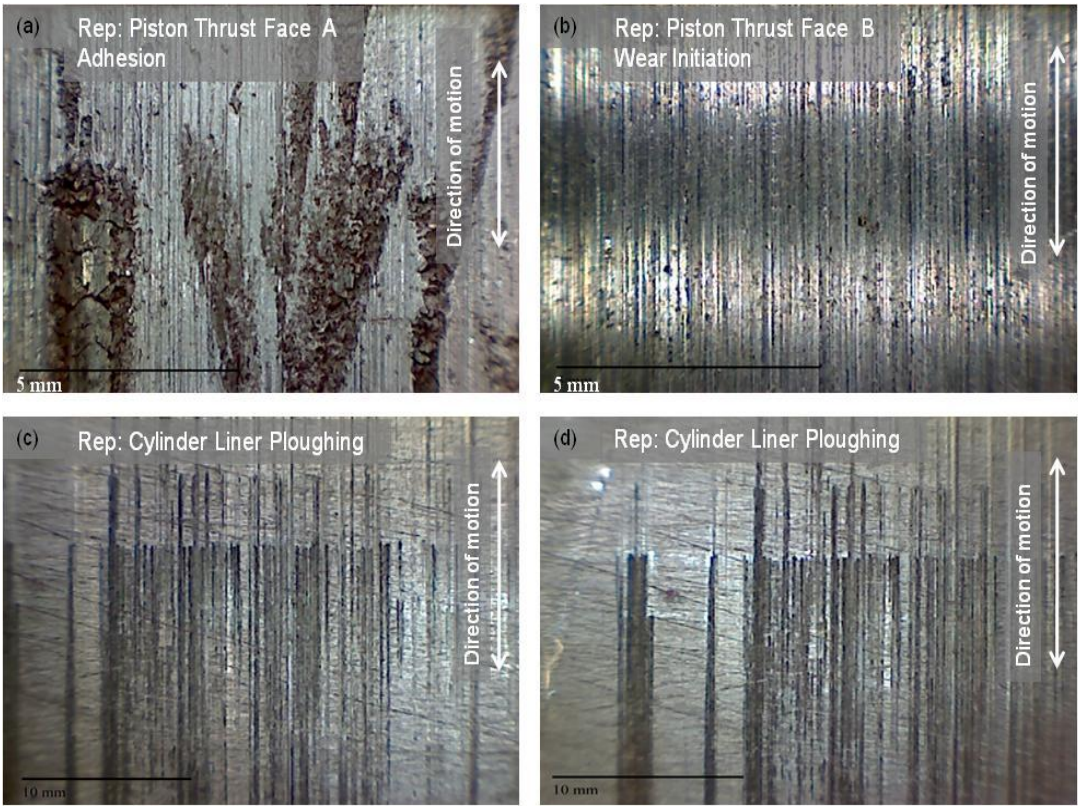


Figure: 8.4 Tiger 1 (a) Rep: Piston Adhesion (b) Rep: Piston Wear Initiation (c) & (d) Rep: Cylinder-liner Ploughing

The transfer of material between the surfaces has acted as an abrasive media further facilitating wear due to which scratches on the piston skirt and wear grooves in the cylinder-liner are visible in Figure: 8.2 and Figure: 8.4 respectively. Furthermore the presence of the material particles established an unstable coefficient of friction between the sliding surfaces leading to scuffing [48, 50]. Scuffing is a complex tribological failure mechanism which could be the result of, severe surface damage when surfaces are in sliding contact, extreme surface roughening with or without material transfer, solid-phase welding damage in sliding surfaces, breakdown of the lubricant film, material properties and operating conditions [133-137]. Surface reliability of the piston-skirt-thrust-face has been lost due to scuffing. Scuffing in the replacement piston was a result of thermo-elastic instability (unbounded growth of temperature and pressure perturbations resulting in very high local temperatures that manifest itself in the form of macroscopic hot spots. The formation of such localised hot spots is indicative of high local stresses that can lead to material degradation) of the piston material, sudden rise in friction, contact temperature and vibration leading to catastrophic roughening and failures of the piston-skirt-thrust-face and the entire piston-liner assembly [138, 139] shown in Figure: 8.4 (a) and (b).

In Figure: 8.4 (c) and (d) of the replacement cylinder-liner, formation of the ploughing is visible due to plastically displaced material. Repeated unidirectional sliding contact between the surfaces and the hard asperities plastically displaces material sideways; material displacement in this way is known as ploughing [140-142]. Displaced material in this case is subjected to strain during sliding contact. When the strain exceeds a critical value, material rupture and formation of the debris starts [140-142]. Formation of debris at the cylinder-liner surface can be observed in Figure: 8.6 (a).The deposited wear particles between the sliding contact of piston and cylinder-liner has lead to the scuffing. In addition a high tendency of adhesion was observed on the piston-skirt as illustrated in Figure: 8.4 (a) [137].

Figure: 8.5 (a) demonstrate the appearance of localised junctions/ micro-welds. The formed junctions were strong and therefore significant wear took place between piston and liner leading to a substantial amount of debris particles formation. Figure: 8.5 (b) showed average surface roughness of 9.09 µm on an area of length 0.58 mm and width 0.43 mm respectively. This is significantly higher when considering friction co-efficient and its implication on frictional heat and wear.

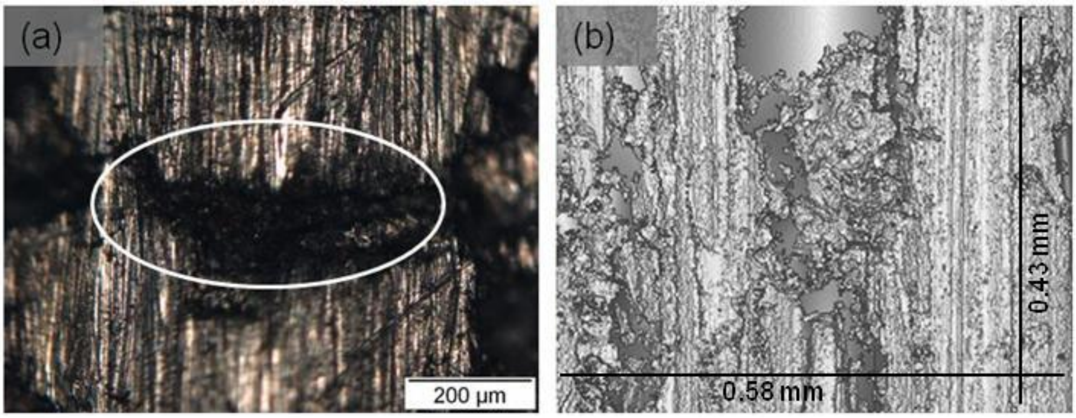


Figure: 8.5 Tiger 1 Rep: Piston (a) Surface Topography (b) WLI Showing Surface Roughness Profile

Figure: 8.6 (a) is the optical micrograph of the cylinder-liner surface illustrating build-up of wear grooves. White light interferometry was conducted to obtain the surface prolife of the cylinder-liner shown in Figure: 8.6 (b) groove formed because of ploughing is shown with a width of 0.23 mm. The depth of the groove shown in Figure: 8.6 (c) was 21.76 µm whereas in Figure: 8.6 (d), 3D surface profile of the groove is shown. Average roughness recorded at the groove shown in Figure: 8.6 (d) was 5.78 µm at an area of length 0.58 mm and width 0.43 mm.

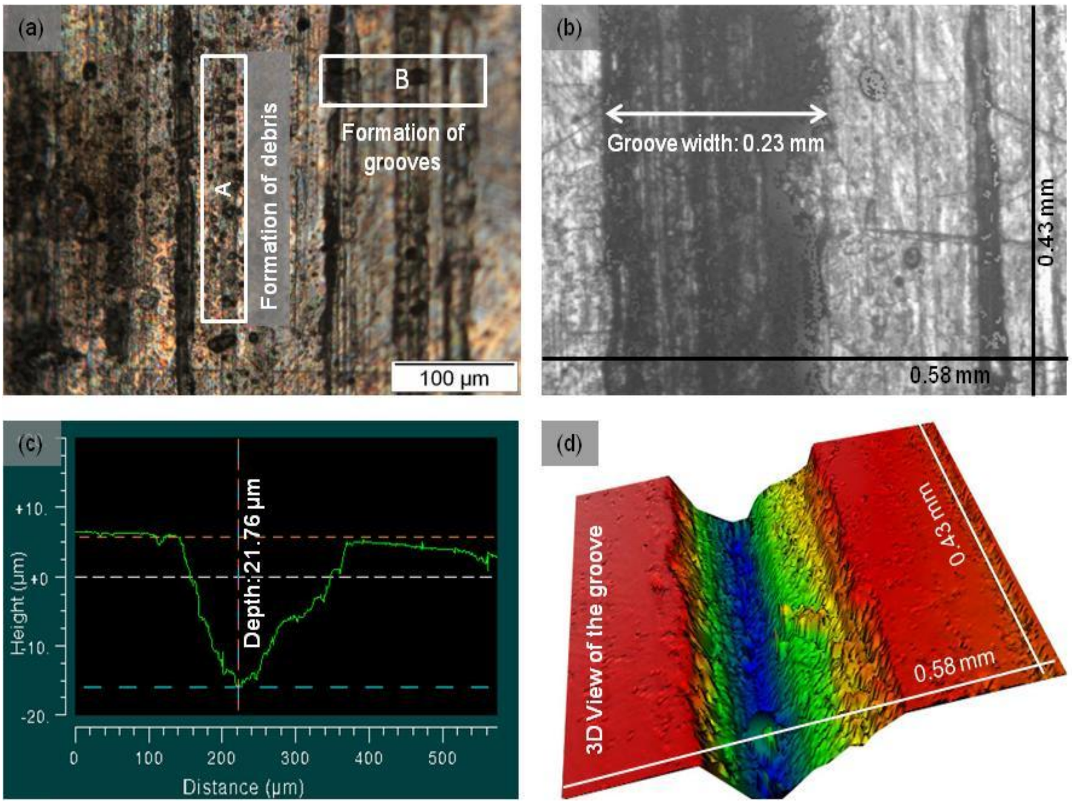


Figure: 8.6 Tiger 1- Rep: Cylinder-liner (a) Surface Topography (b) Groove Width (c) Groove Depth (d) Groove 3D View

8.3. Conclusions

Wear accounts significantly for partial or complete malfunctions of the piston and cylinder-liner assemblies in the engines. Therefore many efforts have been made to improve materials' bulk properties, surface treatment, design and coatings to reduce wear in components/surfaces. Engine performance is immensely attributed to piston's materials properties [143, 144]. Original piston was Al-Si hyper-eutectic alloy and approximately matches RSA - 419, AA - 4019 and AA - 4048. Materials' composition of each standard is given in Figure: 8.7.

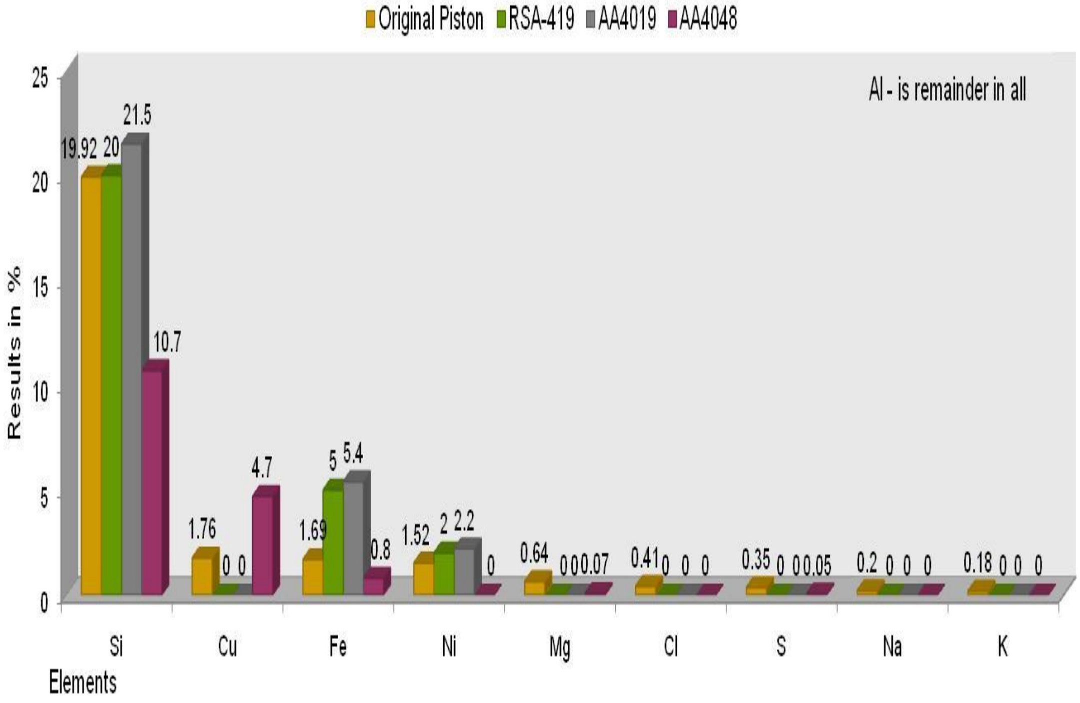


Figure: 8.7 Tiger 1 Materials' Composition of Original Piston and Matching Standards

Al-Si alloys possess low density have high wear resistance, low expansion and thus have been increasingly used in petrol engines [137]. Original piston performed very well, although it had been in use in the engine for a long unknown period and more importantly operated under extreme conditions (WWII).

Failures of the replacement piston can mainly be attributed to material properties for a gasoline engine. Characterisation results of the replacement piston match Al - 2031 and Al - 2618-T6 shown in Figure: 8.8.

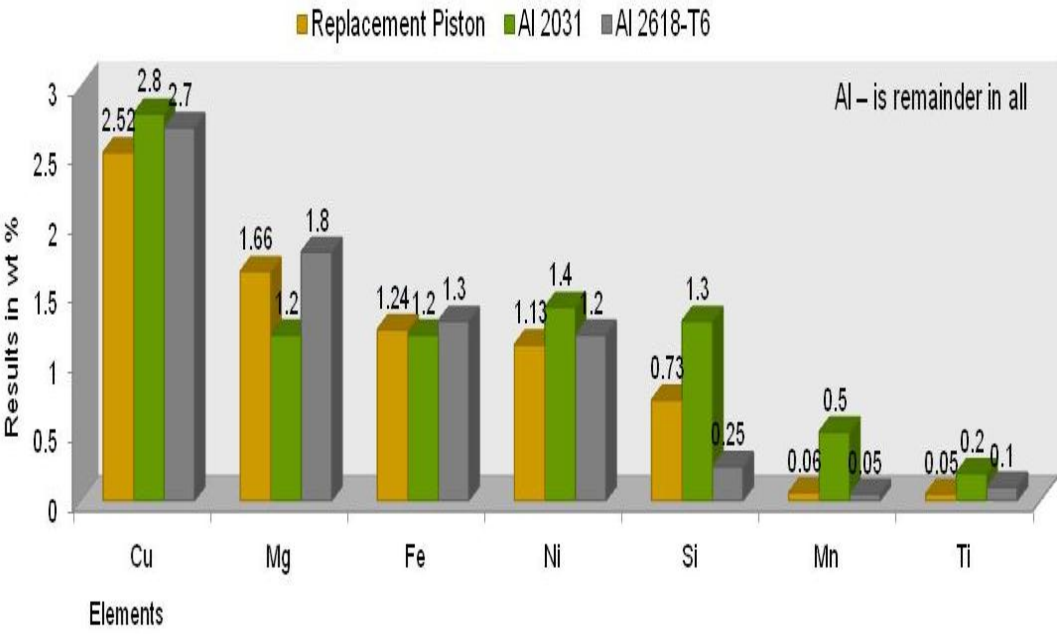


Figure: 8.8 Tiger Materials' Composition of Rep; piston and Matching Standards

One of the major failures of rep: piston was severe scuffing during limited hours of operation. In this case scuffing was the result of thermal expansion of piston leading no/small clearance between piston and cylinder-liner, thus resulting in higher friction, contact, temperature and vibration leading to extreme roughening, and as a result the loss of functionality [138].

Chapter 9 Conclusions and Recommendations

This research presented a case study followed by experimental research on The Tank Museum vehicles' giving consideration to failure attributed to corrosion and wear.

9.1. Conclusions

- This research is significant with the view point that some but important aspects of ageing are identified. Structural degradation through corrosion has been identified and analysed in tanks of historic and cultural significance. Materials were processed/manufactured during 2nd World War, their composition was unknown and information was scarce. Therefore material characterisation was conducted to obtain material compositions and nearest standards was identified.
- A bench mark of material loss due to corrosion so far, has been achieved. Material loss because of corrosion was high in the Centaur comparing to the Sherman, M10, BT R – 60 and King Tiger samples. This data is important in terms of designing a life expectancy programme through mathematical and/or empirical modelling.
- Corrosion analyses of three tanks showed corrosion morphology on the tanks surfaces, corrosion propagation from surface to sub-surface level and corrosion contaminants. During this experimental work various corrosion contaminants, sub-surface crack and defects were also identified. Corrosion residues were relatively thick (approximately 250 µm) on the surfaces of the M10, whereas the phenomenon of sub-surface corrosion pits was wide spread in the Centaur. Corrosion damage in the Centaur is critical and can be classified as a major risk to its structural integrity.
- The phenomenon of corrosion was also influenced by the presence of surface contaminants and sub-surface defects such as slags, sulphide inclusions and corrosive pits. These factors alone and/or in combination with each other were observed to be a serious issue in limiting vehicles' longevity.
- Study of the environments both inside and outside the museum has been conducted to relate corrosion activity within the context. Relative humidity inside museum was observed to be reaching as high as 80%. Outdoor environment in Bovington showed that relative humidity is almost 80% most of the time, however peaks of 100% also occurs. During these analyses average salts and pollutants were also recorded. It was observed that fluctuations in temperature and relative humidity

inside the museum are not viable for the structural health of the vehicles.

- Simulated environmental corrosion tests revealed some degree of corrosion accumulation under controlled environments. Relatively more corrosion was accumulated when the RH value was increased (55%) in all experiments. These results exemplify the role of RH in corrosion. These results shown to be an important factor in determining real time corrosion build-up.
- Samples exposure to accelerated corrosion tests (ASTM G - 85 A5) for only 48 hours, illustrated 100% corrosion accumulation. For all three tanks the material ability to resist adverse environmental conditions was negligible. These results are of particular interest for the vehicles which are exposed in uncontrolled environment.
- Exposure of the primer and coating to prohesion corrosion test showed, that the primer was able to resist failures during 264 hours of exposure. However breakdown of the coating was observed during/after 192nd hour of exposure.
- Original piston which was designed before/during the 2nd World War had enhanced tribological properties. Original piston operated for longer hours under extreme working conditions in the WW2 and has shown excellent resistance towards tribological failures.
- Real time wear evaluation of the Tiger 1 engine revealed that failures of the engine replacement components were mainly attributed to inadequate materials' selection and design.

9.2. Recommendations

- Close proximity of Bovington to the English Channel results in extensive rainfall, wind, temperature fluctuations and high humidity together with high salt content throughout the year. For the outdoor tanks it is important that any surfaces without protection must be protected against such conditions. Tanks inside the museum displaying corrosion also need corrosion treatment. Thus corrosion removal from the surfaces, adequate surface preparation (Appendix K) and application of the protective coatings are required.
- Surface contaminants such as Cl, Na, S and F were identified on the tanks' surfaces. Elimination of such contaminants from the tanks' surfaces is required as they will result in rapid corrosion. The use of cleaning products which contain chlorine and sodium should also be avoided.

- Control of the relative humidity to the optimum level (35 - 45%) is an important factor for the tank museum. This can be achieved through better ventilation, dehumidification and air conditioning. Optimum scale of RH and temperature will help mitigate corrosion, thus achieving extended life of the tanks.
- The use of corrosion inhibitors (Appendix L) based upon their corrosion protection ability; inhibition efficiency and environmental friendliness are recommended for the surfaces where surface treatments are not favoured. Such corrosion inhibitors are added to mineral and vegetable oils and then applied to the surfaces without compromising the originality of the component.
- In the replacement of components such as pistons and cylinder-liners materials' composition for their specific performance should be considered.
- Suitable materials for a specific component for a specific purpose will enhance component reliability and reduce maintenance costs.

Chapter 10 Future Work

This chapter documents future research work which will have immense benefits for preservation of the tanks and scientific value.

10.1. Live Corrosion Condition Monitoring

In-situ corrosion monitoring through linear polarisation resistors (LPR) is an effective method and has proven to be a rapid response technique. LPR sensors are sensitive to early stages of corrosion and give instant feedback of the actual corrosion initiation on surfaces where they are mounted. The network of LPR systems provides a low-cost, non-intrusive way to detect corrosion before it becomes an excessive burden and is a novel method to move from scheduled based maintenance (SBM) to condition based maintenance (CBM)[145].

µLPR are more advanced corrosion monitoring sensors and are based on the established LPRs. µLPR shown in Figure: 10.1 can be installed permanently on the bare metal surface and then coated/painted to record and measure both strain and corrosion rate. Data can be downloaded on a personal computer through a wireless/wired network. Acquired data provides critical assessment of structural health, leading to prediction of failure through corrosion damage.

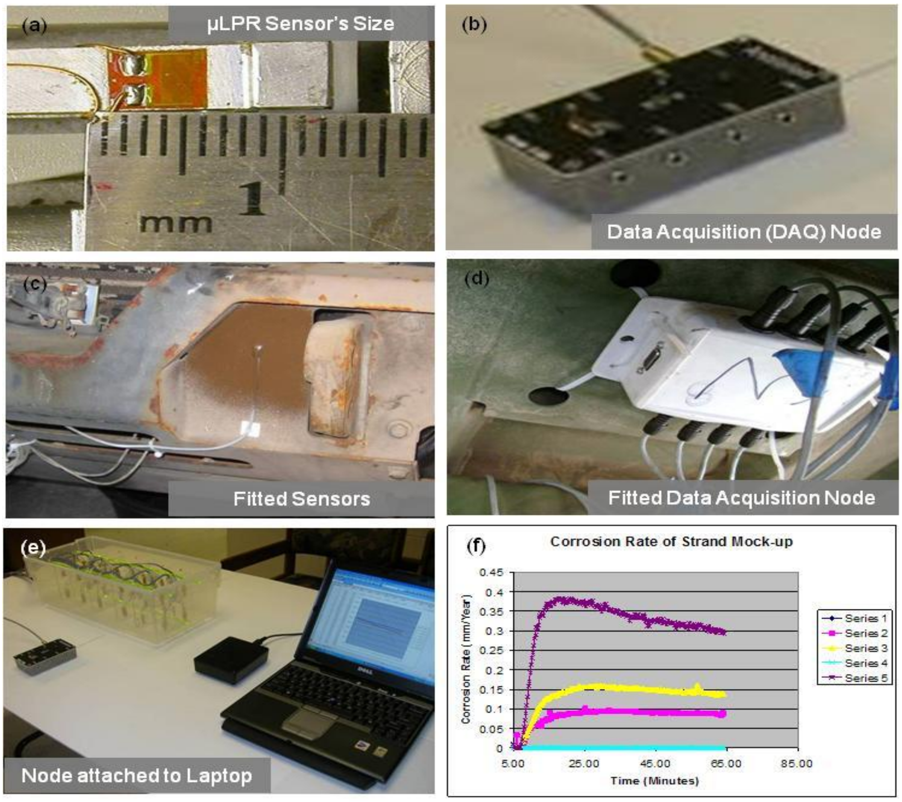


Figure: 10.1 LPR Sensors - Images Courtesy of Analatom

16 µLPR corrosion sensors are acquired during this research and are ready to be installed. Also a frame work of in-situ corrosion monitoring, has been designed to install 16 µLPR on two high value tanks (8 sensors on each tank). 8 sensors attached to data collection node (Figure: 10.1) will be used to monitor corrosion continuously or at regular intervals. Corrosion data under various environments from the data acquisition node can be transferred to a computer for evaluation. Figure: 10.2 illustrate the proposed model of in-situ corrosion monitoring for the Tiger 1.

Images: http://www.fprado.com/armorsite/main.html

Figure: 10.2 Tiger 1 Proposed Model of µLPR Installation

10.2. Corrosion Inhibitors

Further research is needed to investigate state-of-the-art corrosion inhibitors. They must be environmentally friendly, robust and their application on the components may not alter the originality of the artefacts. For these purpose novel corrosion inhibitors LAMCHEM ^{TM} PE - 130 K and LUMULSE GML K GLYCEROL ESTER shown in Figure: 10.3 are obtained. These corrosion inhibitors can be added around 1% into vegetable or mineral oil and then applied to the corrosion affected surfaces. These inhibitors are useful for the tanks surfaces which still have the original coating, and removal of the original paints is not favoured. Experimental research to evaluate the durability of these corrosion inhibitors under real museum environment is suggested.

Figure: 10.3 Corrosion Inhibitors

10.3. Tribological Assessment

In the current research real time tribological assisted damage in pistons and cylinder-liners of the Tiger 1 engine has been successfully analysed. Additional research is needed to evaluate friction and wear at laboratory level. At a laboratory level friction and wear can be evaluated utilising TE - 57 micro-friction using pin-on-plate method under various tribological conditions on both original and matching materials.

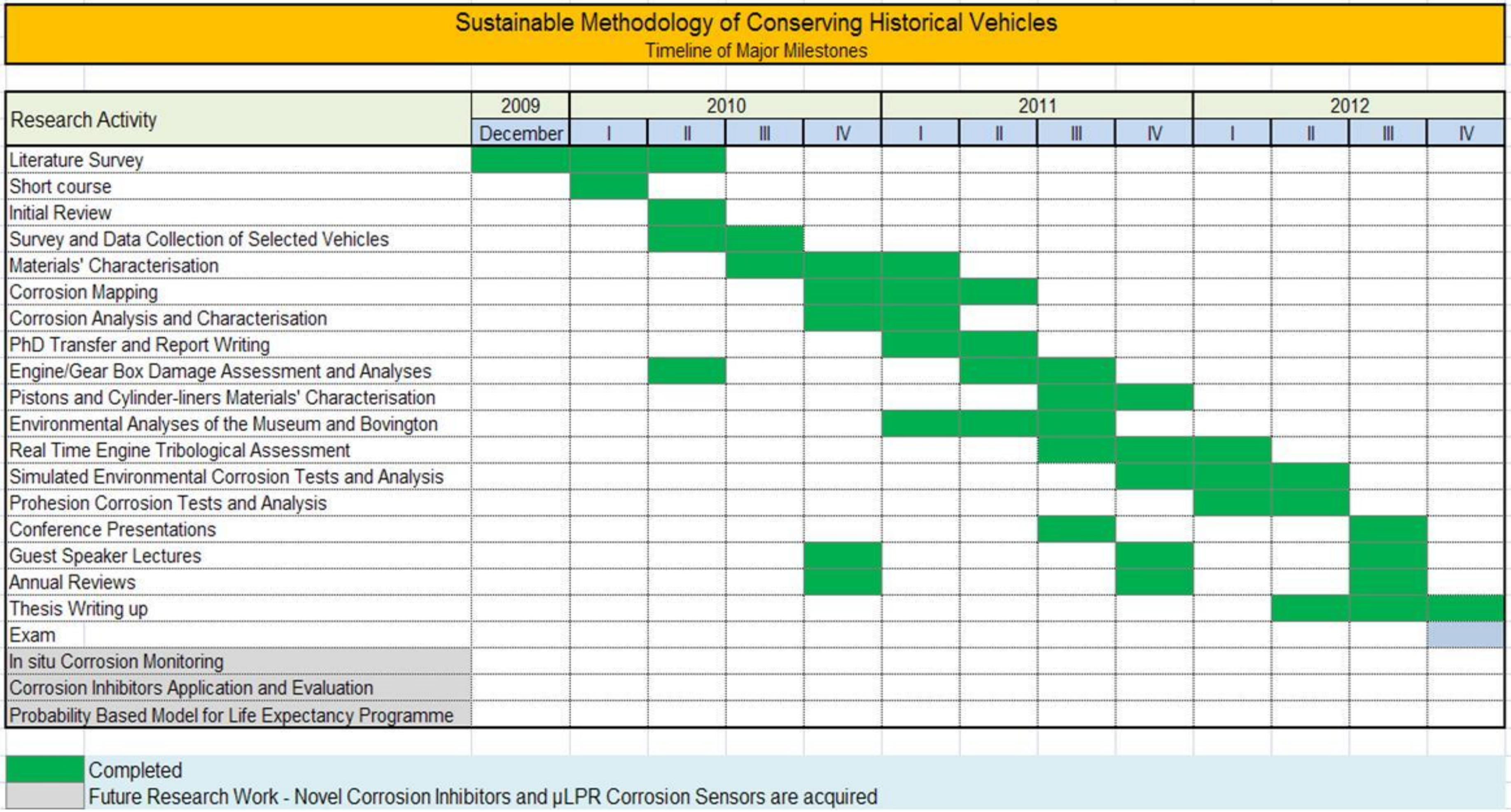
10.4. Life Expectancy Programme

Further research to draw a life expectancy programme is required. This can be achieved through a probability- based model based upon the fundamentals in this research. This model may include (a) pits growth, (b) Cracks propagation under high dynamic loads and corrosive environment, and (c) modelling of the accumulation of corrosion under ideal museum environment using related RH, temperature and electrochemical relations.

10.5. Corrosion of Electronic Components and Degradation of Rubber

Corrosion of electronic components and the degradation of rubber are also areas of major concern. The corrosivity of the solder flux and etching solutions, and cleanliness of the printed circuit boards (PCB) plates are playing a vital role in the deterioration of the overall electronic components. Tyres and other rubber components within the vehicles are exhibit degradation influenced by the environment as well as wear. Further research is suggested to investigate such mechanisms of degradation.

Project Timeline



Sustainable Methodology of Conserving Historical Vehicles

Timeline of Major Milestones

Research Activity	2009	2010				2011				2012			
	December	I	II	III	IV	I	II	III	IV	I	II	III	IV
Literature Survey	🟩	🟩	🟩										
Short course		🟩											
Initial Review			🟩										
Survey and Data Collection of Selected Vehicles			🟩	🟩									
Materials' Characterisation				🟩	🟩	🟩							
Corrosion Mapping					🟩	🟩	🟩						
Corrosion Analysis and Characterisation					🟩	🟩							
PhD Transfer and Report Writing						🟩	🟩						
Engine/Gear Box Damage Assessment and Analyses			🟩				🟩	🟩					
Pistons and Cylinder-liners Materials' Characterisation								🟩	🟩				
Environmental Analyses of the Museum and Bovington						🟩	🟩	🟩					
Real Time Engine Tribological Assessment								🟩	🟩	🟩			
Simulated Environmental Corrosion Tests and Analysis									🟩	🟩	🟩		
Prohesion Corrosion Tests and Analysis										🟩	🟩		
Conference Presentations								🟩				🟩	
Guest Speaker Lectures					🟩				🟩			🟩	
Annual Reviews					🟩				🟩			🟩	
Thesis Writing up											🟩	🟩	🟩
Exam													🟦
In situ Corrosion Monitoring													
Corrosion Inhibitors Application and Evaluation													
Probability Based Model for Life Expectancy Programme													

🟩 Completed

⬜ Future Research Work - Novel Corrosion Inhibitors and µLPR Corrosion Sensors are acquired

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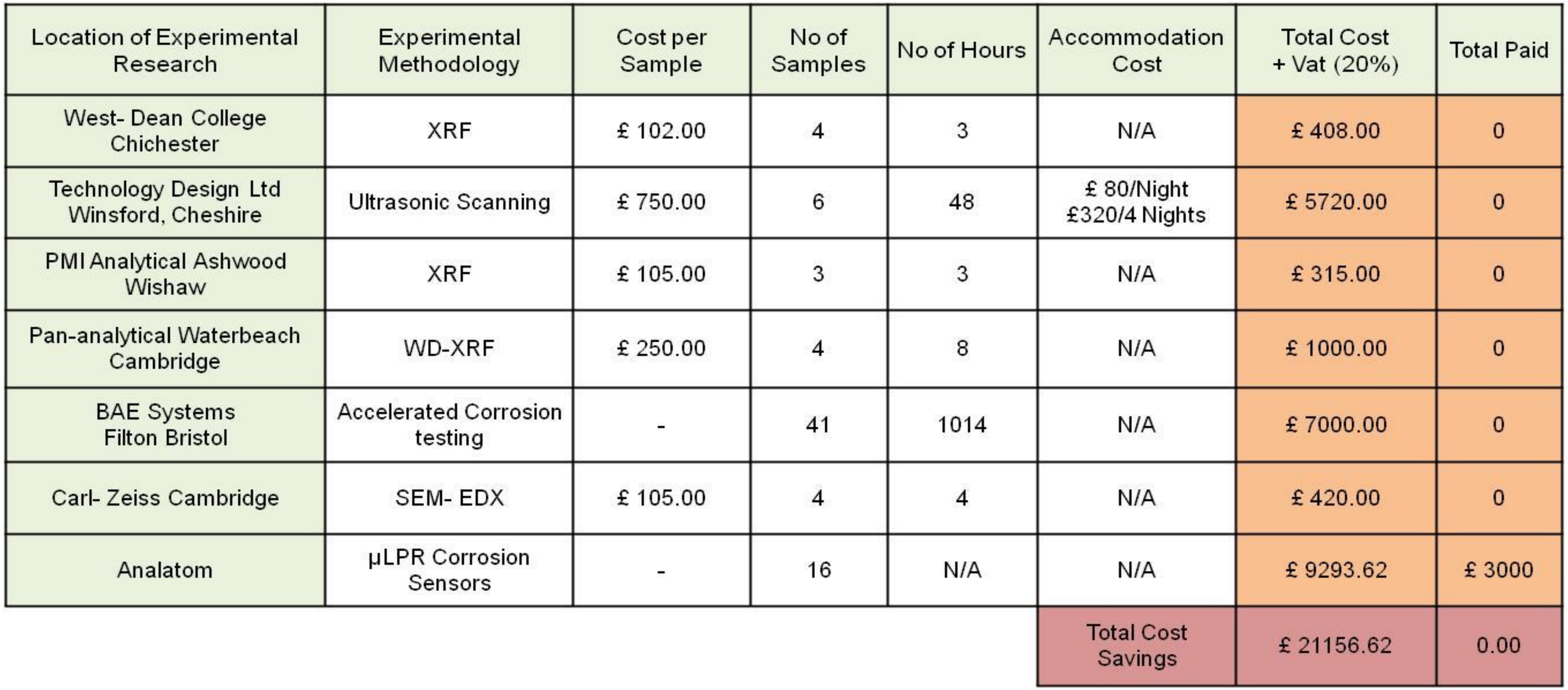
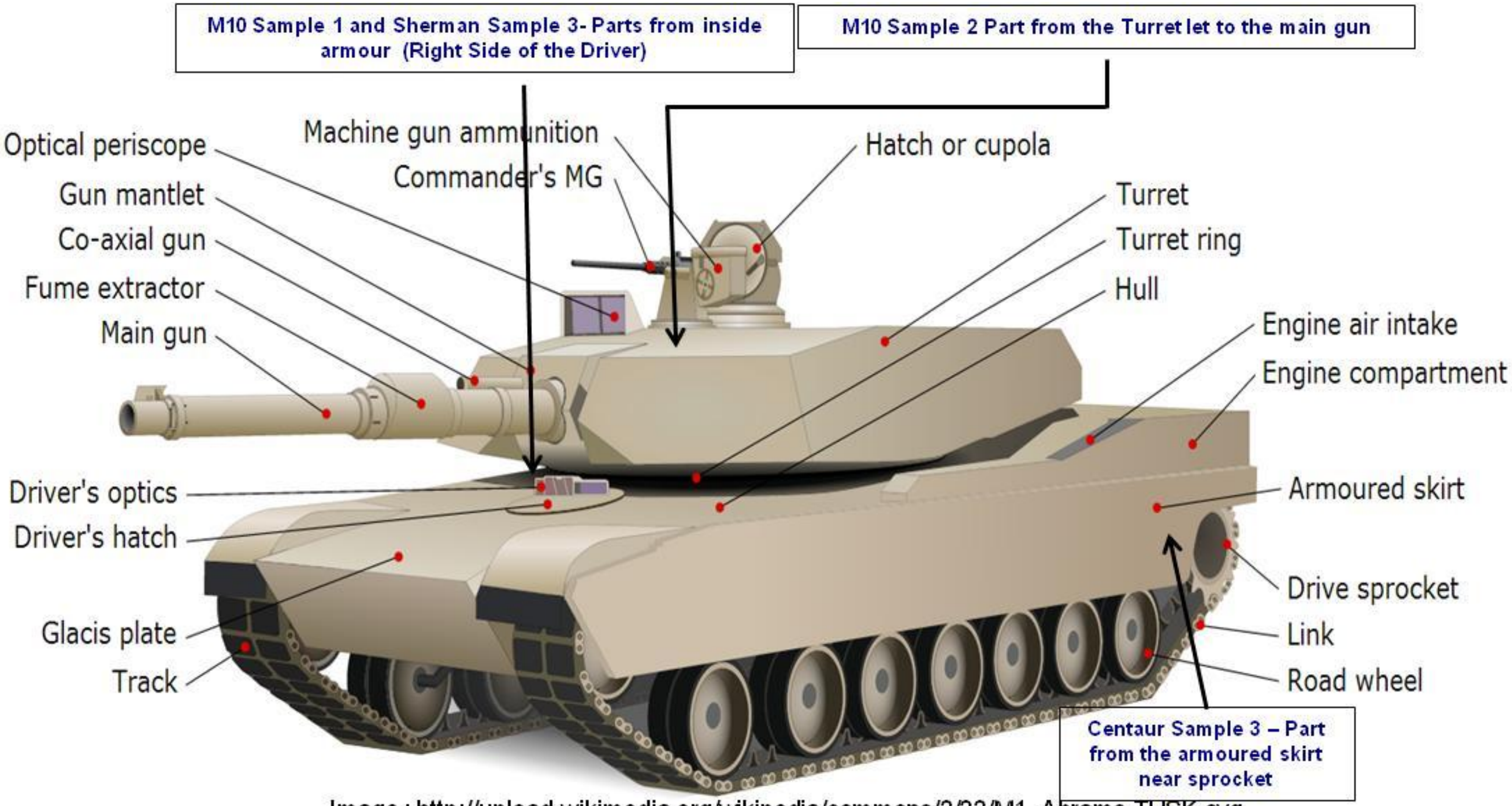
Appendices

Appendix A: Cost Savings through In-Kind Support



Location of Experimental Research	Experimental Methodology	Cost per Sample	No of Samples	No of Hours	Accommodation Cost	Total Cost + Vat (20%)	Total Paid
West- Dean College Chichester	XRF	£ 102.00	4	3	N/A	£ 408.00	0
Technology Design Ltd Winsford, Cheshire	Ultrasonic Scanning	£ 750.00	6	48	£ 80/Night £320/4 Nights	£ 5720.00	0
PMI Analytical Ashwood Wishaw	XRF	£ 105.00	3	3	N/A	£ 315.00	0
Pan-analytical Waterbeach Cambridge	WD-XRF	£ 250.00	4	8	N/A	£ 1000.00	0
BAE Systems Filton Bristol	Accelerated Corrosion testing	-	41	1014	N/A	£ 7000.00	0
Carl- Zeiss Cambridge	SEM- EDX	£ 105.00	4	4	N/A	£ 420.00	0
Analatom	µLPR Corrosion Sensors	-	16	N/A	N/A	£ 9293.62	£ 3000
					Total Cost Savings	£ 21156.62	0.00

Appendix B: Introduction to a Military Tank



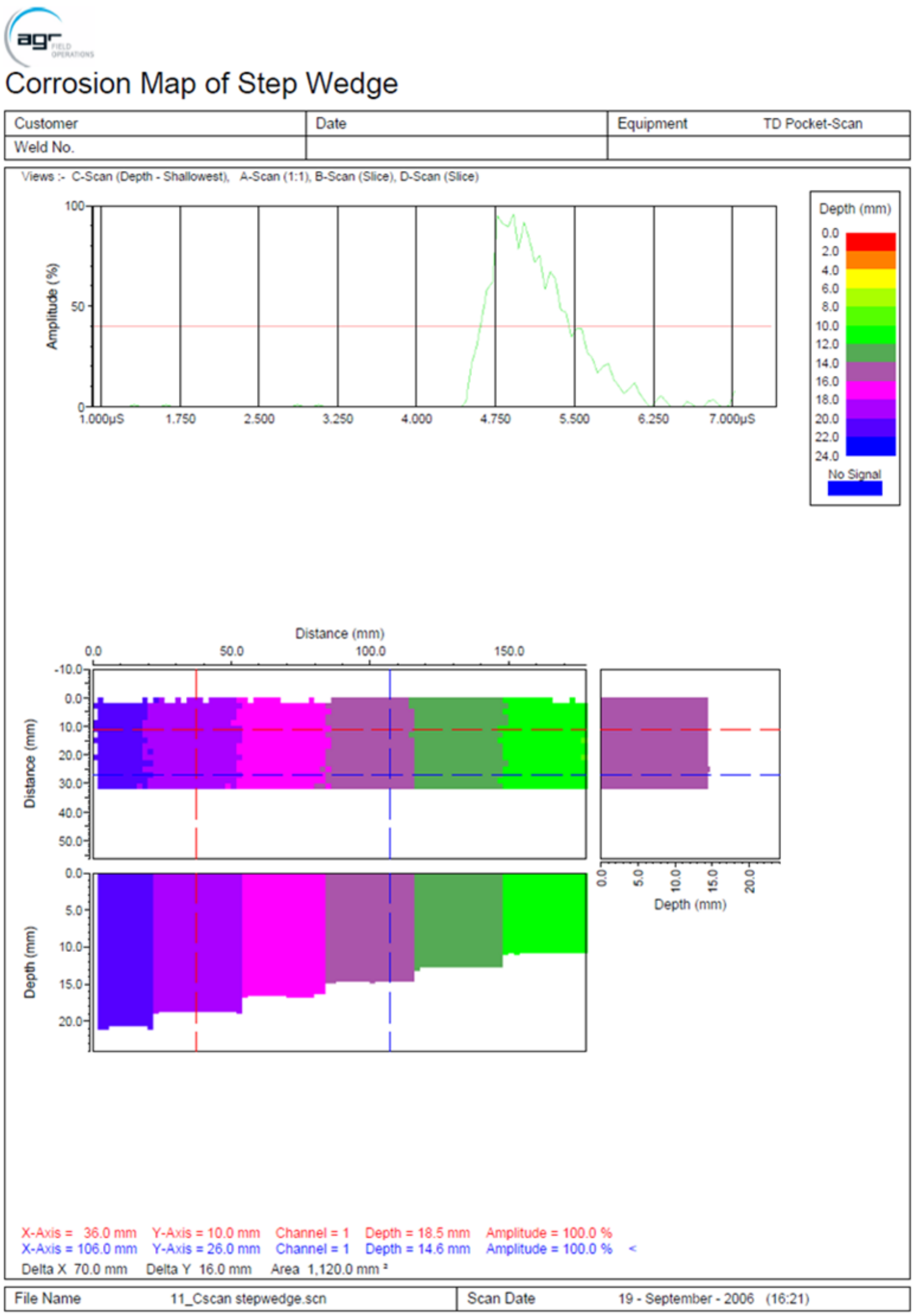
M10 Sample 1 and Sherman Sample 3- Parts from inside armour (Right Side of the Driver)

M10 Sample 2 Part from the Turret let to the main gun

Centaur Sample 3 – Part from the armoured skirt near sprocket

Image : http://upload.wikimedia.org/wikipedia/commons/2/22/M1_Abrams-TUSK.svg

Appendix C: Calibration Certificate for Ultrasonic Testing



Corrosion Map of Step Wedge

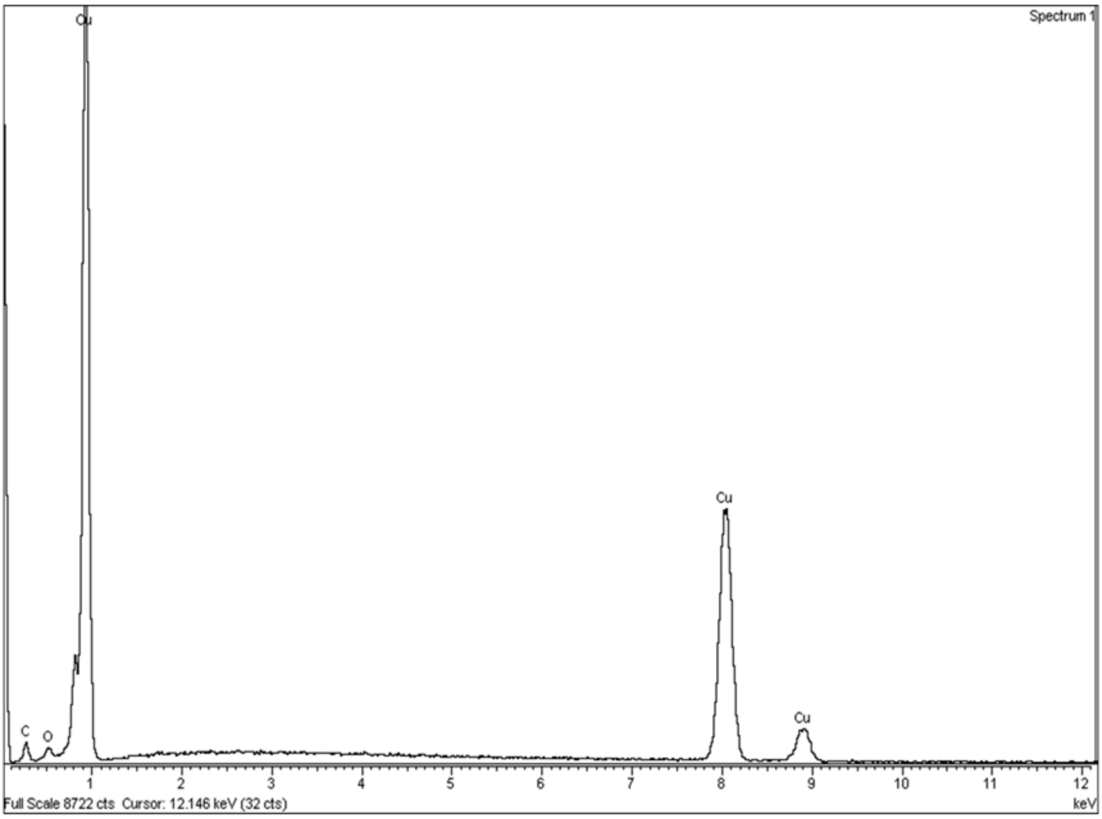
Customer	Date	Equipment	TD Pocket-Scan
Weld No.			

Views :- C-Scan (Depth - Shallowest), A-Scan (1:1), B-Scan (Slice), D-Scan (Slice)

X-Axis = 36.0 mm Y-Axis = 10.0 mm Channel = 1 Depth = 18.5 mm Amplitude = 100.0 %
X-Axis = 106.0 mm Y-Axis = 26.0 mm Channel = 1 Depth = 14.6 mm Amplitude = 100.0 % <
Delta X 70.0 mm Delta Y 16.0 mm Area 1,120.0 mm ²

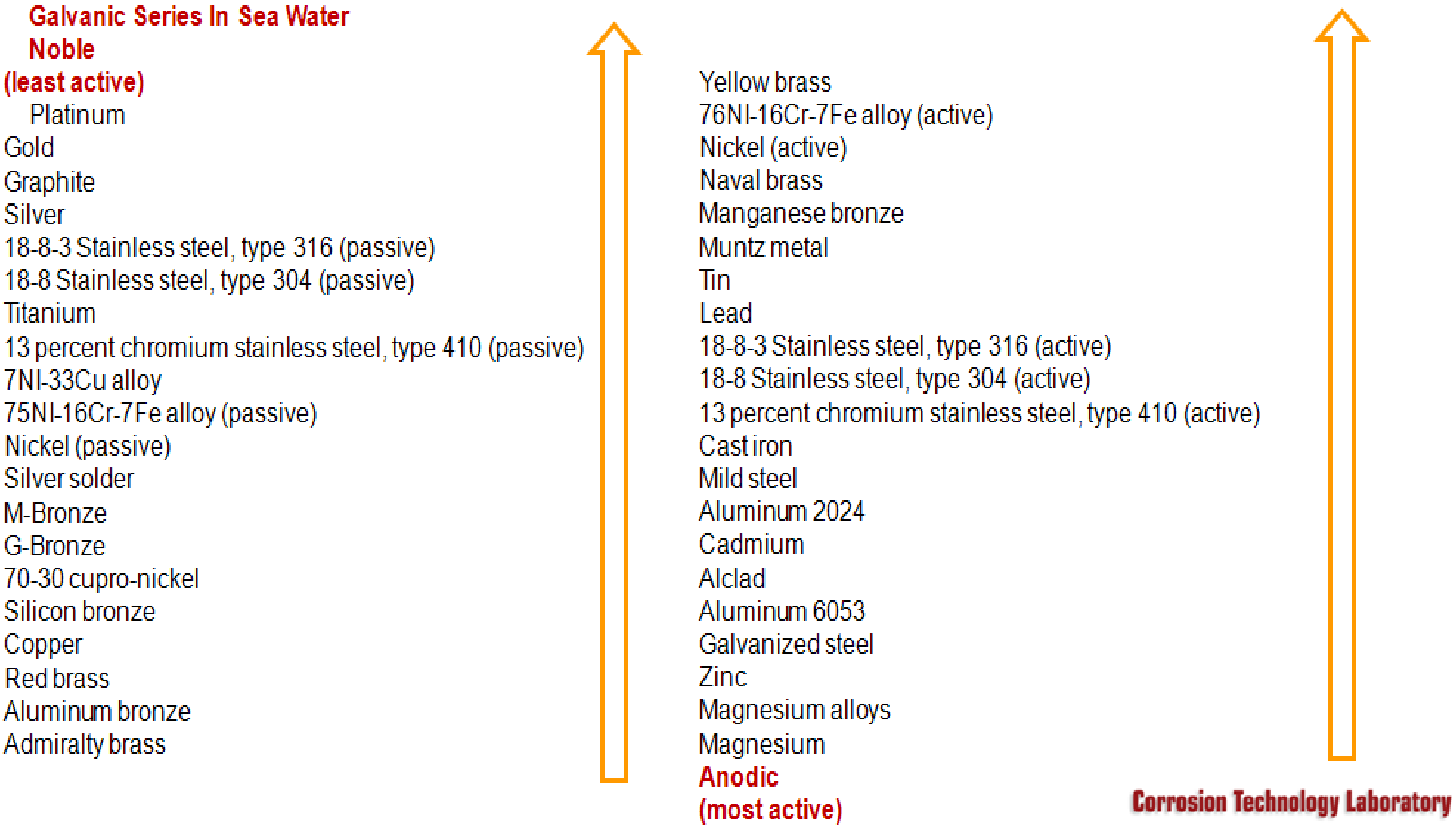
File Name	11_Cscan stepwedge.scn	Scan Date	19 - September - 2006 (16:21)

Appendix D: Certificate of Calibration for EDS



Element	Line	Quant	Area	Sigma	Fit index
	Noise 1	No	69705.3	1682.8	14.4
	Noise 2	No	-83384.4	5275.4	14.9
	Noise 3	No	66371.6	3870.3	14.9
C	K_SERIES	Yes	1398.5	88.5	8.8
O	K_SERIES	Yes	862.0	97.0	1.1
Co	K_SERIES	Yes	-66.6	98.1	3.1
Co	L_SERIES	No	1024.8	311.4	14.7
Cu	K_SERIES	Yes	55237.2	400.3	3.3
Cu	L_SERIES	No	87211.8	569.4	17.3

Appendix E: Galvanic Series in Sea Water



Galvanic Series In Sea Water

Noble

(least active)

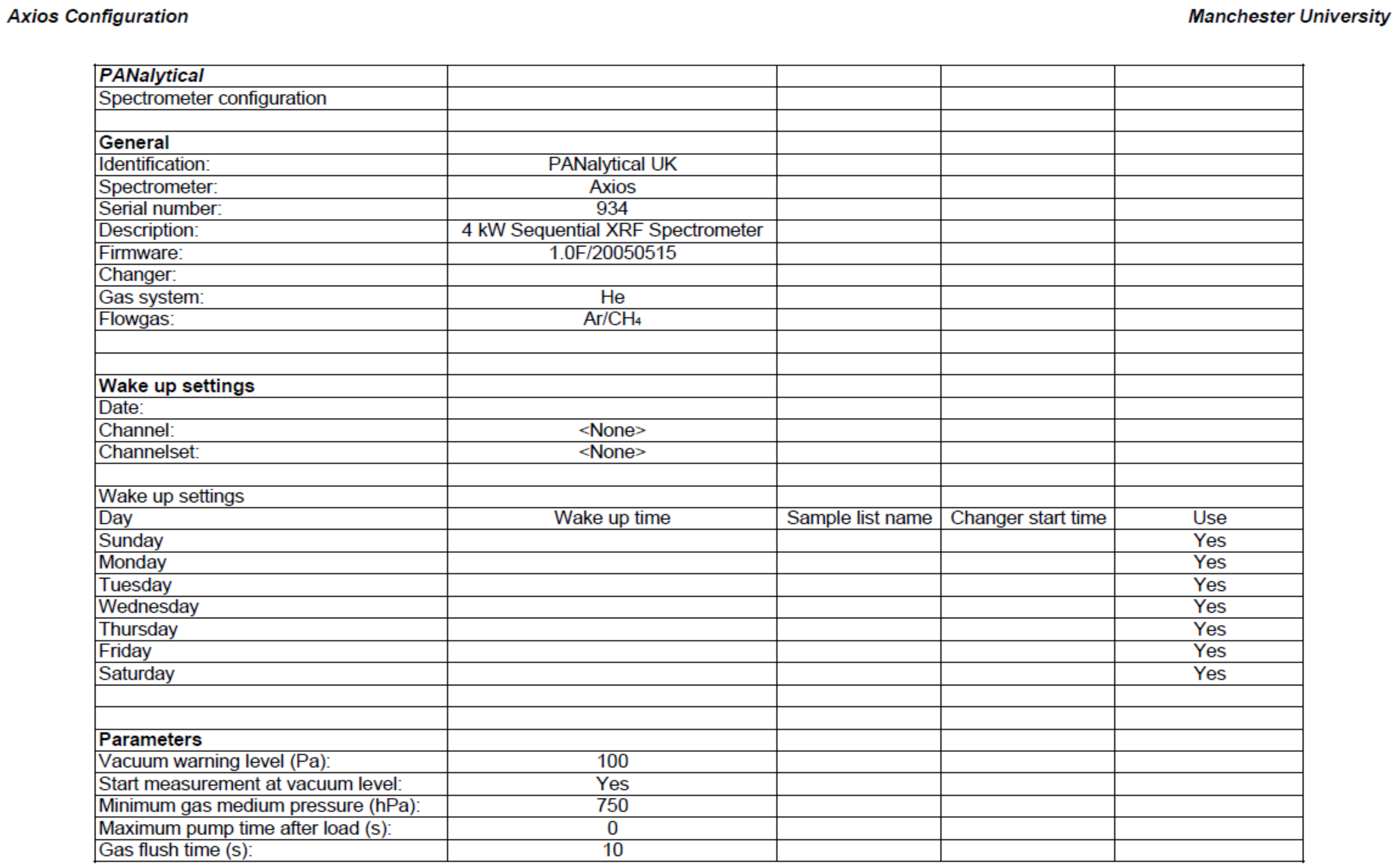
Platinum
Gold
Graphite
Silver
18-8-3 Stainless steel, type 316 (passive)
18-8 Stainless steel, type 304 (passive)
Titanium
13 percent chromium stainless steel, type 410 (passive)
7NI-33Cu alloy
75NI-16Cr-7Fe alloy (passive)
Nickel (passive)
Silver solder
M-Bronze
G-Bronze
70-30 cupro-nickel
Silicon bronze
Copper
Red brass
Aluminum bronze
Admiralty brass
Yellow brass
76NI-16Cr-7Fe alloy (active)
Nickel (active)
Naval brass
Manganese bronze
Muntz metal
Tin
Lead
18-8-3 Stainless steel, type 316 (active)
18-8 Stainless steel, type 304 (active)
13 percent chromium stainless steel, type 410 (active)
Cast iron
Mild steel
Aluminum 2024
Cadmium
Alclad
Aluminum 6053
Galvanized steel
Zinc
Magnesium alloys
Magnesium

Anodic

(most active)

Corrosion Technology Laboratory

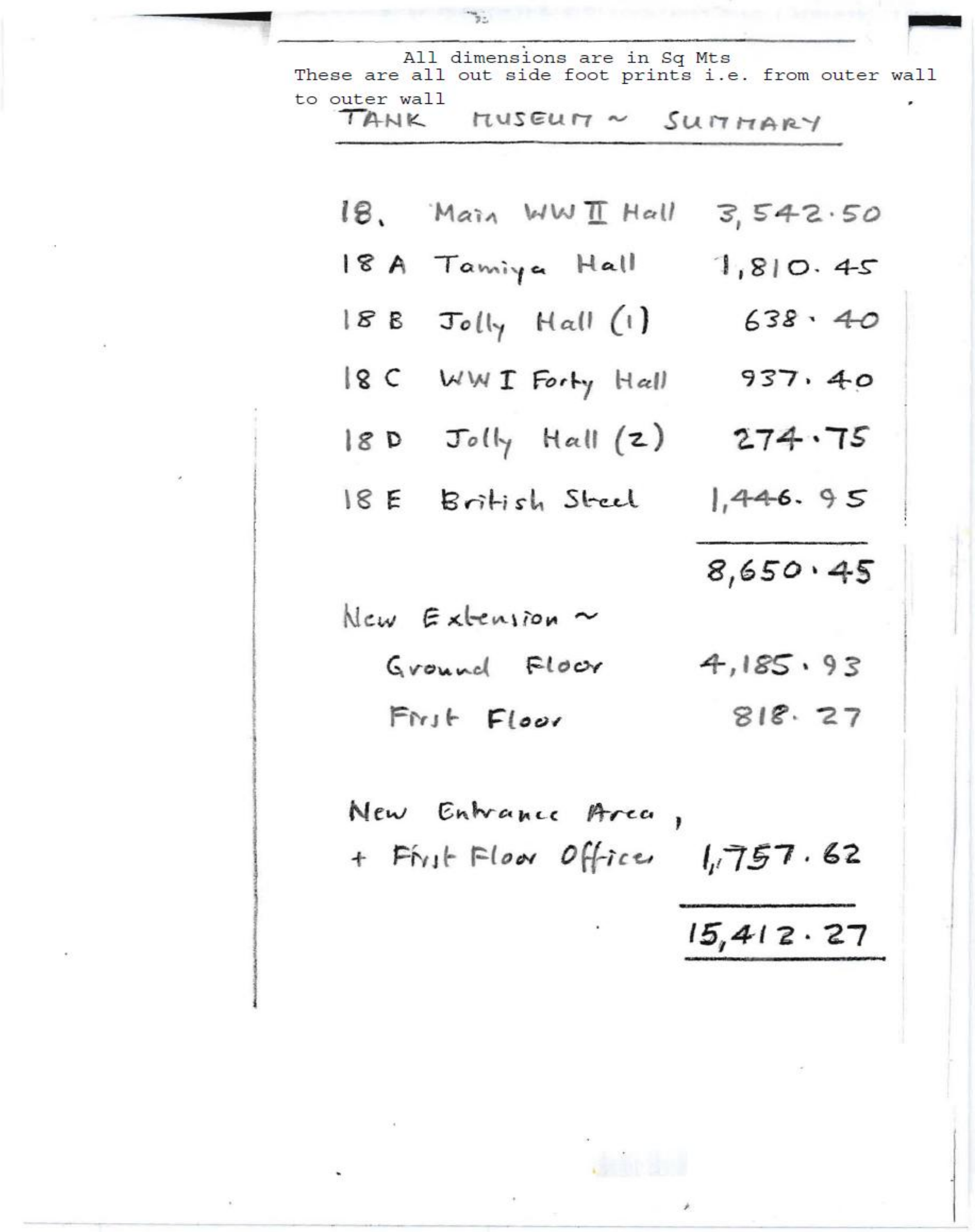
Appendix F: Certificate of Calibration of PANalytical $^{\text{Axios}}$



Axios Configuration ***Manchester University***

PANalytical				
Spectrometer configuration				
General				
Identification:	PANalytical UK			
Spectrometer:	Axios			
Serial number:	934			
Description:	4 kW Sequential XRF Spectrometer			
Firmware:	1.0F/20050515			
Changer:				
Gas system:	He			
Flowgas:	Ar/CH_4			
Wake up settings				
Date:				
Channel:	<None>			
Channelset:	<None>			
Wake up settings				
Day	Wake up time	Sample list name	Changer start time	Use
Sunday				Yes
Monday				Yes
Tuesday				Yes
Wednesday				Yes
Thursday				Yes
Friday				Yes
Saturday				Yes
Parameters				
Vacuum warning level (Pa):	100			
Start measurement at vacuum level:	Yes			
Minimum gas medium pressure (hPa):	750			
Maximum pump time after load (s):	0			
Gas flush time (s):	10			

Appendix G: Area of The Tank Museum



All dimensions are in Sq Mts
These are all out side foot prints i.e. from outer wall to outer wall

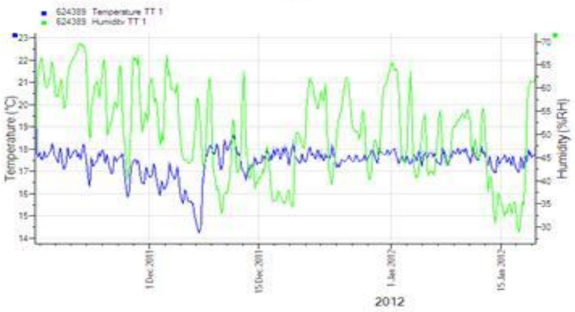
TANK MUSEUM ~ SUMMARY

18.	Main WW II Hall	3,542.50
18 A	Tamiya Hall	1,810.45
18 B	Jolly Hall (1)	638.40
18 C	WW I Forty Hall	937.40
18 D	Jolly Hall (2)	274.75
18 E	British Steel	1,446.95
		8,650.45
	New Extension ~	
	Ground Floor	4,185.93
	First Floor	818.27
	New Entrance Area, + First Floor Offices	1,757.62
		15,412.27

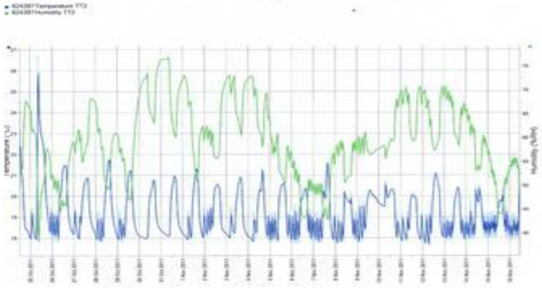
Appendix H: Graphical Representation of Museum - RH and Temperature

(A): RH and Temperature Values of Dec 2011- Jan 2012

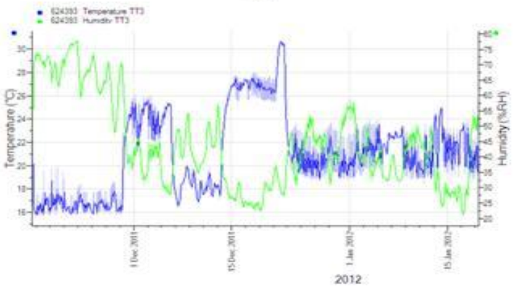
TT 1



TT2

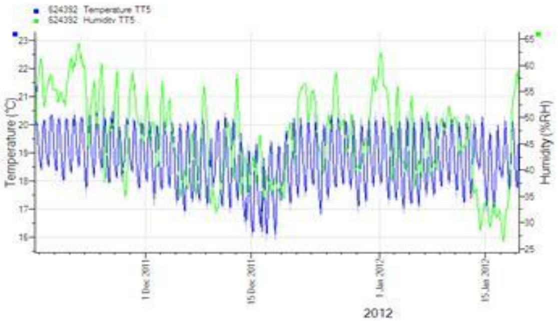


TT3

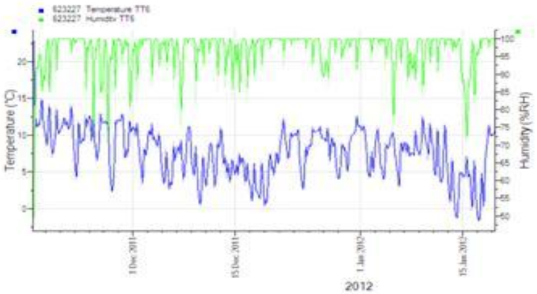


TT4

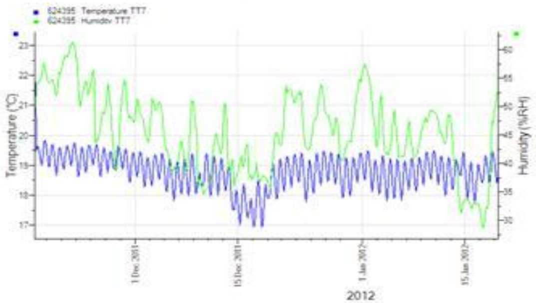
TT5



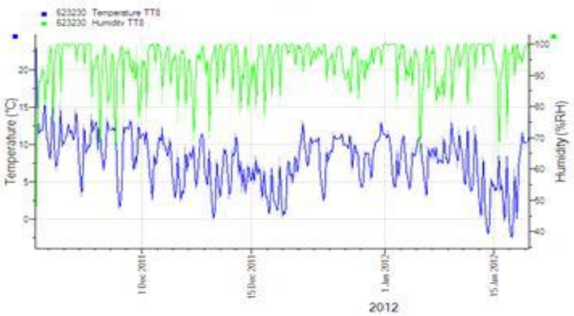
TT6



TT7

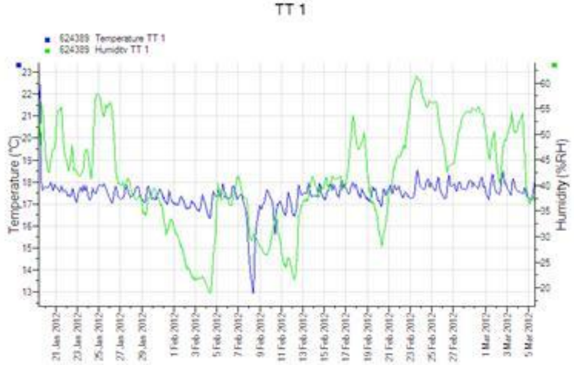


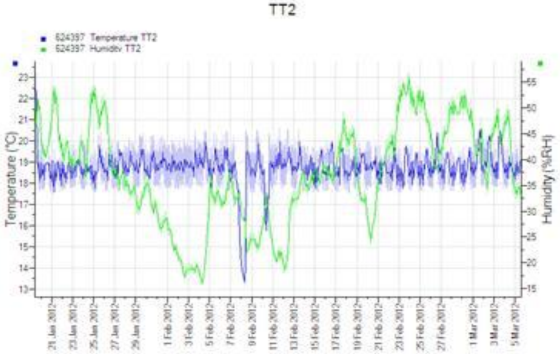
TT8

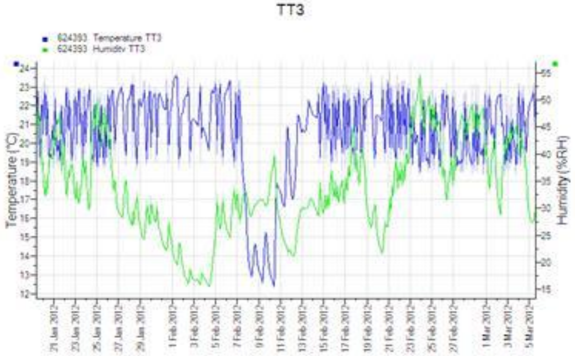


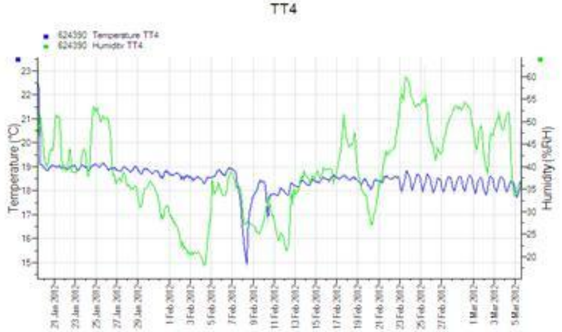
TT9

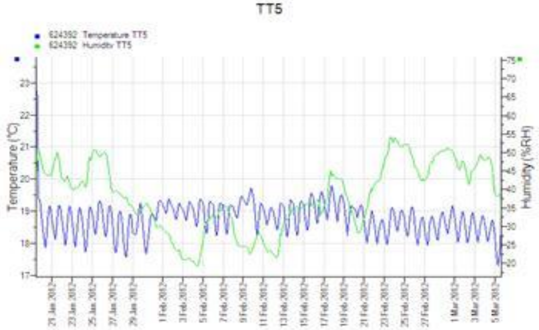
(B): RH and Temperature Values for Jan 2012 – March 2012

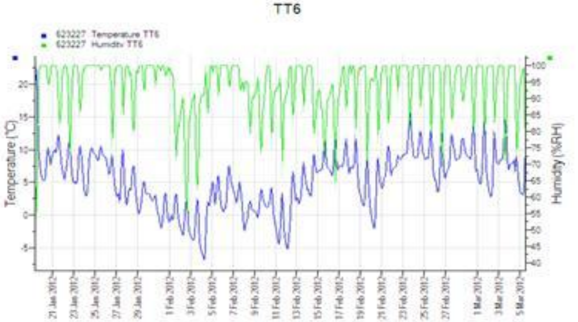


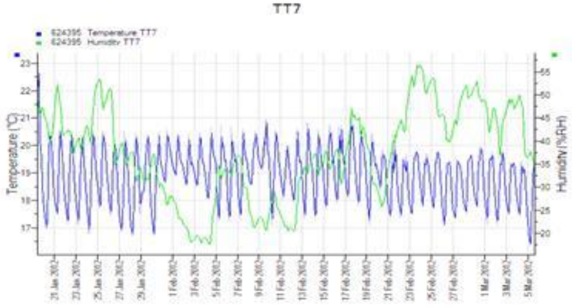


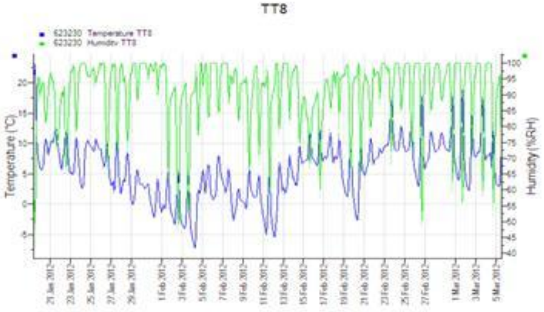






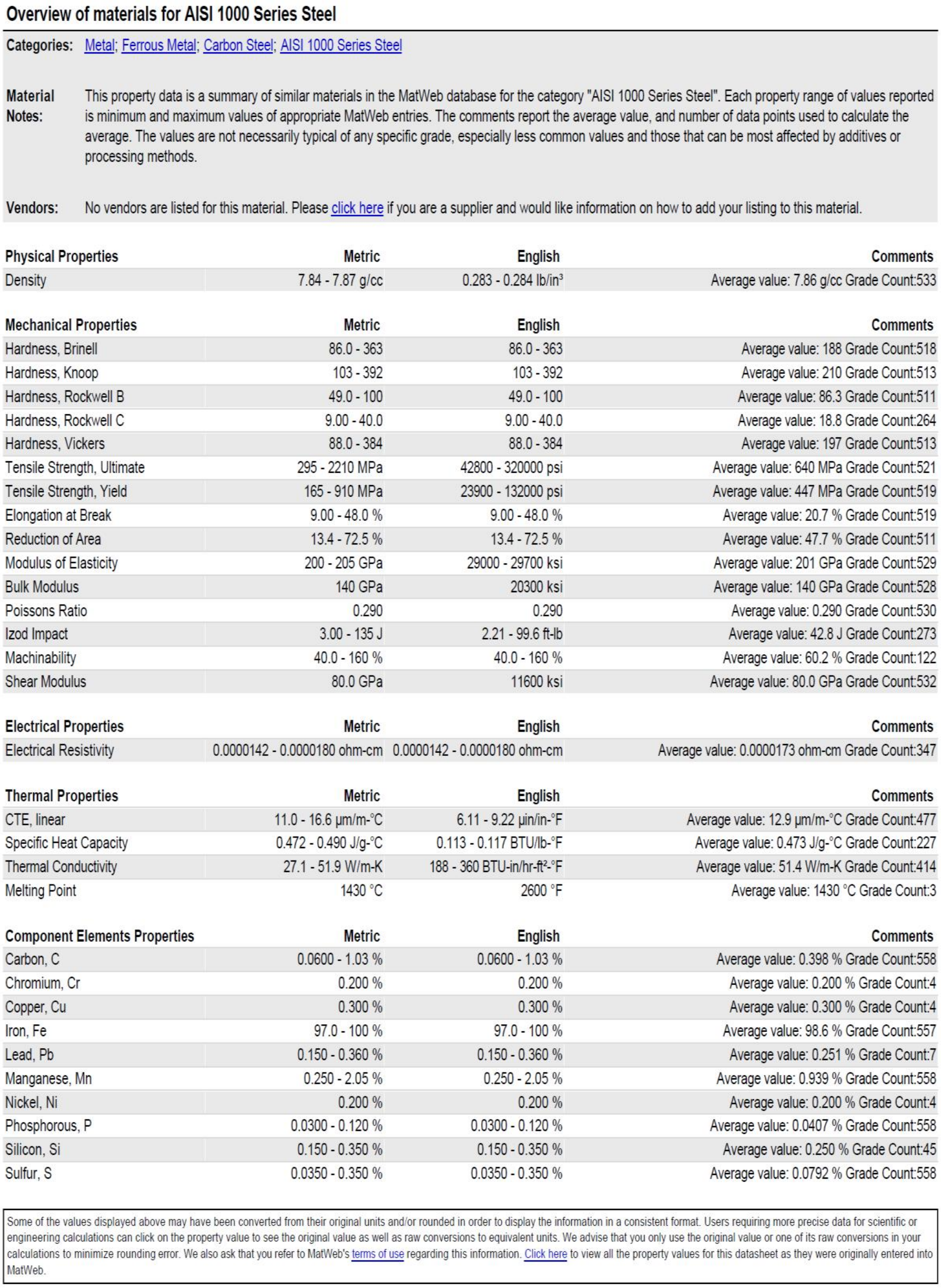






Appendix I: Overview of Materials for AISI Series Steel

(A): AISI 1000



Overview of materials for AISI 1000 Series Steel

Categories: Metal; Ferrous Metal; Carbon Steel; AISI 1000 Series Steel

Material Notes: This property data is a summary of similar materials in the MatWeb database for the category "AISI 1000 Series Steel". Each property range of values reported is minimum and maximum values of appropriate MatWeb entries. The comments report the average value, and number of data points used to calculate the average. The values are not necessarily typical of any specific grade, especially less common values and those that can be most affected by additives or processing methods.

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	**Metric**	**English**	**Comments**
Density	7.84 - 7.87 g/cc	0.283 - 0.284 lb/in³	Average value: 7.86 g/cc Grade Count:533

Mechanical Properties	**Metric**	**English**	**Comments**
Hardness, Brinell	86.0 - 363	86.0 - 363	Average value: 188 Grade Count:518
Hardness, Knoop	103 - 392	103 - 392	Average value: 210 Grade Count:513
Hardness, Rockwell B	49.0 - 100	49.0 - 100	Average value: 86.3 Grade Count:511
Hardness, Rockwell C	9.00 - 40.0	9.00 - 40.0	Average value: 18.8 Grade Count:264
Hardness, Vickers	88.0 - 384	88.0 - 384	Average value: 197 Grade Count:513
Tensile Strength, Ultimate	295 - 2210 MPa	42800 - 320000 psi	Average value: 640 MPa Grade Count:521
Tensile Strength, Yield	165 - 910 MPa	23900 - 132000 psi	Average value: 447 MPa Grade Count:519
Elongation at Break	9.00 - 48.0 %	9.00 - 48.0 %	Average value: 20.7 % Grade Count:519
Reduction of Area	13.4 - 72.5 %	13.4 - 72.5 %	Average value: 47.7 % Grade Count:511
Modulus of Elasticity	200 - 205 GPa	29000 - 29700 ksi	Average value: 201 GPa Grade Count:529
Bulk Modulus	140 GPa	20300 ksi	Average value: 140 GPa Grade Count:528
Poissons Ratio	0.290	0.290	Average value: 0.290 Grade Count:530
Izod Impact	3.00 - 135 J	2.21 - 99.6 ft-lb	Average value: 42.8 J Grade Count:273
Machinability	40.0 - 160 %	40.0 - 160 %	Average value: 60.2 % Grade Count:122
Shear Modulus	80.0 GPa	11600 ksi	Average value: 80.0 GPa Grade Count:532

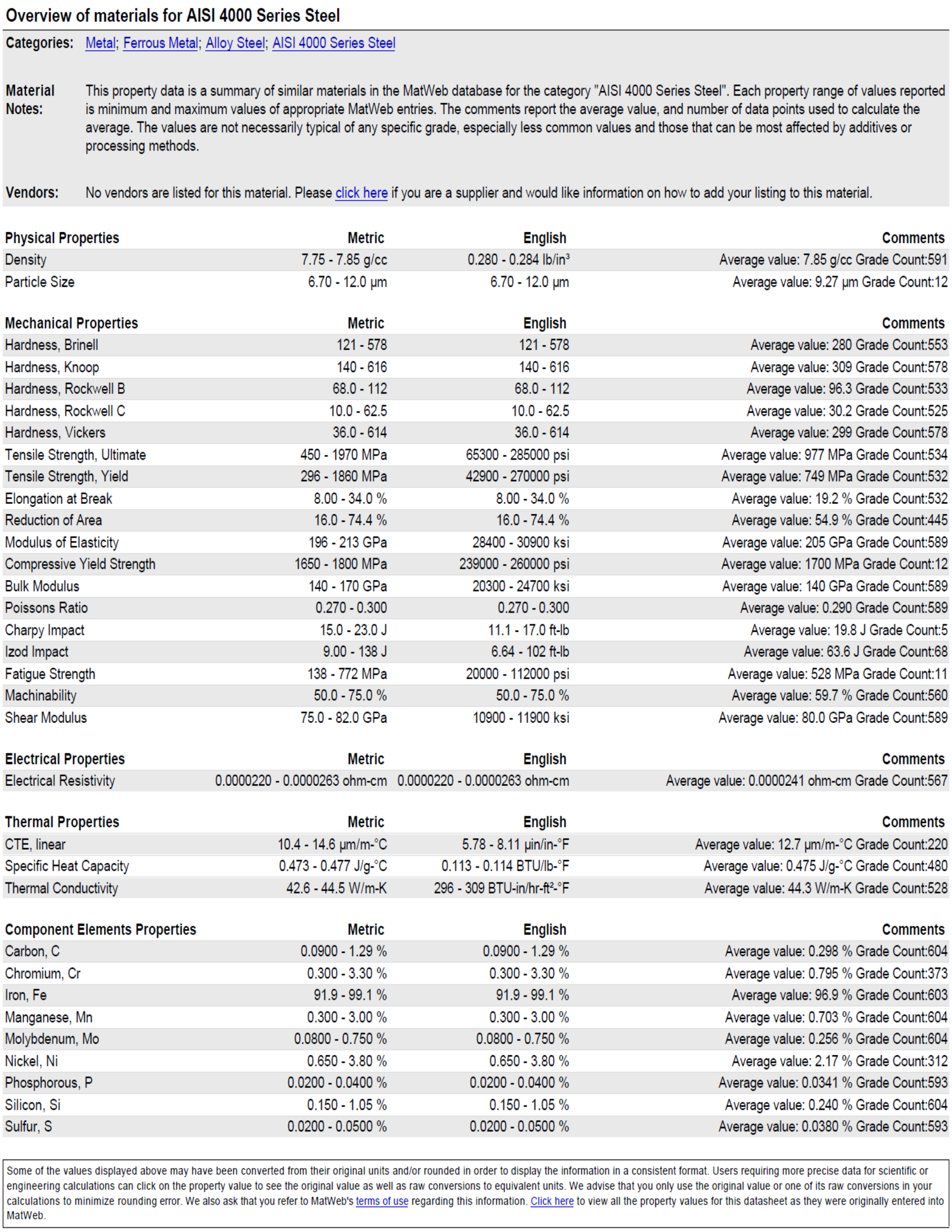
Electrical Properties	**Metric**	**English**	**Comments**
Electrical Resistivity	0.0000142 - 0.0000180 ohm-cm	0.0000142 - 0.0000180 ohm-cm	Average value: 0.0000173 ohm-cm Grade Count:347

Thermal Properties	**Metric**	**English**	**Comments**
CTE, linear	11.0 - 16.6 µm/m-°C	6.11 - 9.22 µin/in-°F	Average value: 12.9 µm/m-°C Grade Count:477
Specific Heat Capacity	0.472 - 0.490 J/g-°C	0.113 - 0.117 BTU/lb-°F	Average value: 0.473 J/g-°C Grade Count:227
Thermal Conductivity	27.1 - 51.9 W/m-K	188 - 360 BTU-in/hr-ft²-°F	Average value: 51.4 W/m-K Grade Count:414
Melting Point	1430 °C	2600 °F	Average value: 1430 °C Grade Count:3

Component Elements Properties	**Metric**	**English**	**Comments**
Carbon, C	0.0600 - 1.03 %	0.0600 - 1.03 %	Average value: 0.398 % Grade Count:558
Chromium, Cr	0.200 %	0.200 %	Average value: 0.200 % Grade Count:4
Copper, Cu	0.300 %	0.300 %	Average value: 0.300 % Grade Count:4
Iron, Fe	97.0 - 100 %	97.0 - 100 %	Average value: 98.6 % Grade Count:557
Lead, Pb	0.150 - 0.360 %	0.150 - 0.360 %	Average value: 0.251 % Grade Count:7
Manganese, Mn	0.250 - 2.05 %	0.250 - 2.05 %	Average value: 0.939 % Grade Count:558
Nickel, Ni	0.200 %	0.200 %	Average value: 0.200 % Grade Count:4
Phosphorous, P	0.0300 - 0.120 %	0.0300 - 0.120 %	Average value: 0.0407 % Grade Count:558
Silicon, Si	0.150 - 0.350 %	0.150 - 0.350 %	Average value: 0.250 % Grade Count:45
Sulfur, S	0.0350 - 0.350 %	0.0350 - 0.350 %	Average value: 0.0792 % Grade Count:558

Some of the values displayed above may have been converted from their original units and/or rounded in order to display the information in a consistent format. Users requiring more precise data for scientific or engineering calculations can click on the property value to see the original value as well as raw conversions to equivalent units. We advise that you only use the original value or one of its raw conversions in your calculations to minimize rounding error. We also ask that you refer to MatWeb's terms of use regarding this information. Click here to view all the property values for this datasheet as they were originally entered into MatWeb.

(B): AISI 4000



Overview of materials for AISI 4000 Series Steel

Categories: Metal; Ferrous Metal; Alloy Steel; AISI 4000 Series Steel

Material Notes: This property data is a summary of similar materials in the MatWeb database for the category "AISI 4000 Series Steel". Each property range of values reported is minimum and maximum values of appropriate MatWeb entries. The comments report the average value, and number of data points used to calculate the average. The values are not necessarily typical of any specific grade, especially less common values and those that can be most affected by additives or processing methods.

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	7.75 - 7.85 g/cc	0.280 - 0.284 lb/in³	Average value: 7.85 g/cc Grade Count:591
Particle Size	6.70 - 12.0 µm	6.70 - 12.0 µm	Average value: 9.27 µm Grade Count:12

Mechanical Properties	Metric	English	Comments
Hardness, Brinell	121 - 578	121 - 578	Average value: 280 Grade Count:553
Hardness, Knoop	140 - 616	140 - 616	Average value: 309 Grade Count:578
Hardness, Rockwell B	68.0 - 112	68.0 - 112	Average value: 96.3 Grade Count:533
Hardness, Rockwell C	10.0 - 62.5	10.0 - 62.5	Average value: 30.2 Grade Count:525
Hardness, Vickers	36.0 - 614	36.0 - 614	Average value: 299 Grade Count:578
Tensile Strength, Ultimate	450 - 1970 MPa	65300 - 285000 psi	Average value: 977 MPa Grade Count:534
Tensile Strength, Yield	296 - 1860 MPa	42900 - 270000 psi	Average value: 749 MPa Grade Count:532
Elongation at Break	8.00 - 34.0 %	8.00 - 34.0 %	Average value: 19.2 % Grade Count:532
Reduction of Area	16.0 - 74.4 %	16.0 - 74.4 %	Average value: 54.9 % Grade Count:445
Modulus of Elasticity	196 - 213 GPa	28400 - 30900 ksi	Average value: 205 GPa Grade Count:589
Compressive Yield Strength	1650 - 1800 MPa	239000 - 260000 psi	Average value: 1700 MPa Grade Count:12
Bulk Modulus	140 - 170 GPa	20300 - 24700 ksi	Average value: 140 GPa Grade Count:589
Poissons Ratio	0.270 - 0.300	0.270 - 0.300	Average value: 0.290 Grade Count:589
Charpy Impact	15.0 - 23.0 J	11.1 - 17.0 ft-lb	Average value: 19.8 J Grade Count:5
Izod Impact	9.00 - 138 J	6.64 - 102 ft-lb	Average value: 63.6 J Grade Count:68
Fatigue Strength	138 - 772 MPa	20000 - 112000 psi	Average value: 528 MPa Grade Count:11
Machinability	50.0 - 75.0 %	50.0 - 75.0 %	Average value: 59.7 % Grade Count:560
Shear Modulus	75.0 - 82.0 GPa	10900 - 11900 ksi	Average value: 80.0 GPa Grade Count:589

Electrical Properties	Metric	English	Comments
Electrical Resistivity	0.0000220 - 0.0000263 ohm-cm	0.0000220 - 0.0000263 ohm-cm	Average value: 0.0000241 ohm-cm Grade Count:567

Thermal Properties	Metric	English	Comments
CTE, linear	10.4 - 14.6 µm/m-°C	5.78 - 8.11 µin/in-°F	Average value: 12.7 µm/m-°C Grade Count:220
Specific Heat Capacity	0.473 - 0.477 J/g-°C	0.113 - 0.114 BTU/lb-°F	Average value: 0.475 J/g-°C Grade Count:480
Thermal Conductivity	42.6 - 44.5 W/m-K	296 - 309 BTU-in/hr-ft²-°F	Average value: 44.3 W/m-K Grade Count:528

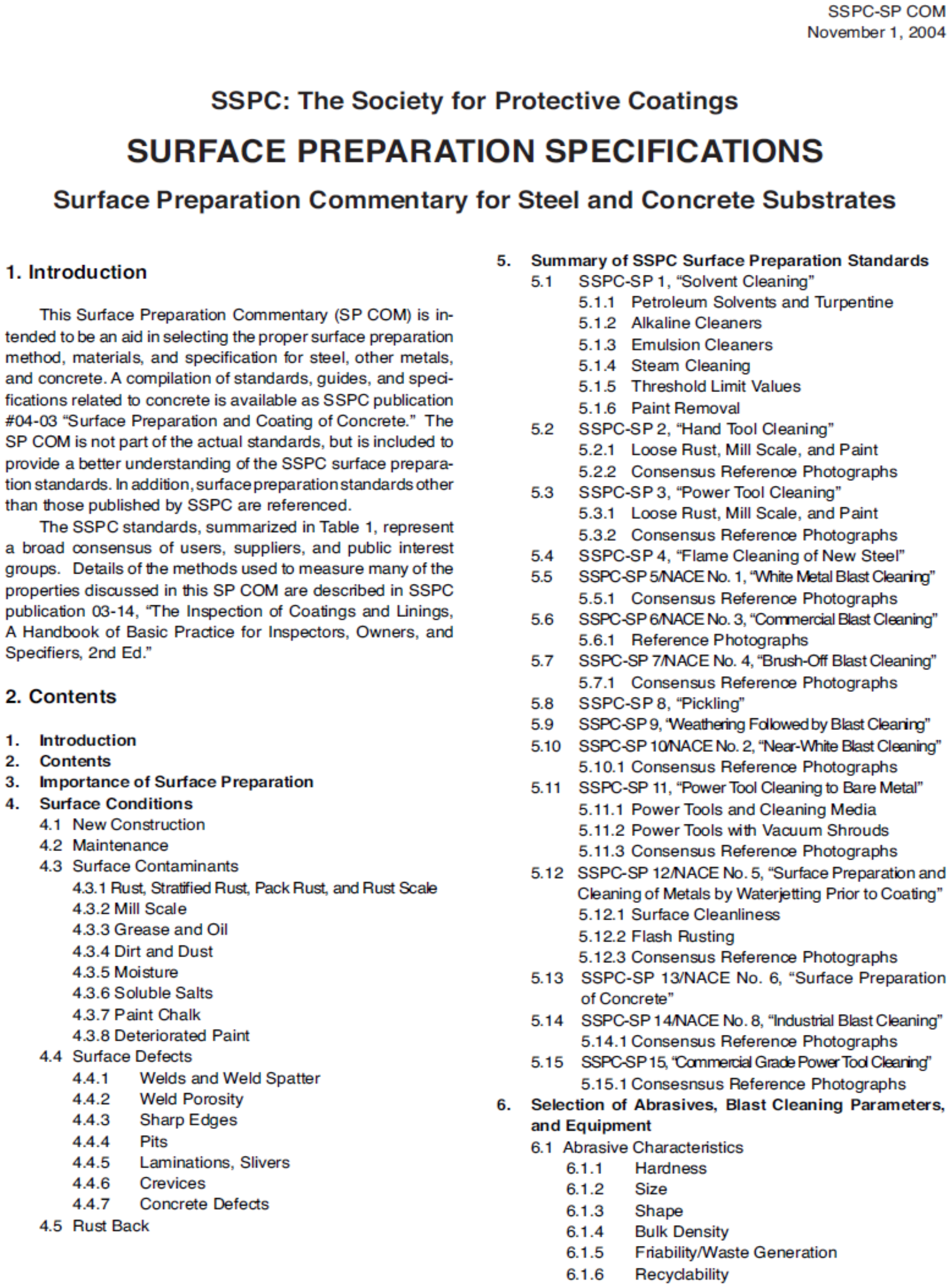
Component Elements Properties	Metric	English	Comments
Carbon, C	0.0900 - 1.29 %	0.0900 - 1.29 %	Average value: 0.298 % Grade Count:604
Chromium, Cr	0.300 - 3.30 %	0.300 - 3.30 %	Average value: 0.795 % Grade Count:373
Iron, Fe	91.9 - 99.1 %	91.9 - 99.1 %	Average value: 96.9 % Grade Count:603
Manganese, Mn	0.300 - 3.00 %	0.300 - 3.00 %	Average value: 0.703 % Grade Count:604
Molybdenum, Mo	0.0800 - 0.750 %	0.0800 - 0.750 %	Average value: 0.256 % Grade Count:604
Nickel, Ni	0.650 - 3.80 %	0.650 - 3.80 %	Average value: 2.17 % Grade Count:312
Phosphorous, P	0.0200 - 0.0400 %	0.0200 - 0.0400 %	Average value: 0.0341 % Grade Count:593
Silicon, Si	0.150 - 1.05 %	0.150 - 1.05 %	Average value: 0.240 % Grade Count:604
Sulfur, S	0.0200 - 0.0500 %	0.0200 - 0.0500 %	Average value: 0.0380 % Grade Count:593

Some of the values displayed above may have been converted from their original units and/or rounded in order to display the information in a consistent format. Users requiring more precise data for scientific or engineering calculations can click on the property value to see the original value as well as raw conversions to equivalent units. We advise that you only use the original value or one of its raw conversions in your calculations to minimize rounding error. We also ask that you refer to MatWeb's terms of use regarding this information. Click here to view all the property values for this datasheet as they were originally entered into MatWeb.

Appendix J: Accumulated Corrosion Areas Measurement of the M10

```
M10 Sample – 1 Count  Label    Scale    Area

6           Measurement 15          Custom (816 pixels = 10.0000 mm)        2.949136
Measurement 15 - Feature 1          Custom (816 pixels = 10.0000 mm)        0.141622
Measurement 15 - Feature 2          Custom (816 pixels = 10.0000 mm)        0.062176
Measurement 15 - Feature 3          Custom (816 pixels = 10.0000 mm)        0.104527
Measurement 15 - Feature 4          Custom (816 pixels = 10.0000 mm)        0.235336
Measurement 15 - Feature 5          Custom (816 pixels = 10.0000 mm)        0.061725
Measurement 15 - Feature 6          Custom (816 pixels = 10.0000 mm)        2.34375

M10 Sample – 2 "Count"              "Label"  "Scale"  "Area"

"3"         "Measurement 19"        "Custom (816 pixels = 10.0000 mm)"      "1.074106"
"Measurement 19 - Feature 1"        "Custom (816 pixels = 10.0000 mm)"      "0.341816"
"Measurement 19 - Feature 2"        "Custom (816 pixels = 10.0000 mm)"      "0.684683"
"Measurement 19 - Feature 3"        "Custom (816 pixels = 10.0000 mm)"      "0.047608"

M10 Sample – 3 Count  Label    Scale    Area     Scale Units

4           Measurement 6 Custom (1084 pixels = 10.0000 mm)       0.1411  mm
Measurement 6 - Feature 1           Custom (1084 pixels = 10.0000 mm)      0.005787          mm
Measurement 6 - Feature 2           Custom (1084 pixels = 10.0000 mm)      0.00834           mm
Measurement 6 - Feature 3           Custom (1084 pixels = 10.0000 mm)      0.068763          mm
Measurement 6 - Feature 4           Custom (1084 pixels = 10.0000 mm)      0.05821           mm

M10 Sample – 4 "Count"              "Label"  "Scale"  "Area"

"34"        "Measurement 17"        "Custom (820 pixels = 10.0000 mm)"      "5.396490"
"Measurement 17 - Feature 1"        "Custom (820 pixels = 10.0000 mm)"      "0.172963"
"Measurement 17 - Feature 2"        "Custom (820 pixels = 10.0000 mm)"      "0.033462"
"Measurement 17 - Feature 3"        "Custom (820 pixels = 10.0000 mm)"      "0.061570"
"Measurement 17 - Feature 4"        "Custom (820 pixels = 10.0000 mm)"      "0.198989"
"Measurement 17 - Feature 5"        "Custom (820 pixels = 10.0000 mm)"      "0.204194"
"Measurement 17 - Feature 6"        "Custom (820 pixels = 10.0000 mm)"      "0.135336"
"Measurement 17 - Feature 7"        "Custom (820 pixels = 10.0000 mm)"      "0.539709"
"Measurement 17 - Feature 8"        "Custom (820 pixels = 10.0000 mm)"      "0.134146"
"Measurement 17 - Feature 9"        "Custom (820 pixels = 10.0000 mm)"      "0.375818"
"Measurement 17 - Feature 10" "Custom (820 pixels = 10.0000 mm)"      "0.163444"
"Measurement 17 - Feature 11" "Custom (820 pixels = 10.0000 mm)"      "0.130428"
```

Appendix K: Surface Preparation Specifications



SSPC-SP COM
November 1, 2004

SSPC: The Society for Protective Coatings

SURFACE PREPARATION SPECIFICATIONS

Surface Preparation Commentary for Steel and Concrete Substrates

1. Introduction

This Surface Preparation Commentary (SP COM) is intended to be an aid in selecting the proper surface preparation method, materials, and specification for steel, other metals, and concrete. A compilation of standards, guides, and specifications related to concrete is available as SSPC publication #04-03 “Surface Preparation and Coating of Concrete.” The SP COM is not part of the actual standards, but is included to provide a better understanding of the SSPC surface preparation standards. In addition, surface preparation standards other than those published by SSPC are referenced.

The SSPC standards, summarized in Table 1, represent a broad consensus of users, suppliers, and public interest groups. Details of the methods used to measure many of the properties discussed in this SP COM are described in SSPC publication 03-14, “The Inspection of Coatings and Linings, A Handbook of Basic Practice for Inspectors, Owners, and Specifiers, 2nd Ed.”

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4. **Surface Conditions**
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   - 4.2 Maintenance
   - 4.3 Surface Contaminants
     - 4.3.1 Rust, Stratified Rust, Pack Rust, and Rust Scale
     - 4.3.2 Mill Scale
     - 4.3.3 Grease and Oil
     - 4.3.4 Dirt and Dust
     - 4.3.5 Moisture
     - 4.3.6 Soluble Salts
     - 4.3.7 Paint Chalk
     - 4.3.8 Deteriorated Paint
   - 4.4 Surface Defects
     - 4.4.1 Welds and Weld Spatter
     - 4.4.2 Weld Porosity
     - 4.4.3 Sharp Edges
     - 4.4.4 Pits
     - 4.4.5 Laminations, Slivers
     - 4.4.6 Crevices
     - 4.4.7 Concrete Defects
   - 4.5 Rust Back
5. **Summary of SSPC Surface Preparation Standards**
   - 5.1 SSPC-SP 1, “Solvent Cleaning”
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     - 5.1.2 Alkaline Cleaners
     - 5.1.3 Emulsion Cleaners
     - 5.1.4 Steam Cleaning
     - 5.1.5 Threshold Limit Values
     - 5.1.6 Paint Removal
   - 5.2 SSPC-SP 2, “Hand Tool Cleaning”
     - 5.2.1 Loose Rust, Mill Scale, and Paint
     - 5.2.2 Consensus Reference Photographs
   - 5.3 SSPC-SP 3, “Power Tool Cleaning”
     - 5.3.1 Loose Rust, Mill Scale, and Paint
     - 5.3.2 Consensus Reference Photographs
   - 5.4 SSPC-SP 4, “Flame Cleaning of New Steel”
   - 5.5 SSPC-SP 5/NACE No. 1, “White Metal Blast Cleaning”
     - 5.5.1 Consensus Reference Photographs
   - 5.6 SSPC-SP 6/NACE No. 3, “Commercial Blast Cleaning”
     - 5.6.1 Reference Photographs
   - 5.7 SSPC-SP 7/NACE No. 4, “Brush-Off Blast Cleaning”
     - 5.7.1 Consensus Reference Photographs
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TABLE 1
SUMMARY OF CURRENT SSPC ABRASIVE AND SURFACE PREPARATION STANDARDS AND SPECIFICATIONS

SSPC SPECIFICATION	DESCRIPTION
AB 1 **Mineral and Slag Abrasives**	Definition of requirements for selecting and evaluating mineral and slag abrasives used for blast cleaning.
AB 2 **Cleanliness of Recycled Ferrous Metallic Abrasive**	Cleanliness requirements for a recycled work mix and a description of the test procedures.
AB 3 **Ferrous Metallic Abrasive**	Requirements of chemical and physical properties of iron and steel abrasives.
SP 1 **Solvent Cleaning**	Removal of oil, grease, dirt, soil, salts, and contaminants by cleaning with solvent, vapor, alkali, emulsion, or steam.
SP 2 **Hand Tool Cleaning**	Removal of loose rust, loose mill scale, and loose paint to degree specified, by hand chipping, scraping, sanding, and wire brushing.
SP 3 **Power Tool Cleaning**	Removal of loose rust, loose mill scale, and loose paint to degree specified, by power tool chipping, descaling, sanding, wire brushing, and grinding.
SP 5/NACE No. 1 **White Metal Blast Cleaning**	Removal of all visible rust, mill scale, paint, and foreign matter by blast cleaning by wheel or nozzle (dry or wet) using sand, grit or shot. For very corrosive atmospheres where high cost of cleaning is warranted.
SP 6/NACE No. 3 **Commercial Blast Cleaning**	Blast cleaning until at least two-thirds of the surface is free of all visible residues with only staining permitted on the remainder. For conditions where a thoroughly cleaned surface is required.
SP 7/NACE No. 4 **Brush-Off Blast Cleaning**	Blast cleaning of all except tightly adhering residues of mill scale, rust, and coatings, while uniformly roughening the surface.
SP 8 **Pickling**	Complete removal of rust and mill scale by acid pickling, duplex pickling, or electrolytic pickling.
SP 10/NACE No. 2 **Near-White Blast Cleaning**	Blast cleaning nearly to White Metal cleanliness, until at least 95% of the surface is free of all visible residues with only staining permitted on the remainder. For high humidity, chemical atmosphere, marine, or other corrosive environments.
SP 11 **Power Tool Cleaning to Bare Metal**	Complete removal of all rust, scale, and paint by power tools, with resultant surface profile.

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SP 12/NACE No. 5 Surface Preparation and Cleaning of Metals by Waterjetting Prior to Coating	Defines four degrees of cleaning for visible contaminants (similar to SP 5, 6, 7, and 10) and three levels of flash rust and describes three levels of non-visible surface cleanliness for non-visible soluble salt contamination.
SP 13/NACE No. 6 Surface Preparation of Concrete	Description of inspection procedures prior to surface preparation, methods of surface preparation, inspection, and classification of prepared concrete surfaces.
SP 14/NACE No. 8 Industrial Blast Cleaning	Between SP 7 (brush-off) and SP 6 (commercial). The intent is to remove as much coating as possible, but contaminants difficult to remove can remain on 10 percent of the surface.
SP 15 Industrial Grade Power Tool Cleaning	Between SP 3 and SP 11. Removes all rust and paint but allows for staining; requires a minimum 1 mil (25 µm) profile.
VIS 1 Guide and Reference Photographs for Steel Surfaces Prepared by Dry Abrasive Blast Cleaning	Standard reference photographs; recommended supplement to SSPC surface preparation standards SSPC-SP 5, 6, 7, 10, and 14.
VIS 2 Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces	A geometric numerical scale for evaluating degree of rusting of painted steel. Color photographs show staining while matching black and white images depict only rust. Three rust distributions, general, spot, and pinpoint, are depicted.
VIS 3 Guide and Reference Photographs for Steel Surfaces Prepared by Power- and Hand-Tool Cleaning	Standard reference photographs; recommended supplement to SSPC-SP 2, 3, 11, and 15.
VIS 4/NACE VIS 7 Guide and Reference Photographs for Steel Surfaces Prepared by Waterjetting	Standard reference photographs depict previously rusted steel (painted and unpainted) cleaned by water jetting. Photographs depict three levels of flash rusting. Recommended as a supplement to SSPC-SP 12.
VIS 5/NACE VIS 9 Guide and Reference Photographs for Steel Surfaces Prepared by Wet Abrasive Blast Cleaning	Standard reference photographs depict previously rusted unpainted steel cleaned by wet abrasive blast cleaning to SSPC SP 6 and SP 10. Photographs depict three levels of flash rusting. Recommended as a supplement to SSPC-SP 6 and SP 10 when wet blast cleaning methods are used.

such as sodium bicarbonate (baking soda) or dry ice (CO_2) can sometimes be used in places where conventional abrasives cannot be used. A class of abrasives has been developed where each abrasive particle is contained in a urethane sponge. The sponge contains the abrasive and facilitates cleanup and recycling. Alternative methods of surface preparation are discussed in more detail in Chapter 2.9 of the SSPC Painting Manual, Vol. 1.

An advantage of all wet blast methods is the control of dust emissions. Wet blast methods may involve water alone, abrasive injected into the water stream, water injected into an abrasive air stream, or a water curtain surrounding an air/abrasive stream. Power tools with vacuum shrouds have also been proven effective in controlling dust emissions, particularly in removing lead-containing paint. It is important to note that surface preparation methods used to control dust may not necessarily eliminate any hazards associated with disturbance of hazardous materials such as lead. In applications where the presence of soluble salts on the steel surface creates a serious problem, such as tank linings, it may be beneficial to incorporate water into the cleaning process.

To gain maximum benefit from a high performance industrial coating, it is not prudent to cut back on the surface preparation. Surface preparation is important even when a "surface tolerant" coating is used. When the manufacturer claims a particular coating will "tolerate" a given amount of rust, old paint, or other contamination on the steel surface, it is likely that the coating will perform even better if the surface is prepared to a higher level of cleanliness.

4. Surface Conditions

The initial condition of the surface to be cleaned will determine the amount of work, time, and money required to achieve any particular degree of surface cleanliness. It is more difficult to remove contaminants from rusty steel than from intact mill scale. Therefore, it is necessary to consider the surface condition prior to selecting the method of cleaning.

The initial condition of the steel may determine the choice of abrasive to be used. Steel shot is an economical and effective choice for removing intact mill scale. However, if the steel is rusted and/or pitted, a more angular abrasive such as steel grit or a nonmetallic mineral abrasive will more effectively "scour out" the rust.

Although there are almost an infinite number of initial conditions, they can be broadly divided into three categories as follows:

- New construction—steel not previously painted
- Maintenance—previously painted steel
- Contaminated surfaces—common to both new construction and maintenance.

4.1 NEW CONSTRUCTION: For new construction there are four surface conditions based upon the rust condition classifications. These initial conditions, defined in SSPC visual consensus references, namely, SSPC-VIS 1, SSPC-VIS 3, and SSPC-VIS 4, are as follows:

Rust Condition A	Steel surface covered completely with adherent mill scale; little or no rust visible
Rust Condition B	Steel surface covered with both mill scale and rust
Rust Condition C	Steel surface completely covered with rust; little or no pitting visible
Rust Condition D	Steel surface completely covered with rust; pitting visible

Rust Conditions A, B, C, and D are also referred to as Rust Grades A, B, C, and D.

4.2 MAINTENANCE: The SSPC documents containing the consensus reference photographs also define conditions E, F, G and H for previously painted surfaces.

Condition E	Light-colored paint applied over a blast-cleaned surface, paint mostly intact.
Condition F	Zinc-rich paint applied over blast-cleaned steel, paint mostly intact.
Condition G	Painting system applied over mill scale bearing steel; system thoroughly weathered, thoroughly blistered, or thoroughly stained.
Condition H	Degraded painting system applied over steel; system thoroughly weathered, thoroughly blistered, or thoroughly stained.

In maintenance repainting, the degree of surface preparation required depends on the new painting system and on the extent of degradation of the surface to be painted. The amount of rusting on a surface is based on the numerical scale of 0 to 10 given in SSPC-VIS 2 (ASTM D 610), "Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces," where a rating of 10 indicates no rust and a rating of 0 indicates more than 50 percent rusting. SSPC-PA Guide 4, "Guide to Maintenance Repainting with Oil Base or Alkyd Painting Systems," suggests the minimum surface preparation needed for each degree of rusting. The SSPC Painting System Commentary will also help in estimating surface preparation requirements.

In estimating rust percentages, photographs and schematic diagrams of the type shown in SSPC-VIS 2 can serve as practical aids. The Guide to SSPC-VIS 2 shows black and white schematics of actual rust patterns which serve as guides for judging the percentage of surface covered by rust (after removal of stains) or rust blisters. SSPC-VIS 2 shows three different configurations of rusting—general, pinpoint, and spot rust.

Comments on surface preparation for maintenance repainting are given in SSPC-PA Guide 4, "Guide to Maintenance Repainting with Oil Base or Alkyd Painting Systems." This guide includes a description of accepted practices for retaining old, sound paint, removing unsound paint, feathering, and spot cleaning.

4.3 SURFACE CONTAMINANTS: Typical contaminants that should be removed during surface preparation are rust, corrosion products, mill scale, grease, oil, dirt, dust, moisture, soluble salts such as chlorides, sulfates, etc., paint chalk, and loose, cracked, or peeling paint.

4.3.1 Rust, Stratified Rust, Pack Rust, and Rust Scale: Rust consists primarily of iron oxides, the corrosion products of steel. Whether loose or relatively tightly adherent, rust must be removed for satisfactory coating performance. Rust resulting from the corrosion of steel is not a good base for applying coatings because it expands and becomes porous. So-called "over-rust primers" (also referred to as "rust converters") do not perform as well as conventional coatings applied over clean steel, and the effectiveness of rust converters is unproven.

Stratified rust, pack rust, or rust scale occur when the iron oxides form in a definite shape rather than in grains or powder. Pack rust typically forms between mating surfaces (e.g., in crevice areas), whereas rust scale and stratified rust form on the surface of the steel (e.g., on steel plates, webs, and flanges). Stratified rust, pack rust, and rust scale can be dislodged from the surface in pieces or layers as large as several inches (centimeters) across. Some of this rust can adhere so tightly to the base metal that a power wire brush will not remove it. Even though it is considered "tightly adherent" because it cannot be lifted with a dull putty knife, it provides a very poor surface to paint over. Eventually the rust will loosen and dislodge from the surface leaving large areas unprotected. Stratified rust, pack rust, and rust scale must be removed with impact tools such as chipping hammers, scabblers, needle guns, and rotary impact flap assemblies.

Ideally, these types of rust should be removed, even for the lowest degrees of hand and power tool cleaning, SSPC-SP 2 and SSPC-SP 3. However, a judgment must be made on each job whether the cost and effort required to remove the stratified rust, pack rust, and rust scale can be justified by the expected increase in the life of the coating system. Where these forms of rust are a problem, the contracting parties should come to an agreement on the extent of removal at the outset of the job.

4.3.2 Mill Scale: Mill scale is a bluish, somewhat shiny oxide residue that forms on steel surfaces during hot rolling. Although initially tightly adherent, it eventually cracks, pops, and disbonds. As a general rule, unless completely removed before painting, it will later cause the coatings to crack and expose the underlying steel. Steel is anodic to mill scale and so corrodes more rapidly in this combination of "dissimilar metals."

Mill scale is erratic in its effect upon the performance of coatings. Tightly adhered or intact mill scale may not have to be removed for mild atmospheric exposure. If, however, the steel surface is to be coated with primers with low wetting properties or exposed to severe environments such as chemical exposures or immersion in fresh or salt water, then removal of mill scale by blast cleaning or power tool cleaning is necessary. Note that the effort required to remove all tightly adherent mill scale usually results in a surface that has less staining than the maximum 33% permitted by SP 6 or SP 15, but may have more staining than the maximum 5% permitted by SP 10 or SP 11.

4.3.3 Grease and Oil: Even thin films of grease and oil, which may not be readily visible, can prevent tight bonding of high performance coatings. Oil paints may be tolerant of thin oil films. Visible deposits of grease and oil should be removed by solvent cleaning, SSPC-SP 1, prior to mechanical cleaning (e.g., power tool or abrasive blast cleaning). If this precleaning is not done, the power tools or abrasive blasting may spread the grease or oil over the surface without removing it.

4.3.4 Dirt and Dust: Dirt and dust can also prevent tight bonding of coatings, and should be removed completely. ISO 8502-3:1982, "Preparation of steel substrates before application of paints and related products–Tests for the assessment of surface cleanliness–Part 3: Assessment of dust on steel surfaces prepared for painting (pressure-sensitive tape method)" provides a method of determining the amount of dust on a surface prior to painting.

4.3.5 Moisture: Steel surfaces must be dry before cleaning and painting. Moisture may either produce flash rusting before painting or accelerate underfilm corrosion after painting. Water can also prevent an organic coating from properly "wetting out" the surface on metal or concrete surfaces, and may disrupt the curing of the coating.

4.3.6 Soluble Salts: Soluble salts are deposited from the atmosphere onto surfaces. If they remain on the surface after cleaning, they can attract moisture which can permeate the coating and cause a blister (osmotic blistering). Salts, particularly chlorides, may also accelerate the corrosion reaction and underfilm corrosion. Methods for measuring the amount of salt on the surface are described in SSPC-TU 4, "Field Methods for Retrieval and Analysis of Soluble Salts on Substrates." In some circumstances it is desirable to remove soluble salts by power washing or other method prior to power tool or abrasive blast cleaning. In other circumstances, salt removal is more efficient after initial power tool or abrasive blast cleaning has been performed.

Sometimes a maximum level of soluble salts is specified in the procurement documents (job specification.) Three commonly specified levels, as verified by field or laboratory analysis using reliable, reproducible test methods, are:

- The surface shall be free of detectable levels of soluble contaminants.
- The surface shall have less than 7 μg/cm^2 (0.0007 grains/in^2) of chloride contaminants, less than 10 μg/cm^2 (0.001 grains/in^2) of soluble ferrous iron levels, or less than 17 μg/cm^2 (0.0017 grains/in^2) of sulfate contaminants.
- The surface shall have less than 50 μg/cm^2 (0.005 grains/in^2) of chloride or sulfate contaminants.

The U.S. Navy has established maximum allowable levels of chloride as measured with an adhesive patch/conductivity meter method. Currently these requirements are 3 μg/cm^2 for tanks and immersed surfaces and 5 μg/cm^2 for topside and non-immersed surfaces. Similarly, the conductivity requirements are 30 μS/cm for immersed surfaces and 70 μS/cm for non-immersed applications.

4.3.7 Paint Chalk: The sun's ultraviolet light causes all exterior organic coatings to chalk to some extent. Chalk is the residue left after deterioration of the coating's surface organic binder. All loose chalk must be removed before coating in order to avoid intercoat adhesion problems. It is often specified that, before topcoating, old paint must have a rating of no less than 8 in accordance with ASTM D 4214, "Test Method for Evaluating Degree of Chalking of Exterior Paint Films."

4.3.8 Deteriorated Paint: All loose paint (can be removed with a dull putty knife and/or fails pre-established adhesion values) must be removed before maintenance painting. Before removing any old paint, it must be determined whether the paint contains significant amounts of lead or other toxic material. If toxic materials are found, special precautions must be taken to protect workers, others in the area, and the environment.

4.4 SURFACE DEFECTS: Coatings tend to draw thin and pull away from sharp edges and projections, leaving little or no coating to protect the underlying steel, thereby increasing the potential for coating failure. Other features of steel that are difficult to properly cover and protect include crevices, weld porosity, laminations, etc., discussed below. The high cost to remedy these surface imperfections requires weighing the benefits of remedial methods such as edge rounding or grinding, versus a potential coating failure. Some high solids coatings, often requiring plural component spray, have edge retentive properties that may lessen the effect of sharp edges.

Poorly adhering contaminants, such as weld slag residues, loose weld spatter, and some minor surface laminations, may be removed by abrasive blast cleaning. Other surface defects, such as steel laminations, weld porosities, or deep corrosion pits, may not be evident until after abrasive blast cleaning. Therefore, the timing of such surface repair work may occur before, during, or after preliminary surface preparation operations have begun.

4.4.1 Welds and Weld Spatter: Weld spatter should be removed prior to blast cleaning. Most weld spatter, except that which is very tightly adherent, can be readily removed using a chipping hammer, spud bar, or scraper. Tightly adhering weld spatter may require removal by grinding. Weld spatter that is not removed will result in a lower coating film thickness (as on sharp edges) and may disbond from the base metal resulting in adhesion failure. Welds can also have sharp projections that may penetrate through the wet paint. NACE RP0178, "Standard Recommended Practice, Fabrication Details, Surface Finish Requirements, and Proper Design Considerations for Tanks and Vessels to Be Lined for Immersion Service," provides details on grinding welds.

4.4.2 Weld Porosity: Although it may be outside the scope of surface preparation for coating application, areas of porosity might warrant further investigation. Unacceptable porosity is defined in the American Welding Society standard AWS D1.1, "Structural Welding Code." Acceptable weld profiles, arc strikes, and weld cleaning are also addressed in Section 3 of AWS D1.1.

4.4.3 Sharp Edges: Sharp edges, such as those normally occurring on rolled structural members or plates, as well as those resulting from flame cutting, welding, grinding, etc., and especially shearing, could have an influence on coating performance and may need to be removed (e.g., grinding, mechanical sanding, filing). Care should be taken to ensure that new sharp edges are not created during the removal operations.

4.4.4 Pits: Deep corrosion pits, gouges, clamp marks, or other surface discontinuities may require grinding prior to painting. The surface may also require filling with weld material.

4.4.5 Laminations, Slivers: Rolling discontinuities (laps) may have sharp protruding edges and deep penetrating crevices. It is beneficial to remove such defects prior to painting. Various methods can be used to eliminate minor slivers (e.g., scraping and grinding), and filling may be necessary. Filling of indentations may also be necessary.

4.4.6 Crevices: Areas of poor design for corrosion protection, such as tack or spot welded connections, back-to-back angles, crevices, etc., may require special attention. Where possible, such deficiencies should be corrected by structural or design modification. Where this is not possible, filling, and/or special surface preparation and painting procedures may be needed.

4.4.7 Concrete Defects: As is the case for steel, repair of surface defects on concrete is important for a successful coating application. Identification and repair of defects in concrete are discussed in Appendix A of SSPC-SP 13, "Surface Preparation of Concrete." Some specific defects that require repair prior to surface preparation and application of a coating or polymer overlay are: mechanical damage, exposed rebar, honeycombs, scaling, spalling, bugholes, pinholes, and generally unsound concrete. The surface must also be cleaned of organic contaminants such as moss, mildew, and algae.

4.5 RUST BACK: Rust back occurs when freshly cleaned steel is exposed to conditions of high humidity, moisture, or a corrosive atmosphere. The time interval between blast cleaning and rust back will vary greatly (from minutes to weeks) from one environment to another. Because of this factor, timeliness of inspection is of great importance. Inspection must be coordinated with the contractor's schedule of operation in such a way as to avoid delay. Acceptance of the prepared surface must be made prior to application of the prime coat, because the degree of surface preparation cannot be readily verified after painting.

Under normal mild atmospheric conditions it is best to coat a blast cleaned surface within 24 hours after blast cleaning. Under no circumstances should the steel be permitted to rust back before painting, regardless of the time elapsed. (With wet abrasive blast cleaning or waterjetting, a certain level of flash rusting may be acceptable.) If visible rust occurs prior to painting, surfaces must be re-cleaned to meet contract cleaning requirements (e.g. SSPC-SP 10). It is incumbent upon the contractor to verify (using recognized quality control tests) and document the quality of the cleaned surface before proceeding with application of the primer even if third-party inspection is required.

Moisture condenses on any surface that is colder than the dew point of the surrounding air. It is therefore recommended that final dry blast cleaning should not be conducted when the steel surface is less than 3 C° (5 F°) above the dew point.

Excessive weathering or exposure of bare steel to chemical contaminants such as chlorides and sulfates prior to blast cleaning should be avoided since pitting of the steel may increase cleaning costs and makes removal of contaminants difficult. After blast cleaning, even slight residues of chlorides, sulfates, or other electrolytes on the steel surface may be harmful and, for some coatings, may cause premature coating failure.

Residual chemical contamination on the surface can cause the steel to rust back quickly. Painting immediately after blast cleaning before the rust back occurs will trap the contamination between the paint and the substrate. Even though the steel "looked" clean when it was painted, it is better to first remove the contamination that caused the rapid rust back before painting.

5. Summary of SSPC Surface Preparation Standards

Although these standards are primarily intended for heavy metal or plate, most are also suitable for light weight or thin section metal. Obviously, caution must be exercised when using methods such as abrasive blast cleaning or waterjetting on thin gage metal since damage by warping may occur from excessive peening of the surface or from the thrust of the water. Occasions will arise where these standards will not result in the type of cleaning desired. In such cases, the contract documents may need to modify the surface preparation standards to obtain the result desired. Regardless of which methods are used, adjacent equipment, pre-finished items, or surfaces that could be damaged from the method of surface preparation must be protected.

Occasionally in maintenance painting, a new paint used to make repairs is incompatible with the existing paint. Under these circumstances all paint, regardless of condition, will have to be removed. A minimum of SSPC-SP 6, "Commercial Blast Cleaning" is usually necessary.

"Good Painting Practice" (Volume 1 of the SSPC Painting Manual), devotes several chapters to mechanical surface preparation, and it also discusses special surface preparation requirements for shops, ships, highways, tanks, vessels, refineries, and various types of plants. Volume 1 should be consulted when choosing a surface preparation standard.

The "Commentary on Paint Specifications" (Chapter 4 of this volume) shows the minimum surface preparation required for each of the SSPC specification paints. Similarly, the "Commentary on Painting Systems" (Chapter 3) shows the recommended minimum surface preparation for each paint system and for the various individual alternative primers within each system, in ten common types of exposure. The guides for each generic coating type discuss in some detail the required surface preparation. For example, SSPC-PS Guide 12.00, "Guide to Zinc-Rich Coating Systems" has a table showing the minimum surface preparation required for each type of zinc-rich coating in ten different environmental zones.

The SSPC surface preparation standards were numbered according to the chronological order in which they were adopted, not according to their degree of thoroughness of cleaning. For example, some time after SSPC-SP 5, "White Metal Blast Cleaning" and SSPC-SP 6, "Commercial Blast Cleaning" were issued, a need arose for a standard between these two. Hence, the standard for Near-White Blast Cleaning was developed, but the next available number was SSPC-SP 10. Similarly, despite the numbering, SSPC-SP 14, "Industrial Blast Cleaning," is a degree of cleaning between SSPC-SP 7 "Brush-Off Blast Cleaning" and SSPC-SP 6. Most recently, SSPC-SP 15, "Commercial Grade Power Tool Cleaning" falls between SSPC-SP 3, Power Tool Cleaning" and SSPC-SP 11, "Power Tool Cleaning to Bare Metal." Table 2 lists the SSPC surface preparation standards in order of thoroughness of cleaning.

5.1 SSPC-SP 1, "SOLVENT CLEANING": This solvent cleaning standard includes simple organic solvent wiping, immersion in solvent, solvent spray, vapor degreasing, alkaline cleaning, emulsion cleaning, and steam cleaning.

Solvent cleaning is used primarily to remove oil, grease, dirt, soil, drawing compounds, and other similar organic compounds. Inorganic compounds such as chlorides, sulfates, weld flux, rust, and mill scale are not removed by cleaning with organic solvents.

TABLE 2
RELATIVE RANKING OF SSPC SURFACE PREPARATION STANDARDS FOR STEEL BASED ON THOROUGHNESS OF CLEANING[1]

Most Thorough Cleaning	Dry Abrasive Blast[2]	Hand and Power Tools	Waterjetting
↑	SP 5		SP 12, WJ-1
	SP 10		SP 12, WJ-2
	SP 6	SP 11	
	SP 14	SP 15	
	SP 7		SP 12, WJ-3
			SP 12, WJ-4
		SP 3	
		SP 2	

[1] This ranking is not meant to imply that different methods of cleaning on the same level are equivalent. For example, SP 14 is not the same as SP 15, nor are either of these the same as SP 12, WJ-3. If SP 14 is desired, but abrasive blast cleaning is not possible, then the closest alternatives would be SP 15 or SP 12, WJ-3.

[2] SSPC-SP 1, Solvent Cleaning, to remove oil and grease is a prerequisite to all abrasive blast and hand and power tool cleaning standards.

Many solvents are hazardous. Care must be taken when using solvents for solvent cleaning. Special safety precautions must be followed with regard to ventilation, smoking, static electricity, respirators, eye protection, and skin contact. Used solvents should always be recycled or disposed of according to applicable environmental regulations.

Detergent/water cleaning is a very gentle method of solvent cleaning. Aqueous solutions of household detergents may be effective in the removal of light deposits of grease and oil. They seldom have adverse effects on substrates.

Alkaline cleaning compounds cover a very wide range in composition and method of use. It is important that residues of alkaline compounds do not remain on the surface after cleaning. The cleaned surface may be tested with litmus paper or universal indicating paper to see that it is neutral or at least no more alkaline than the rinse water that is used. Various solvent, alkaline, and detergent cleaning compounds are discussed in Volume 1 of the SSPC Painting Manual.

5.1.1 Petroleum Solvents and Turpentine: These types of solvents clean the metal by dissolving and diluting the oil and greases which contaminate the surface. All solvents are potentially hazardous and they should be used under such conditions that their concentration in air being breathed by workers is low enough for safety (see Table 3). When used in closed spaces where the safe concentration is exceeded, appropriate respiratory protection should be worn. The fresh air intake should be clear of carbon monoxide or other contaminants

TABLE 3. THRESHOLD LIMIT VALUES (TLV) FOR SOLVENTS[4]

	ACGIH Values				OSHA Industry Values	
	TLV-TWA[1]		TLV-STEL[2]		TLV-TWA[1]	
	ppm	mg/m^3	ppm	mg/m^3	ppm	mg/m^3
Acetone	500	1780	750	2375	1000	
Benzene (Benzol)—Skin	0.5	30	2.5	75	1	–
Carbon Tetrachloride—Skin	5	31	10	63	10	–
Cyclohexane	100	334	–	–	300	1050
Epichlorohydrin—Skin	0.5		–	–	5	19
Ethyl Acetate	400	1440	–	–	400	1440
Ethanol (Ethyl Alcohol)	1000	1880	–	–	1000	1900
Ethylene Dichloride (1,2-Dichloroethane)	10	40	–	–	50	200
Ethylenediamine—Skin	10	25	–	–	10	25
Furfuryl Alcohol—Skin	10	40	15	60	50	200
Methanol (Methyl Alcohol)—Skin	200	–	250	–	200	260
Methylene Chloride (Dichloromethane)	50	174	–	–	25	–
VM & P Naphtha	300	1370	–	–	–	–
Perchloroethylene—Skin	25	170	100	685	100	–
Isopropyl Alcohol—Skin	400	–	500	–	400	980
Stoddard Solvent	100	525	–	–	500	2900
Toluene	50	188	–	–	200	750
Trichloroethylene	100	535	–	–	100	–
Turpentine	100	556	–	–	100	560
Xylene (Xylol)	100	434	150	651	100	435

[1] TLV-TWA (Threshold Limit Value—Time Weighted Average): The time-weighted average concentration for a conventional 8-hour workday and a 40-hour workweek, to which it is believed that nearly all workers may be repeatedly exposed, day after day, without adverse effect.

[2] TLV-STEL (Threshold Limit Value—Short Term Exposure Limit): The maximum concentration to which workers can be exposed for a short time without suffering from irritation, chronic or irreversible tissue damage, or narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue or materially reduce work efficiency, and provided that the daily TLV-TWA is not exceeded. Exposures above the TLV-TWA up to the STEL should not be longer than 15 minutes and should not occur more than four times per day. There should be at least 60 minutes between successive exposures in this range.

[3] In general, the aromatic hydrocarbon content will determine what TLV applies.

[4] Values were obtained from www.osha.gov/dts/chemicalsampling/toc/toc_chemsamp.html. These TLVs are revised periodically. Note that OSHA limits may be different from ACGIH recommendations.

from engine exhausts or other sources. The concentration of solvent in air should not exceed the lower limit of flammability as fire or explosion may result. Some solvents, especially aromatic solvents, will also dissolve the vehicle of paints so they can be removed. It is important that the last wash or rinse be made with clean solvent in every case or a film of oil or grease will be left on the surface when the solvent of the last washing evaporates. This film may interfere with the bond of the paint to the metal.

Petroleum base mineral spirits (aliphatics), with a minimum flash point of 38°C (100°F) should be used as the general purpose solvent for cleaning under normal conditions. In hot weather, or when the temperature is 25 to 35°C (80 to 95°F), high flash aliphatic mineral spirits with a minimum flash point of 50°C (122°F) should be used. In very hot weather, when the temperature is over 35°C (95°F), heavy mineral spirits with a flash point over 60°C (140°F) should be used. Gasoline and V.M. & P. Naphtha are too dangerous for use under ordinary conditions.

Aromatic solvents may be used where greater solvency is required, but they are more toxic and the solvents generally available have low flash points. Benzol (benzene) is the most toxic and should not be used, particularly in view of its low flash point and attendant fire and explosion hazard. Xylene (xylol), toluene (toluol), and high flash naphtha may be used when their concentration in air that is being breathed does not exceed the safe limit (see Table 3). If the concentration is greater, appropriate respiratory protection should be worn. Because of the low flash points of these solvents, fire and explosion hazards are inherent with their use and great caution should be taken to ensure safe working conditions.

Chlorinated hydrocarbons may be used. However, due to toxicity, chlorinated hydrocarbons are not recommended for general use except with special equipment and trained operators. Chlorinated hydrocarbons should never be used where they may affect stainless steel.

In general, solvents are satisfactory for use provided that they meet the flash point requirements above and that they are used under such conditions that the concentration of chlorinated hydrocarbons in air does not constitute a health hazard (see Table 3). NOTE: Always review the MSDS supplied with any solvent for proper safety/health and environmental precautions to be taken when using the solvent.

5.1.2 Alkaline Cleaners: These cleaners saponify certain oils and greases, and their surface active constituents wash away other types of contaminants, such as oil. They may be particularly effective in removing some coating types because the alkali saponifies the dried paint vehicle. Since the soaps formed are soluble in water, the contaminants are more easily removed by washing with water after saponification. Although alkaline cleaners pose no problems to a steel substrate, extended exposure will cause significant damage to aluminum, zinc, wood, or concrete.

The most commonly used alkaline cleaner is trisodium phosphate (TSP), but there are other alkalis which are used. Some of these are mixtures with wetting agents and detergents. They are available as proprietary products and should be used in accordance with directions of the manufacturer. If not used properly, alkaline cleaners will damage oil-base coatings.

If no commercial alkaline cleaner is available, good results may be achieved by the use of 15 grams of trisodium phosphate (TSP) per liter of water (2 oz/gal), to which is also added soap or other suitable detergent at 8 to 15 grams per liter (1 to 2 oz/gal). This solution is best used hot; if used cold, it may be advisable to increase the concentration. This solution is suitable for spraying or scrubbing; if used in dip tanks, the concentration may be tripled. If not washed from the surface, this mixture will soften and eventually loosen many paints. Local sewer disposal regulations should be reviewed before using TSP.

A soap film left on the surface is just as damaging to the paint bond as is an oil or grease film; therefore the surface should be thoroughly washed (preferably with hot water under pressure) to remove this soap and other residue. Moreover, all alkali must be thoroughly removed from the surface or the new paint may be saponified and damaged by it. To test the effectiveness of the wash, universal pH test paper should be placed against the wet steel. The pH of the washed surface should be no greater than the pH of the wash water.

Alkaline cleaners must be used with caution since bad burns may result from contact with some solutions. Particular care should be paid to protecting the eyes of workers; safety goggles or eye shields should be worn. Rubber gloves should be worn if the solutions will contact workers' hands. Where alkaline cleaning compounds are sprayed, respirators should be worn.

5.1.3 Emulsion Cleaners: Emulsion cleaners usually contain oil soluble soaps or emulsifying agents along with kerosene or mineral spirits. They are usually supplied as a concentrate which may be thinned with kerosene or mineral spirits and sprayed on the surface to be cleaned. They are emulsified by the action of water under pressure and washed away along with oil, grease, and other contaminants. They may be diluted with water, emulsified, and used in that condition. In any event, the directions of the manufacturer should be followed.

A residue of emulsion is almost always left on the surface. This residue will leave a thin film of oil on the surface. If the paint to be applied cannot tolerate a slight amount of oil, the residue must be washed from the surface by steam, hot water, detergents, solvents, or alkaline cleaning compounds.

Alkaline emulsion cleaners, which combine the advantages of the alkaline cleaners and the emulsion cleaners, are available.

5.1.4 Steam Cleaning: Steam cleaning may utilize either steam, hot water under pressure, or both.

The steam and hot water, when used to clean the surface, are usually used with a detergent and sometimes also with an alkaline cleaner. The steam and hot water themselves tend to remove the oils, greases, and soaps by thinning them with heat, emulsifying them, and diluting them with water. They can then be easily removed by further washing. When detergent is used, its higher affinity for the metal also causes the oil, grease, and, in some cases, even the paint to loosen, thereby increasing the rate of cleaning.

New paint will not adhere to the metal if any of the oil, grease, soap, detergent, or alkali is left on the surface. A final washing with clean water is therefore always necessary.

5.1.5 Threshold Limit Values: Threshold limit values (TLVs) of common cleaning solvents can be obtained from the OSHA web site www.osha.gov/dts/chemicalsampling/toc/toc_chemsamp.html (see Table 3). The American Conference of Governmental Industrial Hygienists (ACGIH) also publishes a booklet listing their recommended TLVs and Biological Exposure Indices (BEIs). Note that OSHA limits may be different from ACGIH recommendations. These TLVs are revised periodically.

5.1.6 Paint Removal: Although not addressed in SSPC-SP 1, many of the cleaning methods may adversely affect existing paint. A strong solvent used in solvent cleaning may cause the existing paint to soften or disbond from the substrate. The adhesive nature of the old paint is reduced by chemical action on the paint. Where complete paint removal is the primary object, caustic soda (sodium hydroxide) or a commercial paint stripper may be used. Alkali cleaners remove oil base paint and solvent cleaners remove latexes and lacquers. Steam can be used to remove old paint by degrading the vehicle of the old paint by virtue of the high temperatures so that it loses its strength and its bonding to the metal. Information on chemical stripping can be found in the technology update SSPC-TU 6, "Chemical Stripping of Organic Coatings from Steel Structures," and in Volume 1 of the SSPC Painting Manual.

5.2 SSPC-SP 2, "HAND TOOL CLEANING": Hand tool cleaning is a method of surface preparation often used for normal atmospheric exposures, for interiors, and for maintenance painting when using paints with good wetting ability. Hand cleaning will remove loose rust, loose paint, and loose mill scale but will not remove all residue of rust or intact mill scale. For cleaning small, limited areas prior to maintenance priming, hand cleaning will usually suffice.

Care in hand tool cleaning is also especially important if the prime coat is to be applied by spray, because a sprayed coating may bridge gaps and crevices, whereas brushing works the paint into these areas.

The hand tool cleaning specification requires that oil and grease, along with any other visible contaminants, be removed as specified in SSPC-SP 1, "Solvent Cleaning" prior to hand tool cleaning. On welded work, particular care should be taken to remove as much welding flux, slag, and fume deposit as is possible since these are notorious in promoting paint failure on welded joints. All loose matter should be removed from the surface prior to painting. Blowing off with clean, dry, oil-free compressed air, brushing, or vacuum cleaning are satisfactory removal methods.

5.2.1 Loose Rust, Mill Scale, and Paint: Determination of the degree of cleaning required to comply with SSPC-SP 2 is often very difficult. The problem is in establishing whether a residue is "adherent" or "loose." The standard considers the residue adherent if it cannot be lifted with a dull putty knife, a somewhat subjective criterion. Tightly adherent rust scale is discussed in Section 4.3.1.

One possible solution is for the contracting parties to establish a standard cleaning procedure in which the type of tool, force, speed, etc., are all stipulated.

Another possibility is for the contracting parties to agree on a sample area (sometimes called a "job standard") that shows the standard of cleanliness for a particular job. The sample area should be representative of the surface to be cleaned, and may be a separate specimen or a designated flat portion of the actual surface. After the contracting parties agree on the cleanliness desired, the surface is protected and retained for comparison.

It is emphasized that this practice establishes a standard of cleanliness, but not a production rate. As long as the cleaned surface is as clean as job standard, the actual production rate of cleaning is not in question. The job standard is of value in resolving differences of opinion as to whether the surface has been properly cleaned.

5.2.2 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, SSPC-VIS 3 or other consensus reference photographs may be used to supplement the cleaning criteria of SSPC-SP 2. Table 4A gives the correlation between the SSPC and the ISO pictorial standards.

5.3 SSPC-SP 3, "POWER TOOL CLEANING": Similar to hand tool cleaning, power tool cleaning removes loose rust, loose mill scale, and loose paint. Intact materials may remain. Power tools use electrical and pneumatic equipment to provide faster cleaning. They include sanders, wire brushes or wheels, chipping hammers, scalers, rotating flaps (rotopeen), needle guns, hammer assemblies, and right angle or disk grinders. Some have high efficiency particulate air (HEPA) vacuum lines attached to reduce air pollution and collect debris produced in the cleaning operation. Power tools clean by impact, abrasion, or both. Cleaning of metal surfaces is less expensive using power tools than using hand tools. Less particulate contamination of the environment occurs with power tools as opposed to abrasive blasting. Thus, power tools are used frequently for spot cleaning of damaged coatings, where contamination of adjacent areas by abrasive is unacceptable, and when a surface-tolerant coating such as oil-based paint is to be used.

The power tool cleaning standard requires that oil and grease, along with any visible salts, be removed as specified in SSPC-SP 1, "Solvent Cleaning" prior to power tool cleaning. On welded work, particular care should be taken to remove as

TABLE 4A
COMPARISON OF SSPC AND ISO SURFACE PREPARATION STANDARDS FOR POWER- AND HAND-TOOL CLEANED STEEL

Surface Preparation Standard		Initial Condition of Steel		Reference Photographs	
SSPC	**ISO**	**Rust Condition**	**Description**	**SSPC-VIS 3**[1]	**ISO 8501-1**[2]
SP 11 Power Tool Cleaning to Bare Metal		A	intact mill scale	A SP 11	*
		B	partially rusted mill scale	B SP 11	*
		C	100% rusted, no pits	C SP 11	*
		D	rusted and pitted	D SP 11	*
		E	paint mostly intact	E SP 11, E SP 11/R	*
		F	zinc-rich paint	F SP 11, F SP 11/R	*
		G	deteriorated paint over mill scale	G SP 11	*
SP 15 Commercial Grade Power Tool Cleaning		A	intact mill scale	*	*
		B	partially rusted mill scale	B SP 15	*
		C	100% rusted, no pits	C SP 15	*
		D	rusted and pitted	D SP 15	*
		E	paint mostly intact	E SP 15	*
		F	zinc-rich paint	F SP 15	*
		G	deteriorated paint over mill scale	G SP 15	*
SP 3 Power Tool Cleaning	St 3	A	intact mill scale	A SP 3/PWB, A SP 3/SD	*
		B	partially rusted mill scale	B SP 3/PWB, B SP 3/SD	B St 3
		C	100% rusted, no pits	C SP 3/PWB, C SP 3/SD	C St 3
		D	rusted and pitted	D SP 3/PWB, D SP 3/SD	D St 3
		E	paint mostly intact	E SP 3/PWB, E SP 3/SD	*
		F	zinc-rich paint	F SP 3/PWB, F SP 3/SD	*
		G	deteriorated paint over mill scale	G SP 3/PWB, G SP 3/SD	*
SP 2 Hand Tool Cleaning	St 2	A	intact mill scale	A SP 2	*
		B	partially rusted mill scale	B SP 2	B St 2
		C	100% rusted, no pits	C SP 2	C St 2
		D	rusted and pitted	D SP 2	D St 2
		E	paint mostly intact	E SP 2	*
		F	zinc-rich paint	F SP 2	*
		G	deteriorated paint over mill scale	G SP 2	*

* = no photograph

[1] SSPC-VIS 3 contains photographs for SP 11, SP 15, SP 3, and SP 2.

[2] The United Kingdom Standard BS 7079 Part A1 is equivalent to ISO 8501-1 and depicts the degrees of cleanliness of unpainted steel. BS 7079 Part A2 is equivalent to ISO 8501-2 and depicts the same degrees of cleanliness of previously painted steel.

much welding flux, slag, and fume deposit as is possible since these are notorious in promoting paint failure on welded joints. All loose matter should be removed from the surface prior to painting. Blowing off with clean, dry, oil-free compressed air, brushing, or vacuum cleaning are satisfactory methods.

Care is necessary in the use of power tools to prevent excessive roughening of the surface, as ridges and burrs can contribute to paint failure because sharp edges may not be protected by adequate thickness of paint. Excessive power wire brushing can also be detrimental to the performance of the paint since the surface (particularly mill scale) is easily burnished to a smooth, slick finish to which paint will not adhere.

5.3.1 Loose Rust, Mill Scale, and Paint: Determination of the degree of cleaning required to comply with this standard is often very difficult. The problem is in establishing whether a residue is "adherent" or "loose." The standard considers the residue adherent if it cannot be lifted with a dull putty knife, a somewhat subjective criteria. Tightly adherent rust scale is discussed in Section 4.3.1.

One possible solution is for the contracting parties to agree on a standard cleaning procedure in which the type of tool, force, speed, etc., are all stipulated.

Another possibility is for the contracting parties to agree on a sample area (sometimes called a "job standard") that shows the standard of cleanliness for a particular job. The sample area should be representative of the surface to be cleaned, and may be a separate specimen or a designated flat portion of the actual surface. After the contracting parties agree on the cleanliness desired, the surface is protected and retained for comparison.

It is emphasized that this practice establishes a standard of cleanliness, but not a production rate. As long as the cleaned surface is as clean as job standard, the actual production rate of cleaning is not in question. The job standard is of value in resolving differences of opinion as to whether or not the surface has been properly cleaned.

5.3.2 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, SSPC-VIS 3 may be used to supplement the cleaning criteria of this standard. Table 4 gives the correlation between the SSPC and the ISO pictorial standards.

5.4 SSPC-SP 4, "FLAME CLEANING OF NEW STEEL": This standard was discontinued in 1982.

5.5 SSPC-SP 5/NACE No. 1, "WHITE METAL BLAST CLEANING": White Metal Blast Cleaning is generally used for exposures in very corrosive atmospheres and for immersion service where the highest degree of cleaning is required and a high surface preparation cost is warranted.

Blast cleaning to white metal will result in high performance of the paint systems due to the complete removal of all rust, mill scale, and foreign matter or visible contaminants from the surface. In ordinary atmospheres and general use, white metal is seldom warranted.

The use of this grade of blast cleaning without rust back is particularly difficult in the environments where it is most needed as a preparation for painting; for example, in humid chemical environments. White Metal Blast Cleaning should be conducted at a time when no contamination or rusting can occur, and when prompt painting is possible. A good rule is that no more surface should be prepared for painting than can be coated the same day.

5.5.1 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, SSPC-VIS 1 may be used to supplement the cleaning criteria of this standard. Table 4B gives the correlation between the SSPC and the ISO pictorial standards. When using consensus reference photographs, it should be recognized that the color or hue of the cleaned surface may appear different from the photographs due to the nature of the steel, the abrasives used, the presence of existing coatings, and other factors.

5.6 SSPC-SP 6/NACE No. 3, "COMMERCIAL BLAST CLEANING": Commercial Blast Cleaning should be employed for all general purposes where a high, but not perfect, degree of blast cleaning is required. It will remove all rust, all mill scale, and all other detrimental matter from the surface, but will permit a great deal of staining from rust, mill scale, or previously applied paint to remain. The surface will not necessarily be uniform in color, nor will all surfaces be uniformly clean. The advantage of Commercial Blast Cleaning lies in the lower cost for providing a degree of surface preparation that should be suitable for the majority of cases where blast cleaning is believed to be necessary. However, if it is possible that Commercial Blast Cleaning will result in a surface unsatisfactory for the service, SSPC-SP 10 (near-white) or SSPC-SP 5 (white metal) should be specified.

When a project specification includes maintenance painting, if it is intended that some of the existing coating be permitted to remain (e.g. because it is thin, well adherent, and compatible with the new coating system), the contract documents should stipulate the extent of the surface to be cleaned in accordance with this standard. SSPC-PA 1, "Shop, Field, and Maintenance Painting of Steel," and SSPC-PA Guide 4, "Guide to Maintenance Repainting with Oil Base or Alkyd Painting Systems," cover additional maintenance painting procedures.

5.6.1 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, SSPC-VIS 1 or other consensus reference photographs may be used to supplement the cleaning criteria of this standard. Table 4A gives the correlation between the SSPC and the ISO pictorial standards. When using consensus reference photographs, it should be recognized that the color or hue of the cleaned surface may appear different from the photographs due to the nature of the steel, the abrasives used, the presence of existing coatings, and other factors such as angle of lighting and profile depth.

TABLE 4B
COMPARISON OF SSPC AND ISO SURFACE PREPARATION STANDARDS FOR BLAST CLEANED STEEL

Surface Preparation Standard		Initial Condition of Steel		Reference Photographs	
SSPC/NACE	**ISO[1]**	**Rust Condition**	**Description**	**SSPC-VIS 1[2]/SSPC-VIS 5**	**ISO 8501-1**
SP 5/NACE No. 1 White Metal Blast Cleaning	Sa 3	A	intact mill scale	A SP 5, A SP 5-N1, A SP 5-N2, A SP 5-N3 A SP 5-M1, A SP 5-M2, A SP 5-M3[3]	A Sa 3[4]
		B	partially rusted mill scale	B SP-5	B Sa 3[4]
		C	100% rusted, no pits	C SP-5	C Sa 3[4]
		D	rusted and pitted	D SP-5	D Sa 3
		G	deteriorated paint over mill scale	G_1 SP 5, G_2 SP 5, G_3 SP 5, G_1 SP 5 P, G_1 SP 5 H, G_1 SP 5 L, G_1 SP 5 D, G_3 SP 5 P, G_3 SP 5 H, G_3 SP 5 L, G_3 SP 5 D	*
SP 10/NACE No. 2 Near-White Blast Cleaning	Sa 2 1/2	A	intact mill scale	A SP 10	A Sa 2 1/2
		B	partially rusted mill scale	B SP-10	B Sa 2 1/2
		C	100% rusted, no pits	C SP-10, C WAB-10[5]	C Sa 2 1/2
		D	rusted and pitted	D SP-10, D WAB-10	D Sa 2 1/2
		G	deteriorated paint over mill scale	G_1 SP 10, G_2 SP 10, G_3 SP 10	*
SP 6/NACE No. 3 Commercial Blast Cleaning	Sa 2	A	intact mill scale	*	*
		B	partially rusted mill scale	B SP-6	B Sa 2
		C	100% rusted, no pits	C SP-6, C WAB-6	C Sa 2
		D	rusted and pitted	D SP-6, D WAB-6	D Sa 2
		G	deteriorated paint over mill scale	G_1 SP 6, G_2 SP 6, G_3 SP 6	*
SP 14/NACE No. 8 Industrial Blast Cleaning		A	intact mill scale	*	*
		B	partially rusted mill scale	*	*
		C	100% rusted, no pits	*	*
		D	rusted and pitted	*	*
		G	deteriorated paint over mill scale	G_1 SP 14, G_2 SP 14, G_3 SP 14	*
SP 7/NACE No. 4 Brush-Off Blast Cleaning	Sa 1	A	intact mill scale	*	*
		B	partially rusted mill scale	B SP-7	B Sa 1
		C	100% rusted, no pits	C SP-7	C Sa 1
		D	rusted and pitted	D SP-7	D Sa 1
		G	deteriorated paint over mill scale	G_1 SP 7, G_2 SP 7, G_3 SP 7	*

* = no photograph

[1] ISO standards Sa 3, Sa 2 1/2, Sa 2, Sa 1, St 2 and St 3 approximate the corresponding SSPC standards.

[2] SSPC-VIS 1 contains photographs for SP 5, SP 6, SP 7, SP 10, and SP 14.

[3] Alternate non-metallic abrasives: A SP 5-N1, A SP 5-N2, A SP 5-N3
Alternate metallic abrasives: A SP 5-M1, A SP 5-M2, A SP 5-M3

[4] ISO 8501-1 photographs (1978 through 1989 printing) may not adequately illustrate the corresponding SSPC surface preparation
ISO photograph illustrating B Sa 2 shows dark areas that could be interpreted as mill scale and, therefore, represents SSPC-SP 14 and does not represent SSPC-SP 6.
ISO photographs illustrating A Sa 3, B Sa 3 and C Sa 3 do not adequately illustrate the surface texture of typically blast cleaned steel.The United Kingdom Standard BS 7079 Part A1 is equivalent to ISO 8501-1 and depicts the degrees of cleanliness of unpainted steel. BS 7079 Part A2 is equivalent to ISO 8501-2 and depicts the same degrees of cleanliness of previously painted steel.

[5] SSPC-VIS 5 photographs of wet abrasive blast cleaning are indicated by WAB.

5.7 SSPC-SP 7/NACE No. 4, "BRUSH-OFF BLAST CLEANING": Brush-off blast cleaning should be employed when the environment is mild enough to permit tight mill scale, tight paint (if the surface was previously painted), and tight rust to remain on the surface. The surface resulting from this method of surface preparation should be free of all loose mill scale, loose paint, and loose rust. The small amount of rust remaining should be an integral part of the surface. The surface should be sufficiently abraded to provide a good anchor for paint. The low cost of this method may result in economical protection in mild environments.

It is not intended that brush-off blast cleaning be used for very severe surroundings. Brush-off blast cleaning is generally intended to supplant power tool cleaning where facilities are available for blast cleaning. With this method of surface preparation, as with any other, it is understood that the rate of cleaning will vary from one part of the structure to another depending upon the initial condition of the surface. Because of the high rate of cleaning, the cost is low relative to the higher grades of blast cleaning. Paints which are used should have a fair degree of wetting because of the material that is allowed to remain on the surface.

When a project specification includes maintenance painting, if brush-off blast cleaning of the entire surface is specified, the existing coating should be compatible with the new coating system and should be of adequate integrity to withstand the impact of the abrasive. If a substantial amount of the coating will be removed by this method, then a higher level of cleaning should be specified, e.g. SSPC-SP 14 (industrial) or SSPC-SP 6 (commercial). SSPC-PA 1, "Shop, Field, and Maintenance Painting of Steel," and SSPC-PA Guide 4, "Guide to Maintenance Repainting with Oil Base or Alkyd Painting Systems," cover additional maintenance painting procedures.

5.7.1 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, SSPC-VIS 1 or other consensus reference photographs may be used to supplement the cleaning criteria of this standard. Table 4A gives the correlation between the SSPC and the ISO pictorial standards.

5.8 SSPC-SP 8, "PICKLING": Pickling is considered a desirable method of removing rust and mill scale from structural shapes, beams, and plates when the cost of such removal is felt to be justified. Properly accomplished, pickling produces a surface that will promote long paint life with most coatings, but pickling is most commonly associated with hot dipped galvanizing.

Where production is sufficiently high to keep the equipment in use, pickling results in low cost shop preparation. It is impractical for field use.

Facilities are extremely limited for pickling of large fabricated members or large structural beams. However, there are a number of facilities for large steel plates and structural members that are not exceedingly long. Small-scale pickling facilities are widely available.

Hydrochloric acid dissolves scale faster than does sulfuric acid, but hydrochloric acid is seldom heated for greater action because of the greater amounts of toxic hydrogen chloride fumes emitted. Any acid used should contain an appropriate inhibitor to control the chemical action. Considerable use is made of the duplex type of pickling where sulfuric acid is used to remove the rust and scale, and phosphoric acid is used for a final phosphate treatment. Special precautions including fresh water rinsing are necessary to remove residues of unreacted sulfuric or hydrochloric acid.

Design of fabricated steel may require special consideration to eliminate pockets or crevices which trap acid during pickling. This may be avoided by pickling in phosphoric acid. Pickled steel, like blast cleaned steel, should be painted as soon as possible after cleaning. A more detailed discussion of pickling is available in Volume 1 of the SSPC Painting Manual.

5.9 SSPC-SP 9, "WEATHERING FOLLOWED BY BLAST CLEANING": This standard was discontinued in 1971. Weathering prior to blast cleaning has been found to be a very harmful practice, especially in corrosive environments, since deleterious surface impurities are much more difficult to remove after weathering away of mill scale.

5.10 SSPC-SP 10/NACE No. 2, "NEAR-WHITE BLAST CLEANING": In many exposures involving a combination of high humidity, chemical atmosphere, marine, or other corrosive environment, the use of SSPC-SP 5 "White Metal Blast Cleaning" was found to be overly expensive due to the disproportionately large amount of work required to remove the last vestiges of streaks and shadows. There are many applications in which these traces can be tolerated without appreciable loss in coating life. Therefore, the need for a grade of blast cleaning beyond that of SSPC-SP 6 but less than SSPC-SP 5 was demonstrated. The near-white blast cleaning standard was developed to fill this need.

Near-white blast cleaning can be employed for all general purposes where a high degree of surface cleanliness is required. It will remove all rust, mill scale, and other detrimental matter from the surface but streaks and stains are permitted to remain. The surface will not necessarily be completely uniform in color, nor will all surfaces be uniformly clean. However, it is explicit in this standard that shadows, streaks, or discolorations, if any, be slight and be distributed uniformly over the surface—not concentrated in spots or areas.

The advantage of near-white blast cleaning lies in the lower cost for surface preparation that is satisfactory for all but the most severe service conditions. Depending upon the initial condition of the new or previously painted steel, it has been variously estimated that near-white blast cleaning can be carried out at a cost of 10 to 35% less than that of SSPC-SP 5. These numbers are estimates only and will not hold true in all cases.

The verbal description calling for at least 95% of the surface being equivalent to SSPC-SP 5 is based upon a large number of visual observations and a limited number of light reflectivity measurements. It is hoped that the amount of surface impurity can be quantified by specific measurement technique, but efforts to date have been unsuccessful except on a laboratory basis. It is believed, however, that a visual estimate of the amount of residuals can be agreed upon between owner and contractor.

When a project specification includes maintenance painting, if it is intended that some of the existing coating be permitted to remain (e.g., because it is thin, well adherent, and compatible with the new coating system), the contract documents should stipulate the extent of the surface to be cleaned in accordance with this standard. SSPC-PA 1, "Shop, Field, and Maintenance Painting of Steel," and SSPC-PA Guide 4, "Guide to Maintenance Repainting with Oil Base or Alkyd Painting Systems," cover additional maintenance painting procedures.

5.10.1 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, SSPC-VIS 1 or other consensus reference photographs may be used to supplement the cleaning criteria of this standard. Table 4B gives the correlation between the SSPC and the ISO pictorial standards. When using consensus reference photographs, it should be recognized that the color or hue of the cleaned surface may appear different from the photographs due to the nature of the steel, the abrasives used, the presence of existing coatings, and other factors.

5.11 SSPC-SP 11, "POWER TOOL CLEANING TO BARE METAL": Power tool cleaning to remove tightly adherent material produces a surface that is visibly free from all rust, mill scale, and old coatings, and that has a surface profile of at least 25µm (1 mil). SSPC-SP 11 is the highest level of power tool cleaning. It produces a greater degree of cleaning than SSPC-SP 3 (which does not remove tightly adherent material) and SSPC-SP 15, "Commercial Grade Power Tool Cleaning" which allows substantial staining. SSPC-SP 11 may be considered for coatings requiring a bare metal substrate.

The surfaces prepared according to this standard are not to be compared to surfaces cleaned by abrasive blasting. Although this method produces surfaces that resemble near-white or commercial blast, they are not necessarily equivalent to those surfaces produced by abrasive blast cleaning as called for in SSPC-SP 10 (near-white) or SP 6 (commercial) due to characteristics of the profile.

The SSPC-SP 11 standard gives the specifier an opportunity to select a method of cleaning suitable for certain coatings in areas where wet or dry abrasive blasting or waterjetting is prohibited or not feasible. Examples of other circumstances where this standard may be applied are as follows:

- touch-up of welded or damaged areas of erection assemblies
- reducing volume of hazardous waste produced by abrasive blasting
- cleaning around sensitive equipment or machinery

5.11.1 Power Tools and Cleaning Media: A power tool cleaning system consists of a surface cleaning medium for abrading the surface and a powered tool for driving that medium. The standard distinguishes between media that clean the surface and those that produce a profile. Similarly, power tools are classified as surface cleaning type or profile producing type.

Surface cleaning power tools are those that drive two main classes of surface cleaning media: 1) non-woven abrasive wheels and discs; 2) coated abrasive discs, flap wheels, bands, or other coated abrasive devices.

Profile-producing power tools are described as those on which rotary impact or peening media are mounted, and those on which steel needles (needle guns) are mounted, although other tools and media that can produce the appropriate profile are acceptable. In instances where a profile already exists, such as on previously painted surfaces, only surface cleaning power tools and media may be required, if the appropriate degree of cleanliness is created without reducing the profile to less than 25 micrometers (1 mil). Where an existing profile is reduced to less than 25 micrometers (1 mil) in the process of cleaning, surface profiling power tools are required to restore the appropriate profile.

Where there is no existing profile, then both cleanliness and profile must be produced as specified. This may require using both kinds of tools and media, although in some cases a surface profiling tool/medium may adequately clean the surface without requiring a separate cleaning operation with surface cleaning tools/media. It should be noted that misuse of power tools on metals can produce a burnished rather than a textured surface that compromises coating adhesion.

Cleaning of metal surfaces is usually faster and less expensive using abrasive blasting than using power tools, without considering the cost of mobilization and containment for the control of dust and debris. However, power tools are used frequently for spot cleaning of damaged coatings where contamination of adjacent areas by abrasive is unacceptable. Less particulate contamination of the environment occurs than from abrasive blasting.

5.11.2: Power Tools With Vacuum Shrouds: Special power tools may also have high-efficiency particulate air (HEPA) vacuum lines attached to reduce air pollution and to contain the debris generated at the point-source during coating removal. The vacuum shroud surrounds only the tool itself, providing a localized containment of the debris at the point of generation.

The method of operation of vacuum shrouded tools is similar to that of non-vacuum shrouded tools. This is difficult when cleaning irregular surfaces. As a result, special custom shrouds can be fitted onto the ends of the tools. Some tools however, are not amenable to shrouds, and therefore the collection of debris is not as efficient. A surface can be cleaned to comply with SSPC-SP 3, SSPC-SP 15 "Industrial Grade Power Tool Cleaning," or SSPC-SP 11, using these vacuum shrouded tools.

5.11.3 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, SSPC-VIS 3 or other consensus reference photographs may be used to supplement the cleaning criteria of this standard. Table 4A lists the SSPC-VIS 3 consensus reference photographs that correspond to various initial surface conditions. SSPC-VIS 1 and ISO 8501-1 are not suitable for assessing surfaces cleaned to bare metal by power tools.

5.12 SSPC-SP 12/NACE No. 5, "SURFACE PREPARATION AND CLEANING OF METALS BY WATERJETTING PRIOR TO COATING": As is the case with dry abrasive blast cleaning, high pressure waterjetting (HP WJ) and ultra-high pressure waterjetting (UHP WJ) can be used to prepare surfaces to various degrees of cleanliness. Waterjetting is used when abrasive blasting is not possible or not desired, or when it is necessary to remove a high percentage of soluble salt contamination. Waterjetting does not produce a profile. However, if a profile exists under old paint that is being removed, the original profile can be restored by waterjetting. SSPC-TR 2/NACE 6G198, "Wet Abrasive Blast Cleaning," discusses wet methods using abrasive.

Water cleaning uses pressures less than 70 MPa (10,000 psi) and high-pressure waterjetting (HP WJ) uses pressures above this value. Ultrahigh-pressure waterjetting (UHP WJ) uses pressures above 210 MPa (30,000 psi).

5.12.1 Surface Cleanliness: SSPC-SP 12 defines four degrees of VISUAL cleanliness which can be summarized as follows:

- WJ-1 Clean to the bare substrate; the most thorough level
- WJ-2 Very thorough or substantial cleaning; randomly dispersed visible stains of previously existing rust, tightly adherent thin coatings, and tightly adherent foreign matter is allowed on only 5 percent of the surface
- WJ-3 Thorough cleaning; randomly dispersed visible stains of previously existing rust, tightly adherent thin coatings,, and tightly adherent foreign matter is allowed on only 33 percent of the surface
- WJ-4 Light cleaning; all loose material is removed.

These four conditions of waterjetting were originally meant to parallel the four degrees of abrasive blast cleaning (SSPC-SP 5, SSPC-SP 10, SSPC-SP 6, and SSPC-SP 7). However, SSPC-SP 12 has evolved to the point where WJ-2 and WJ-3 allow thin paint to remain, while the dry abrasive blast cleaning standards SSPC-SP 10 and SP 6 continue to allow only stains of paint.

One of the advantages of waterjetting is the removal of soluble contaminants. In an appendix, SSPC-SP 12 describes three levels of nonvisual surface cleanliness based on the amount of water-soluble chlorides, iron-soluble salts, and sulfates:

- NV-1 No salts detected
- NV-2 Less than 7 $\mu g/cm^2$ chloride ion contaminants, 10 $\mu g/cm2$ ferrous ion, and 17 $\mu g/cm^2$ sulfate ion
- NV-3 Less than 50 $\mu g/cm^2$ chloride and sulfate contaminants

Methods for measuring the amount of salt on the surface are described in SSPC-TU 4, "Field Methods for Retrieval and Analysis of Soluble Salts on Substrates" (to be reissued in 2005 as SSPC-Guide 15). The choice of visual and nonvisual cleanliness is determined by the existing condition of the surface, the coating to be applied, and the exposure environment.

5.12.2 Flash Rusting: With any wet method of surface preparation, the cleaned surface will eventually exhibit a rust bloom or flash rust as the surface dries. Non-uniform rusting with areas of heavy rust usually indicates the presence of soluble salts on the surface. A uniform rust bloom may be an acceptable surface to paint. Visible flash rusting can be light, medium, or heavy. The coating manufacturer must be consulted to determine the extent of rust bloom that their coating can tolerate for the given exposure. Inhibitors can be added to the water to prevent flash rusting, but the coating manufacturer must be consulted to verify compatibility with the level of inhibitor used.

5.12.3 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, SSPC-VIS 4 or other consensus reference photographs may be used to supplement the cleaning criteria of this standard. SSPC-VIS 4 contains photographs showing steel of original rust condition C cleaned to WJ-2 and WJ-3, each with light, medium, or heavy flash rusting. A parallel set of photographs is given for original rust condition D. In addition, there are four different painted surfaces each cleaned to the four degrees of waterjetting, WJ-1 through WJ-4. When using the consensus reference photographs, it should be recognized that the color or hue of the cleaned surface may appear different from the photographs due to the nature of the steel, the presence of existing coatings, and other factors.

5.13 SSPC-SP 13/NACE NO. 6, "SURFACE PREPARATION OF CONCRETE": This standard gives requirements for surface preparation of concrete by mechanical, chemical, or thermal methods prior to the application of bonded protective coating or lining systems. The requirements of this standard are applicable to all types of cementitious surfaces including cast-in-place concrete floors and walls, precast slabs, masonry walls, and shotcrete surfaces.

An acceptable prepared concrete surface should be free of contaminants, laitance, loosely adhering concrete, and dust, and should provide a sound, uniform substrate suitable for the application of protective coating or lining systems. When required, a minimum concrete surface strength, maximum moisture content, and surface profile range should be specified in the procurement documents.

SSPC-SP 13/NACE No. 6 contains sections on definitions, inspection procedures before surface preparation, the methods of surface preparation, inspection, and acceptance criteria for light service and for severe service.

5.14 SSPC-SP 14/NACE No. 8, "INDUSTRIAL BLAST CLEANING": Industrial blast cleaning is used when the objective is to remove most of the coating, mill scale, and rust, but the extra effort required to remove every trace of these materials is determined to be unwarranted. Industrial blast cleaning provides a greater degree of cleaning than SSPC-SP 7 but less than SSPC-SP 6.

The difference between an industrial blast and a brush-off blast is that the objective of a brush-off blast is to allow as much of an existing coating to remain as possible, while the objective of the industrial blast is to remove most of the coating. The industrial blast allows defined mill scale, coating, and rust to remain on less than ten percent of the surface and allows defined stains to remain on all surfaces. A commercial blast provides a higher level of cleaning, and the surface is free of mill scale, rust, and coatings, allowing only random staining to remain on no more than 33 percent of each 9 in^2 (60 cm^2) increment of the surface.

5.14.1 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, VIS 1 or other consensus reference photographs may be used to supplement the cleaning criteria of this standard. Table 4A gives the correlation between the SSPC and the ISO pictorial standards. When using the photographic standards, it should be recognized that the color or hue of the cleaned surface may appear different from the photographs due to the nature of the steel, the abrasives used, the presence of existing coatings, and other factors.

5.15 SSPC-SP 15, "Commercial Grade Power Tool Cleaning": A surface cleaned with power tools to commercial grade is visibly free from all rust, mill scale, and old coatings; and it has a surface profile of at least 25 μm (1 mil). SSPC-SP 15 provides a higher level of cleanliness than SSPC-SP 3, "Power Tool Cleaning" in that all paint, rust, and mill scale are removed. SSPC-SP 15 provides a lesser level than SSPC-SP 11, "Power Tool Cleaning to Bare Metal" because staining is permitted on 33 percent of the surface. Both SSPC-SP 15 and SSPC-SP 11 require a minimum 25 μm (1 mil) profile.

The surfaces prepared according to this standard are not to be compared to surfaces cleaned by abrasive blasting. Although this method produces surfaces that resemble commercial blast cleaned surfaces, they are not necessarily equivalent to those surfaces produced by abrasive blast cleaning to SP 6. After power tool cleaning to SP 15, slight residues of rust and paint may remain in the bottoms of pits if the original surface is pitted. Commercial blast cleaning (SP 6) allows only staining of the surface, and does not permit residue to remain in pit bottoms.

SSPC-SP 15 helps to bridge the gap between the marginal surface preparation described in SP 3, "Power Tool Cleaning" and the more thorough cleaning described in SP 11, "Power Tool Cleaning to Bare Metal." It gives the specifier an opportunity to select a method of cleaning suitable for certain coatings in areas where the added expense of going to SP 11 is not justified by an anticipated increase in coating life. Examples of circumstances where this standard may be applied are as follows:

- touch-up of welded or damaged areas of erection assemblies
- reducing volume of hazardous waste produced by abrasive blasting
- cleaning around sensitive equipment or machinery
- cleaning where abrasive blasting is not permitted.

5.15.1 Consensus Reference Photographs: If mutually agreed upon or if specified in the procurement documents, SSPC-VIS 3 or other consensus reference photographs may be used to supplement the cleaning criteria of this standard. Table 4A lists the SSPC-VIS 3 photographs that correspond to various initial surface conditions. SSPC-VIS 1 and ISO 8501-1 are not suitable for assessing surfaces cleaned to commercial grade by power tools.

6. Selection of Abrasives, Blast Cleaning Parameters, and Equipment

The selection of the size and type of abrasive which will most effectively and economically produce the desired surface finish is not an exact science because of the many variables involved. These variables include the following at a minimum:

- The nature of the steel being cleaned, i.e., the hardness and the degree of rusting which may have developed prior to blast cleaning.
- The basic purpose for blast cleaning, which may include either new construction or maintenance and repair programs.
- The type of surface finish desired, i.e., degree of cleanliness and height of profile required to meet the specification or requirement of the paint to be applied. See SSPC report, "Surface Profile for Anti-Corrosion Paints," (SSPC 74-01).
- The type of blast cleaning systems which may be employed, e.g., centrifugal wheel or air blast recirculating abrasive systems, or open nozzle airblasting with expendable abrasives.

In general, select the smallest size abrasive that will produce the desired cleaning results. Usually, this will give the fastest, most economical cleaning operation.

Non-traditional blast cleaning media may be expendable or recyclable. Such materials include sponge, dry ice, sodium bicarbonate and ice crystals. All require specialized equipment and may or may not create a surface profile.

General information concerning the chemical and physical properties of cast steel shot and grit, and the physical properties of various non-metallic abrasives along with information on their usage, are presented in the following sections.

6.1 ABRASIVE CHARACTERISTICS: Selecting the appropriate type of abrasive for the job is important because the type of abrasive can have a significant influence on the appearance of the blast cleaned surface, productivity, and subsequent clean-up. Abrasives vary in hardnesses, particle size distribution, shape, bulk density, friability, waste generation, and recyclability. The following is a discussion of these characteristics and how they influence abrasive performance. Some physical data on non-metallic abrasives are given in Table 5.

TABLE 5
PHYSICAL DATA ON NON-METALLIC ABRASIVES

	Hardness (Mohs)	Shape	Specific Gravity	Bulk Density		Color	Free Silica (wt %)	Degree of Dusting	Reuse
				lb/ft^3	kg/m^3				
				Naturally Occurring Abrasives					
Silica Sand	5	Rounded	2 to 3	100	1600	White	90+	High	Poor
Heavy Mineral Sand	5 to 7	Rounded	3 to 4	125	2000	Variable	<5	Medium	Good
Flint	6.5 to 7	Angular	2 to 3	80	1300	Lt. Gray	90+	Medium	Good
Garnet	7 to 8	Angular	4	145	2300	Pink	Nil	Medium	Good
Zircon	7.5	Cubic	4.5	185	3000	White	Nil	Low	Good
Kieserite	3.5	Angular	2.6	90	1400	White	Nil	Medium	Poor
Novaculite	4	Angular	2.5	100	1600	White	90+	Low	Good
				By-Product Abrasives					
Boiler Slag	7	Angular	2.8	85	1400	Black	Nil	High	Poor
Copper Slag	8	Angular	3.3	110	1800	Black	Nil	Low	Good
Nickel Slag	8	Angular	2.7	85	1400	Green	Nil	High	Poor
Walnut Shells	3	Cubic	1.3	45	720	Brown	Nil	Low	Poor
Peach Shells	3	Cubic	1.3	45	720	Brown	Nil	Low	Poor
Corn Cobs	4.5	Cubic	1.3	30	480	Tan	Nil	Low	Good
				Manufactured Abrasives					
Silicon Carbide	9	Angular	3.2	105	1700	Black	Nil	Low	Good
Aluminum Oxide	8	Blocky	4.0	120	1900	Brown	Nil	Low	Good
Glass Beads	5.5	Spherical	2.5	100	1600	Clear	67	Low	Good
Crushed Glass	6 to 8	Irregular	2.5	63 to 91	1000-1500	Gray	67	Low	Poor
Sodium Bicarbonate	2.5	Powder	2.2	60	960	White	Nil	None	Poor
Sponge	0.016	Granular	0.29-1.45	5 to 25	80 to 400	Various	Nil	Low	Good
Plastic Beads	3.5	Blocky		55	880	Various	Nil	Low	Fair
Dry Ice	Nil	Cylinder	62.4	50	800	White	Nil	Low	Poor

6.1.1 Hardness: Metallic abrasive hardness is measured on the Rockwell C scale while non-metallic abrasive hardness is measured on the Mohs scale. Hardness is important because the harder an abrasive, the deeper the profile it is likely to generate.

6.1.2 Size: Specifications may include abrasive sieve size designation, because particle size plays a major role in productivity and in the subsequent profile generated. The role of abrasive size will be discussed in more detail under the section dealing with productivity.

6.1.3 Shape: Abrasive particles range from spherical to sharply angular. Spherical to rounded particles clean by impact, producing a peened surface. Angular to irregularly shaped particles clean by scouring or cutting the surface, producing an etched surface.

6.1.4 Bulk Density: The bulk density of an abrasive is a measure of an abrasive's weight per unit volume and is usually expressed in kilograms per cubic meter or pounds per cubic foot. For example, the bulk density of sand is approximately 160 km/m^3 (100 lb/ft^3) whereas for steel grit abrasives, it is typically 400 km/m^3 (250 lb/ft^3). Bulk density is important when lifting abrasive filled bulk containers. Using the bulk density values for sand and steel shown above, a 2.8 m^3 (100 ft^3) container filled with sand weighs 4500 kg (5 tons), whereas the same container filled with steel grit weighs 11,000 kg (12.5 tons).

6.1.5 Friability/Waste Generation: Abrasive friability is a measure of an abrasive's resistance to breakdown on impact. The more friable an abrasive, the greater the tendency for the abrasive to breakdown on impact, thereby generating more waste and dust.

6.1.6 Recyclability: Recyclability is a property of an abrasive that allows it to be reused many times without excessive breakdown. In order to meet the strict cleanliness requirements for recycling, the abrasive must also be able to withstand the rigorous cleaning process for removal of contaminants from the abrasive mix. Most mineral and byproduct abrasives can be recycled 1 to 3 times, but they have difficulty meeting the strict cleanliness requirements for recycling. Metallic abrasives, on the other hand, show the lowest friability, generate the least amount of waste, can be recycled many times, and meet the strict cleanliness requirements for recycling. Usually, the greater the hardness of a metallic abrasive, the more quickly it breaks down and the fewer times it can be recycled.

6.2 FACTORS AFFECTING SURFACE PROFILE: Surface profile is a measure of surface roughness resulting from abrasive blast cleaning. The height of the profile produced on the surface is measured from the bottoms of the lowest valleys to the tops of the highest peaks.

The thickness and generic type of paint to be applied determines the allowable minimum and maximum profile height. The abrasive size is then chosen to achieve that profile. SSPC-AB 1, "Mineral and Slag Abrasives," defines five abrasive grades yielding profile heights from 13 to 150 micrometers (0.5 to 6.0 mils).

6.2.1 PROFILE HEIGHT: SSPC studies have shown that metallic abrasives larger than those which will pass through a 16 mesh sieve (ASTM E 11) may produce a profile which is too deep to be adequately covered with a single coat of primer. Accordingly, it is recommended that the use of larger abrasives be avoided whenever possible. However, when heavy mill scale or rust are present, abrasives of a larger size may be needed. In these cases two coats of primer may be needed instead of the usual one coat. Alternatively, if the nozzle pressure is

TABLE 6
APPROXIMATE PROFILE HEIGHT OF BLASTED STEEL
USING DIFFERENT SIZE ABRASIVES*

ABRASIVE	Profile Height 25 μm 1 mil	 37μm 1.5 mil	 50 μm 2 mil	 63 μm 2.5 mil	 75-100 μm 3-4 mil
Silica Sand	30/60 mesh	16/35 mesh	16/35 mesh	8/35 mesh	8/20 mesh
Steel Grit	G80	G50	G40	G40	G25
Steel Shot	S110	S170	S280	S280	S330
Garnet	80 mesh	36 mesh	36 mesh	16 mesh	16 mesh
Aluminum Oxide	100 grit	50 grit	36 grit	24 grit	16 grit

* These profile heights are typical if the nozzle pressure is between 620 and 700 kPa (90 and 100 psi).

increased, a smaller size abrasive may remove heavy paint or scale more effectively than a larger abrasive at the lower pressure. Higher nozzle pressures may still produce larger profiles.

Table 6 gives the range of maximum and average maximum profile heights to be expected under normal good operating conditions (wheel and nozzle). At nozzle pressures in excess of 760 kPa (110 psi), the profile may be significantly higher.

Profile comparators are available to aid in estimating the average maximum profile of surfaces blasted with sand, steel grit, and steel shot. Surface profile can also be measured by use of replica tape. Methods for measuring profile are described in ASTM D 4417, "Test Method for Field Measurement of Surface Profile of Blast Cleaned Steel" and in NACE RP0287, "Field Measurement of Surface Profile of Abrasive Blast Cleaned Steel Surfaces Using a Replica Tape." A report, "Surface Profile for Anti-Corrosion Paints," (SSPC 74-01), is available from SSPC describing methods of measuring profile and relating profile to blast cleaning conditions and to coating performance.

When the abrasive media impacts the surface it creates surface profile. It is this profile (or "anchor pattern") that is necessary for most coating systems to adhere to the substrate. The depth of the profile is controlled by the following parameters:

- Abrasive Size: The larger the abrasive, the larger the profile.
- Abrasive Type: Angular abrasives create a deeper profile than round abrasives of the same size.
- Hardness: The harder the abrasive the deeper the profile.
- Blast Nozzle Air Pressure: The higher the nozzle pressure the deeper the profile.
- Type of Blast Nozzle: A venturi nozzle generates a deeper profile than a straight bore nozzle with the same diameter opening.
- Distance of Blast Nozzle to Surface: The closer to the work the deeper profile.
- Angle of Blast Nozzle to Surface: The greater the angle from the perpendicular to surface, the less the profile.

Altering any of these parameters during the blasting operation could affect profile and surface cleanliness. To avoid undesirable changes in profile and surface cleanliness, blasting trials are recommended before changing any of the parameters noted above.

A small abrasive can produce larger profiles if the impact velocity is increased by either increasing the wheel speed or increasing nozzle pressure. If a small abrasive is used, there will be more impacts per pound of abrasive than if a larger abrasive is used. The abrasive must be large enough to remove the rust and mill scale present. The rule of thumb is to use the smallest abrasive that will do the job.

6.2.2 PROFILE TEXTURE (ROUGHNESS): A 2 mil profile produced by a round abrasive (steel shot) will have a different texture than a 2 mil profile produced by an angular abrasive (steel grit), Similarly, a surface blasted with a small abrasive at a high pressure may have the same profile height as a surface blasted with a large abrasive at a lower pressure, but the small abrasive will produce more peaks. Coating systems may have measurably different performance characteristics over these two types of surface. For example, the angular profile produced by grit is required for metallizing (see SSPC-CS 23.00/AWS C2.23/NACE No. 12).

Shot produces a surface composed of rounded craters. Grit produces a more irregular surface with many smaller peaks between adjacent large peaks. It is only the tallest peaks and lowest valleys that determine the profile height. Nonmetallic abrasives create profiles with the maximum amount of roughness.

The surface roughness can be measured quantitatively with a stylus instrument (e.g., a profilometer). This is a device that drags a needle across about an inch (2.5 cm) of the surface and electronically computes the distance between the highest peak and the lowest valley, the number of peaks, and the average peak height. Laser versions are also available.

The rougher the profile (the more peak/valleys) the more metal/paint interface is available for bonding. However, if the valleys are too deep and narrow, the coating may not be able to penetrate to the bottom of the valleys, thereby leaving a void at the bottom of the pits. Rough surfaces can be advantageous if the coating is able to completely wet the surface.

6.3 PARAMETERS THAT AFFECT PRODUCTIVITY: Factors such as initial steel condition, specified degree of cleaning, and accessibility are job specific. Eleven controllable parameters that affect the productivity of abrasive blast cleaning are described below.

6.3.1 Particle Size: Decreasing abrasive particle size can dramatically increase cleaning rate. Increasing abrasive particle size may be necessary to remove heavy coatings and scale. The general rule is to use the smallest size abrasive that will do the job.

6.3.2 Hardness: Generally, the harder the abrasive, the better it will perform. However, very hard abrasives shatter on impact expending most of their energy in particle breakdown and dust generation. As with selecting abrasive size, the general rule is to select the minimum abrasive hardness that will effectively do the job.

6.3.3 Shape: Rounded particles are most effective in removing brittle coatings such as mill scale, whereas angular or irregular shaped particles are more effective in removing softer coatings such as rust and paint.

6.3.4 Specific Gravity: The higher the specific gravity, the more energy a given size abrasive particle will impart to the surface on impact, thereby increasing productivity. Generally, a higher specific gravity implies a higher bulk density.

6.3.5 Nozzle Pressure: The higher the nozzle pressure the more productive the blast operation. For example, for each 7 kPa (1 psi) increase there is a 1.5 percent increase in productivity. Most equipment for dry abrasive blasting has a practical upper limit of 1000 kPa (150 psi).

6.3.6 Nozzle Type: It is important to choose the right nozzle for the job. For example, straight bore nozzles give a tight blast pattern that is best suited for blast cleaning small areas such as handrails, spot blasting, weld seams, etc. Venturi bore nozzles create a wide blast pattern and are best suited for large area blast cleaning. Venturi bore nozzles increase nozzle velocity by as much as 100% and therefore are 35% more efficient compared to straight bore nozzles of the same diameter.

6.3.7 Nozzle to Surface Distance: For optimum cleaning rate the nozzle to surface distance is around 46 cm (18 in). However, this distance can vary depending on the type of surface contamination being removed, nozzle pressure, abrasive type, and nozzle type.

6.3.8 Impact Angle: An 80 to 90 degree angle is best suited for removing mill scale or heavy rust and for cleaning pitted areas; a 45 to 60 degree angle is best for peeling heavy layers of paint or rust; a 60 to 70 degree angle is recommended for general cleaning. Operator technique in controlling the motion of the nozzle determines the impact angle at any instant.

6.3.9 Abrasive Metering: Each abrasive type has a different optimum flow rate through the metering valve. Before starting any blast cleaning job, it is important to conduct a test blast with the metering valve set at lean, moderate, and high abrasive flow rates to find the optimum flow for the given abrasive.

6.3.10 Abrasive Cleanliness: A clean, dry, dust-free abrasive is essential for optimum productivity. Check the abrasive before starting a job and regularly thereafter for foreign matter, moisture, and dust.

6.3.11 Embedment: Some abrasive products, particularly non-metallics, tend to embed in the blast cleaned surface. Conduct a test blast with the abrasive and evaluate the blast cleaned surface to be sure the amount of embedment does not exceed the job specification requirements.

6.4 ABRASIVE TYPES: Abrasives, the material in the blasting operation that does the work, can be divided into two major categories: metallic, generally ferrous, abrasives and non-metallic abrasives. The non-metallic abrasives can be further subdivided into naturally occurring, by-product, or manufactured abrasives.

6.4.1 Metallic Abrasives: Steel shot consists of nearly spherical particles of steel obtained by granulating a molten stream of metal with water, air, or other methods. Steel shot will generally conform to SSPC-AB 3 "Ferrous Metallic Abrasive" in terms of hardness, chemical composition, size, and microstructure.

Cast steel grit consists of angular particles produced by crushing steel shot (SAE J827). Steel grit is available in a wide range of hardness, from 30 to 66 on the Rockwell C scale (R_c), produced by varying the tempering time cycles to which the grit is subjected. Generally, three hardness ranges are most commonly produced: 40 to 50 R_c, 55 to 60 R_c, and 60 to 66 R_c. The first two hardness ranges are used for structural steel, and the latter is used primarily for selective application where deep, consistent, sharp etched finishes are required, or where moderate etches on extremely hard surfaces are needed.

In addition to steel shot and grit, iron grit may also conform to SSPC-AB 3. Iron abrasive is characterized by high carbon content and hardness typically over 55 R_c. The particle shape requirements for iron grit are less stringent than those for steel grit.

Iron abrasive cannot be recycled as many times as steel abrasive, but it can be recycled many more times than nonmetallic abrasives. Iron abrasive is less costly to purchase than steel abrasive. In situations where full recovery is not possible, such as a bridge containment, iron abrasive has an economic advantage over steel abrasive. Steel abrasive is more cost effective in centrifugal wheel machines in a shop.

Metallic shot will produce a peened surface texture whereas grit produces more of an etched surface texture. The etch becomes more pronounced with increasing abrasive hardness.

Typical applications of various steel abrasives, referring to rust condition classifications described in Section 4.1 are:

- Shot: Commonly used on new steel (rust conditions A and B) to remove mill scale using centrifugal wheel machines
- Grit (40-50 R_c): Most effective on rust conditions C and D, but also commonly used for rust conditions A and B
- Shot/Grit Mixture (Shot 40-50 R_c/Grit 55-60 R_c): Used on new steel to remove both mill scale and rust. Shot/grit mixes demand careful attention and close control of abrasive additions by the operator to maintain the shot/grit ratio.

6.4.2 Non-Metallic Abrasives: Non-metallic abrasives can be categorized as naturally occurring, by-product, or manufactured. Naturally occurring abrasives include silica sand, olivine sands, staurolite and other minerals, flint, garnet, zirconium, and novaculite. Byproduct abrasives include those from smelters (nickel or copper slag) and utility generators (coal or boiler slag) and those from agricultural products (walnut shells, peach shells, or corncobs). Manufactured abrasives include silicon carbide, aluminum oxide, and glass beads.

Commonly used non-metallic abrasives for surface preparation of steel to be painted include silica sand, coal and smelter slags, staurolite, olivine, and garnet. Some countries have banned the use of abrasives with a high free-silica content because of possible health hazards. The U.S. Navy specification MIL-A-22262, "Abrasive Blasting Media, Ship Hull Blast Cleaning," allows the maximum crystalline silica content of the abrasive to be 1.0 percent by weight. This level of silica corresponds to a Class A abrasive as described in SSPC-AB 1, "Mineral and Slag Abrasives."

6.5 BLAST EQUIPMENT: For the most economical production, the appropriate blast cleaning equipment must be used.

6.5.1 Conventional Blasting: Air abrasive blasting equipment has five basic components: air compressor, air hose, blasting machine (sand pot), blast hose, and nozzle. The compressor must be large enough to supply the volume of air needed at the correct pressure, and this depends on factors such as nozzle size, number of nozzles, and length and size of air hose. Nozzles are available in several lengths, designs, sizes of openings, and lining materials. Nozzle lengths of 13 to 20 cm (5 to 8 inches) are generally used for removing tightly adhering rust and scale. Shorter nozzles 8 cm (3 in) or less are more appropriate for use behind beams and in other areas difficult to access using full range of motion.

Where shop cleaning of steel is possible, centrifugal wheel blasting units using recyclable steel abrasive are the most economical. Both centrifugal wheel and air blasting are discussed in detail in Volume 1 of the SSPC Painting Manual.

6.5.2 Vacuum Blasting: Vacuum blast cleaning is less productive than conventional blast cleaning and therefore is typically used for small localized areas. Vacuum blast cleaning can achieve the highest levels of surface preparation while minimizing worker exposure to emissions of dust and debris. The tools must be properly operated and fitted with the appropriate shroud in order to maintain the seal between the blast nozzle and the substrate. Compressed air is used to propel abrasive particles against the surface to be cleaned. The blast nozzle is fitted into a localized containment assembly (surrounding the nozzle only) which is equipped with a vacuum. Dust, abrasive, and old paint are sent to a recycler. The cleaned abrasive is returned for re-use. Aluminum oxide or metallic abrasives such as iron or steel grit or steel shot are commonly used.

6.5.3 Abrasive Blast Cleaning Above 760 kPa (110 psi): Over the last several years many blast cleaning operators have been developing techniques that will allow them to blast clean at nozzle pressures greater than 760 kPa (110 psi). The primary driving force has been dramatic increases in productivity. For every 7 kPa (1 psi) increase in nozzle pressure there is a 1.5 percent increase in productivity. For example, going from 690 to 760 kPa (100 to 110 psi) is a 10 percent increase in nozzle pressure but a 15 percent increase in productivity. Going from 690 to 860 kPa (100 to 125 psi) results in a 38 percent increase in productivity.

Another important advantage of higher nozzle pressures is the ability to use finer abrasives to achieve a given profile. Using finer abrasives means more abrasive impacts per unit time, which translates into faster cleaning and higher productivity. Steel or iron abrasives are recommended for high pressure blasting because they do not break down at these elevated pressures. When using non-metallic abrasives at elevated pressures, much of the energy imparted to the abrasive particles is dissipated in the pulverizing of the abrasive particles, thus, reducing cleaning efficiency and dramatically increasing dust levels.

7. Summary of SSPC Abrasive Standards

7.1 SSPC-AB 1, "MINERAL AND SLAG ABRASIVES": This standard defines the requirements for selecting and evaluating nonmetallic mineral and slag abrasives used for blast cleaning steel and other surfaces for painting. The standard defines two types: 1) natural mineral abrasives, including sand, flint, garnet, staurolite, and olivine; and 2) slag abrasives, including coal slag, copper slag or nickel slag. The abrasives covered by the standard are primarily intended for one-time use without recycling.

The abrasives are also classified based on the crystalline silica content and the profile produced by the abrasive. The surface profile is determined by a blasting test conducted on 60 cm x 60 cm (2 ft by 2 ft) steel plates. Other properties stipulated include specific gravity, hardness, weight change on ignition, water-soluble contaminants, moisture content, and oil content.

For a given abrasive type, the surface profile is determined by the size and shape of the abrasive particles. The abrasive supplier is required to furnish a representative sieve analysis of the abrasive used in the profile determination. This sieve analysis then becomes the typical particle size distribution for subsequent delivery of the abrasive. Additional information on physical properties of non-metallic abrasives is given in Table 5.

7.2 SSPC-AB 2, "CLEANLINESS OF RECYCLED FERROUS METALLIC ABRASIVES": This standard gives the cleanliness requirements for recycled work mix ferrous metallic abrasives. The limits and test methods are given for non-abrasive residue, lead content, water-soluble contaminants, and oil content.

7.3 SSPC-AB 3, "FERROUS METALLIC ABRASIVE": This standard defines the physical and chemical requirements for steel and iron abrasives. Abrasive size is determined by sieve analysis. Abrasive shape, divided into shot or grit, is determined by the percentage of round and elongated particles in a sample. The minimum specific gravity is 7.0 for steel abrasive and 6.8 for iron abrasive. A specified percent of the abrasive must be retained on the appropriate take-out screen after 100 cycles in a durability test. Properties include requirements for carbon, manganese, and phosphorous content as well as conductivity and cleanliness.

8. Wet Abrasive Blast and Waterjetting Methods

Methods of coating removal that involve water may or may not include abrasive. Several wet abrasive blast methods are described in SSPC-TR 2/NACE 6G198, "SSPC/NACE Joint Technical Report, Wet Abrasive Blast Cleaning." The standard for waterjetting without abrasives is the joint surface preparation standard SSPC-SP 12/NACE No. 5, "Surface Preparation and Cleaning of Metals by Waterjetting Prior to Coating." The joint consensus reference photographs are contained in SSPC-VIS 4/NACE VIS 7, "Guide and Consensus reference Photographs for Steel Surfaces Prepared by Waterjetting." SSPC and NACE restrict the terms "blast" or "blasting" to refer to processes that involve abrasives. If no abrasives are present, the preferred terms are cleaning or jetting.

In the past, the term "water blasting" has generically referred to the use of 34 to 170 MPa (5,000 to 25,000 psi) water for cleaning where abrasives may or may not be added. Currently in SSPC, the term "water blasting" indicates that an abrasive has been added to the water stream; it is not used as a defined term in either wet abrasive blast or waterjetting documents.

8.1 WATER CLEANING AND WATERJETTING (WITHOUT ABRASIVE): Contaminants can be removed from a surface with water at pressures from 0.1 to over 300 MPa (15 psi to 45,000 psi). Water cleaning in its most general sense is simply removal of surface contaminants such as dirt, soil, and salts from a surface with liquid water. The definitions of low, high, and ultra-high pressure and the use of "cleaning" compared to "jetting" are based on the nozzle pressure and are related to the water velocity. Pressures below 34 MPa (5,000 psi) are defined as low; pressures above 34 MPa (5,000 psi) are defined as high pressure. The term "jetting" is used when the velocity of the water exceeds 335 m/s (1100 ft/s). That condition occurs around 70 MPa (10,000 psi). The reader is cautioned that different sectors may use the terms "low, medium, or high" at other levels or velocities; for example ASTM E1575 (Standard Practice for Pressure Water Cleaning and Cutting) uses the term "high" for anything above 6.9 MPa (1000 psi). See Table 7.

8.1.1 Degrees of Cleaning: Joint surface preparation standard SSPC-SP 12/NACE No. 5 (waterjetting) defines four degrees of visual cleaning based on the amount of VISIBLE contaminants remaining on the surface. SSPC-SP 12/NACE No. 5 does not relate water pressure nor volume to the degree of visual cleaning.

The appearance of a surface cleaned by water can differ from that of a surface cleaned by abrasive blasting. If the coating to be removed is intact, the resultant surface will look like the original blasted surface, but darker and dull. If the coating is breached or there is rust to be removed, the surface can be mottled or very non-uniform. Every defect is revealed. The surface can show variation in texture, shade, color, tone, pitting, or flaking. A brown-black discoloration of ferric oxide can remain as a tightly adherent thin film on corroded or pitted steel.

Because water cleaning and waterjetting are used in maintenance cleaning, not on new steel, the coating manufacturer should be contacted for details of coating performance over residual paint, rust, and mill scale.

Water cleaning and waterjetting can remove soluble salts. Salts can adversely affect coating performance by causing underfilm corrosion or osmotic blistering. Some claim it may be useful to add a salt remover or rinse aid to achieve the desired nonvisual cleanliness. It is necessary to rinse from the surface any product used in cleaning to achieve the desired level of cleanliness. In all cases, it is recommended that surfaces be tested for nonvisible contaminants after washing and prior to coating to ensure compliance with recommended guidelines or specified limits. A corrosion inhibitor may be added to prevent the formation of flash rust.

8.1.2 Profile: Because waterjetting does not provide an anchor pattern needed for coating adhesion, water cleaning or waterjetting is used primarily for recoating or relining projects where there is an adequate preexisting profile. Water alone, under various pressures, can be used to remove coating materials, deleterious amounts of water-soluble surface contaminants, rust, shotcreting spatter, and surface grease and oil. It can not efficiently remove tight mill scale or tightly adherent magnetite. An existing profile under the paint or rust can be restored down to the bottom of the pits.

8.1.3 Water Consumption: Low pressure water cleaning (LP WC) is often called pressure washing or power washing. Pressure washing of an existing coating is done to remove salts and surface contaminants (chalk, dirt, etc.) prior to "cleaning" the surface for painting. Cleaning steel for coatings can be achieved with water pressures as great as 300 MPa (45,000 psi) or above and water volumes of only 6 to 55 liters (1.5 to 15

TABLE 7
SSPC DEFINITIONS OF WATER CLEANING AND WATERJETTING

Low-Pressure Water Cleaning (LP WC)	Less than 34 MPa (less than 5,000 psi)
High-Pressure Water Cleaning (HP WC)	34 to 70 MPa (5,000 to 10,000 psi)
High-Pressure Waterjetting (HP WJ)	70 to 210 MPa (10,000 to 30,000 psi)
Ultrahigh-Pressure Waterjetting (UHP WJ)	Over 210 MPa (30,000 psi)

gallons) per minute. While pressures up to 700 MPa (100,000) psi are used commercially under controlled situations, in 2004 an upper limit of 340 MPa (50,000 psi) is being used in field cleaning equipment designed for the coatings industry. Caution must be maintained with water cleaning or waterjetting to avoid injuries to personnel and structures.

8.1.4 Equipment: The pumps, nozzles, and access equipment have evolved tremendously since 1990. Vacuum shrouds, remote controls, filtration, and collection, in both manual and non-manual systems, are available. The water stream can be combined with a vacuum system to remove the water from the surface immediately, thereby preventing flash rust. After filtration the water is then recycled. If effluent jetting water is captured for reuse in the jetting method, caution should be used to avoid introducing any contaminants of concern back to the cleaned substrate. Dust emissions are low because the particulates are wetted and do not disperse in the atmosphere. The environmental risk is low as long as the water is properly contained or collected. The rate of coating removal can approach or exceed that of dry abrasive blasting depending on the coating system and the complexity of the structure and project.

8.1.5 Flash Rust: Levels of flash rusting are defined in SSPC-VIS 4/NACE VIS 7, "Guide and Consensus reference Photographs for Steel Surfaces Prepared by Waterjetting." Flash rust and rust bloom are evaluated separately from visual cleanliness prior to recoating. If the surface is cleaned by waterjetting, the uniform rust bloom may not be a problem provided the desired nonvisible cleanliness is achieved and verified by testing. Section 8.3 is a more thorough discussion of flash rusting.

8.2 WET ABRASIVE BLAST CLEANING: The methods, equipment, and other features of wet abrasive blast cleaning are described in SSPC-TR 2/NACE 6G198, "Wet Abrasive Blast Cleaning." Two systems for wet abrasive blast cleaning are described: pressurized water/abrasive blasting, which uses water to propel the abrasive, and air/water/abrasive blasting, which uses compressed air to propel the abrasive. The system processes range from mostly abrasive with a small amount of water to mostly water with a small amount of abrasive.

Wet abrasive blasting is a process that can produce surface cleanliness and anchor patterns (surface roughness) similar to those obtained with dry abrasive blasting. The level of surface preparation specified is the same as if dry abrasive blasting was the process being used, that is SSPC-SP 5, SP 10, SP 6, SP 14, and SP 7. However, because the visual appearance of wet abrasive blasted surfaces is not necessarily the same as the visual appearance of dry abrasive blasted surfaces, inspectors should exercise care and judgment. SSPC-VIS 5/NACE VIS 9, "Guide and Consensus reference Photographs for Steel Surfaces Prepared by Wet Abrasive Blast Cleaning" is a separate visual guide for wet abrasive blasting. Acceptable variations in appearance that do not affect surface cleanliness include variations caused by type of steel, original surface condition, thickness of the steel, weld metal, mill or fabrication marks, heat treating, heat affected zones, blasting abrasives, and differences due to blasting technique.

Surfaces cleaned by wet abrasive blasting typically appear darker and duller in appearance than surfaces cleaned with the same abrasive in dry abrasive blasting. Wide variations in appearance can be observed among abrasives within a given generic class. See SSPC-VIS 1 for illustrative photographs for dry blasting.

When the surface is still damp or wet, it will appear darker, and defects and variations in shading are magnified. As the surface dries, streaks will form which are not necessarily depicted in small unit size photographs, but which can be clearly seen on larger areas.

Wetted abrasive should be removed from the substrate after blasting. This is frequently accomplished with a low pressure water cleaning. Sometimes a soluble salt remover is added to the water. If rust back is of concern, an inhibitor can be added to the water. The coating manufacturer should confirm that the use of additives to the water will not effect coating performance.

8.2.1 Air/Water/Abrasive Blasting: Air/water/abrasive blasting is a cleaning method in which water is injected into the air/abrasive stream generated by conventional air-pressurized abrasive blasting equipment, or in which the premixed abrasive/water combination is forced into the blast air stream generated by a conventional air compressor. Other generic terms to describe specific air/water/abrasive blast cleaning methods are water shroud blasting, wet-head blasting, wet blasting, low volume water abrasive blasting, water induction nozzle (WIN), and slurry blasting.

Water helps to remove contaminants from the substrate, to wet the abrasive, and to substantially reduce dispersion of fine particulates (dust). Particulates are often caused by the breakup of the abrasives, surface corrosion products, and paint if the surface has been previously painted. Dust suppression is achieved by thoroughly wetting the abrasive and other particles to encapsulate them with a thin film of moisture. The objective is to suppress the dusting effect caused by the impact of the abrasive on the substrate, while retaining the blasting characteristics of dry abrasive, including creation of an anchor profile. The amount of water varies; removal of salts is a secondary objective.

The equipment used for wet abrasive blasting generally consists of conventional dry abrasive blasting equipment supplemented with modules to inject water into the abrasive stream, or specialized equipment that creates an abrasive/water slurry that is forced into the compressed blast air stream. Several methods exist for introducing water into the air stream. With radial water injectors (water rings), water induced nozzles, and coaxial water injectors, water is injected near the blast nozzle.

A hybrid process sometimes called AIWB, abrasive injected water blasting, was introduced after SSPC-TR 2/NACE 6G198 was published. This AIWB process mixes a conventional abrasive air stream with water jets up to 240 MPa (35,000 psi) at the nozzle. The volume of abrasive can be varied. It mixes a conventional abrasive air stream using 0.2 to 1.1 kg/min (0.5 to 2.5 pounds/min) with the water jet stream up to 240 MPa (35,000 psi) at the nozzle. It uses both a conventional fluid pump and a compressed air stream and produces a diffuse spread pattern.

With slurry blasters, the water is injected into the air/abrasive stream at some point substantially upstream from the blast nozzle or at the abrasive hopper, rather than at the nozzle. In the low volume, low pressure water abrasive blasting system (LV LP WB), four parts of abrasive are wetted with one part of water in a hopper. This slightly wetted abrasive slurry is carried in a conventional compressed air stream and produces results very similar to dry abrasive blasting. There is minimal water run-off.

8.2.2 Water/Abrasive Blast Cleaning: The methods, equipment, and other features of water/abrasive blast cleaning are described in SSPC-TR 2/NACE 6G198, "Wet Abrasive Blast Cleaning." Water/abrasive blast cleaning is a cleaning method in which abrasive is injected into the water stream generated by conventional fluid pumps. Other generic terms to describe specific water/abrasive blast cleaning methods are slurry blasting, abrasive water jet (AWJ), or abrasive injected waterjetting/blasting (AIWJ), abrasive injected ultra-high pressure (UHP AB), high pressure abrasive blast (HP AB); low pressure abrasive blast (LP AB).

The typical devices used for this method of cleaning consist of a fluid pump with a venturi nozzle of some type in which the water flow draws the abrasive into the water stream or the abrasive media is injected into the water stream under pressure. The addition of expendable abrasives to high pressure water jets improves the productivity of the technique, enables the removal of intact materials, and facilitates the creation of a surface profile.

Because the fluid stream is well defined, these devices usually cut a narrow blast pattern. The hybrid system described in 8.2.1, a rotating injection nozzle designed for pressure washers, and the UHP AB systems produce diffuse spread patterns.

8.3 FLASH RUST AND RUST BLOOM: Steel that is cleaned with water can rust rapidly. The rate of re-rusting will depend on the purity of the water, the amount of oxygen dissolved in the water, the amount and type of ions (chloride, sulfate, etc.) left on the surface, the temperature, and the drying time. In 1991, G.C. Soltz reported that steel will not rust in 100% relative humidity if all of the salts are removed. [G.C. Soltz, "The Effects of Substrate Contaminants on the Life of Epoxy Coatings Submerged in Sea Water," National Shipbuilding Research Program, March 1991.] This is true, but when water condenses on the surface, the steel rusts. In practical terms, tap water, rainwater, pond water, and the water that is typically found in nature or used for cleaning will contain soluble materials and dissolved oxygen. Soluble salt removers and/or inhibitors can be added to the water during the cleaning process to reduce the potential of flash rusting (see Section 8.4). The use of low conductivity water with the removal of all salts (as measured by field tests) will significantly reduce the amount of flash rust. The amount of flash rust also can be significantly reduced with the addition of forced air drying or use of a vacuum shroud which does not allow the water to remain on the surface as it is drying.

Flash rust and rust bloom are often used interchangeably. However, all rust bloom is not flash rust. Rust bloom is usually thought to be somewhat uniform rust spread evenly over a large section of the surface. This condition can occur on both wet or dry blast cleaned steel and can take days to develop. The distinguishing feature of flash rust is that it occurs within minutes or hours of cleaning. Flash rusting can form quickly to change the initial appearance. It is not the rust itself, but the source of the re-rusting that is of concern to the coating manufacturers, as inert iron oxides (rust) are used as pigments. Very dark, splotchy rust spots which appear to be isolated in localized areas usually indicate that spots of salt contaminant are left in pits, under metal lips, or in crevices. These non-visible contaminants are found to be detrimental to coating performance. A light, easily removed rust bloom is considered inert and a sign of general steel oxidation. Coating manufacturers have concerns about performance when their coatings are applied over loose dust or loose rust. The level of rust bloom that can be tolerated in a given environment must be determined for each coating system by the coating manufacturer.

Flash rusting is not addressed in the dry abrasive blast cleaning standards except in the notes. Re-rusting of dry abrasive blasted steel, as there is little moisture present in the preparation process, can be a sign that non-visual contaminants have been left on the steel, which is generally not acceptable to the coatings manufacturers. G.C. Soltz has found that, for abrasive blasting, coating the surface before it has re-rusted is no assurance that the coating performance will not be compromised. [G.C. Soltz, "Understanding How Substrate Contaminants Affect the Performance of Epoxy Coatings & How To minimize Contamination," SSPC 1998 Proceedings, "Increasing the Value of Coatings", p 208-219.] The Journal of Protective Coatings and Linings (JPCL) has other articles published on this subject.

Flash rusting by water is addressed in SSPC-VIS 4/NACE VIS 7, "Guide and Consensus reference Photographs for Steel Surfaces Prepared by Waterjetting." The consensus reference photographs depict steel with light, medium, or heavy flash rusting prior to re-coating. Depending on the particular coating and exposure environment, the coating manufacturer may allow flash rusting at one of these levels. The SSPC report, "Maintenance Coating of Weathering Steel," (92-08), found that coatings can perform quite well over a blasted surface that has a uniform rust bloom.

8.4 INHIBITORS AND SALT REMOVERS: To some extent, the surface preparation industry does not always distinguish clearly between rust inhibitors and salt removers. If salts are removed, the corrosion rate is reduced because the strength of the electrolyte in the corrosion cell is decreased. An inhibitor generally retards the reaction of oxygen or oxidizing agents with iron. Inhibitors and/or soluble salt removers can be added to the pressurized cleaning water or to a rinse water to temporarily prevent rust formation.

Environmental and health concerns in recent years have prompted changes in the chemistry of rust inhibitors. The chemical components of rust inhibitors includes polyphosphates, volatile amines, benzoates, nitrites, surface tension reducers, organic acids, chelating agents, and other proprietary compounds. These can also be included in the formulation of water-borne paints to reduce rust bloom. Additives containing soluble salts or film formers, while providing short-term protection, can adversely affect the long-term performance of the coating system.

Chemical rinse aids range from very acidic to neutral to basic. The product literature normally focuses on the perceived benefits of the materials, and not on the chemistry. The material safety data sheet will generally list the pH.

If an additive is used in the water, it is imperative that the coating manufacturer be queried about the compatibility of the coating with the water additive such as an inhibitor or soluble salt remover. Some coatings manufacturers will accept the compatibility process in ASTM D 5367, "Practice for Evaluating Coatings Applied over Surfaces Treated with Inhibitors Used to Prevent Flash Rusting of Steel When Water or Water/Abrasive Blasted." Other coatings manufacturers prefer their own in-house test methods. At the present time many coatings manufacturers prefer placing their coatings over a clean, light flash rust whose origin is not in question rather than adding the uncertainty of an inhibitor, chemical rinse aid, or soluble salt remover.

9. Other Cleaning Methods

9.1 CHEMICAL STRIPPING: Paint strippers are frequently used to remove paint from industrial structures. Alkaline strippers are more effective in removing oil-based paints, and solvent type strippers are more effective in removing latex paints. It may be necessary to use both types to strip alternating layers of oil and latex coatings from a surface. Strippers usually contain a thickener to provide more contact time for solvent or chemical attack on the paint. Some are covered with a sheet of plastic to increase the contact time. Chemical stripping is one method of removing old, lead-containing paint.

An alkaline (caustic) based or solvent based chemical stripper is applied to the surface using trowels, brushes, rollers, or spray application. After the specified dwell time, the stripper is removed using traditional scrapers, although water cleaning or ice blasting can be used. Mill scale and rust are not removed, and a profile is not generated, but an existing profile can be restored.

A relatively new class of chemical strippers are selective adhesion release agents (SARA) based on alcohol hydroxy-carboxylic acid peroxide (AHP). These are slow acting but are environmentally friendly. A permeable cloth can be placed on the ground at the base of the structure to collect the paint debris, while the stripper can be absorbed into the ground. SARA strippers do not work well on highly cross-linked novolac epoxies, rigid urethanes, and vinyl esters, but they are useful in removing alkyds, latexes, polyurethanes, epoxy esters, and amine and polyamide epoxies.

The specific type of stripper must be selected based upon the generic type of the existing coating system as well as health, safety, and environmental concerns. Some of the strippers require a minimum four hours set time while others may require two full days. In addition, many of the solvent strippers involve chemical reactions which generate heat. This heat must be contained in order for the chemical reaction to continue, which may require covers if ambient temperatures are too low. Many paint strippers are available for the complete immersion of painted surfaces, but these are generally specialty items.

Once the strippers have performed the desired softening of the existing coating system, they are frequently removed by a scraper. Water cleaning or ice blasting methods increase the volume of waste due to the addition of the water. Even for the removal of non-lead containing coatings, the resulting waste stream may be classified as hazardous due to either the caustic or the solvent component. Information on chemical stripping can be found in the technology update SSPC-TU 6, "Chemical Stripping of Organic Coatings from Steel Structures" and in Volume 1 of the SSPC Painting Manual.

9.2 SODIUM BICARBONATE (BAKING SODA) BLAST CLEANING: A relatively new, low-dusting method of blast cleaning uses a slurry of water and sodium bicarbonate, a water soluble non-reactive salt, to remove paint from a surface. The portable unit can be wheeled from one location to another. Once in place, the system requires a source of compressed air (typically 600-700 kPa [85-100 psi] at the nozzle), clean water, and drainage. In most cases, special ventilation or dust collection is unnecessary. The operator can vary the angle of attack, standoff, and dwell time to strip layer by layer or all at once.

This blast medium is a formulation of sodium bicarbonate and is free from silica dusts and toxic fumes. The medium is claimed to be effective in:

- removing surface rust from screws and other metal parts without imbedding itself into the material being stripped
- removing coatings down to the metal or one layer at a time
- controlling layer removal, allowing for an extra measure of safety when used on galvanized or other specialty protected metals
- removing grease, oil, paint, and dirt from flat or contoured surfaces, cooling towers, motor parts, and hard-to-reach equipment parts.

This system was developed for removal of aircraft coatings and similar materials from surfaces which do not require "profiling". It also reduces dusting.

For blasting alone, productivity depends on the coating being removed and the degree of cleaning. Removal rates can be as high as 11 m^2/h (120 ft^2/h) for removal of thin deteriorated films. Removal of deteriorated thicker films may be much slower, on the order of 2 to 5 m^2/h (20 to 50 ft^2/h). Intact films may not be dislodged using sodium bicarbonate blasting. Sodium bicarbonate blasting is discussed in Volume 1 of the SSPC Painting Manual.

9.3 PLIANT MEDIA BLASTING (SPONGE JETTING): Another low dusting method of cleaning, sponge jetting, involves the use of specialized blasting equipment that propels a manufactured urethane sponge against the surface to be cleaned. The sponge particles are approximately 3 to 6 mm (1/8 to 1/4 inch) in diameter and are available in a mild grade for degreasing and aggressive grades for paint or mill scale removal. The aggressive grades have the sponge formed around an abrasive. Abrasives include staurolite, garnet, and steel grit.

The productivity is lower than traditional abrasive blast cleaning (30-50% of the productivity), but typically will be higher than power tool cleaning to bare metal and vacuum blast cleaning. White metal quality of preparation is possible and a surface profile of approximately 50 micrometers (2 mils) can be achieved. The dust generated is low because the cells of the sponge help to suppress the dust, and the paint tends to be dislodged in larger chips rather than being pulverized, as is the case with traditional abrasive blast cleaning.

9.4 CARBON DIOXIDE (DRY ICE) BLASTING: In this dust free method, liquid carbon dioxide is formed into pellets of dry ice using specialized equipment. The CO_2 pellets are approximately the size of rice. The pellets are conveyed through a blast hose using compressed air in a manner similar to open abrasive blast cleaning. The pellets exit through a specialized nozzle assembly.

An advantage of CO_2 blasting is a reduction in the volume of debris created as the abrasive sublimes upon use. As a result, the waste involves only the paint being removed. Carbon dioxide is also non-conductive and will not create a spark, and therefore can be considered for use in areas where any sparking is unacceptable.

Disadvantages are that the abrasive does not appear to be hard enough to productively remove heavy coatings, rust, or mill scale. More than just stains of old primer will remain on the surface. Tight coatings are difficult to remove without frosting the surface. The equipment is also expensive. Carbon dioxide blast cleaning is discussed in more detail in Volume 1 of the SSPC Painting Manual.

9.5 ELECTROCHEMICAL STRIPPING: A very recent method of paint removal is electrochemical stripping. By applying cathodic current to a painted metal substrate, disbonding of the coating is achieved. The benign electrolyte is contained in a liquid-absorbent material to which a counter electrode is attached. This combination, often combined with a liner, is applied to the painted metal surface, with magnets in the case of steel. If the paint is intact it must be scored to initiate current flow. After electrochemical treatment for 0.5 to 2 hours at 8 to 10 volts, the pads are removed and paint fragments are recovered. No particles become airborne making this method attractive for lead paint removal.

Banks of conducting pads may cover an area up to 14 m^2 (150 ft^2) and can be run simultaneously. This method was developed particularly for application on highway structures to remove lead based alkyd-type coatings, but it may be employed for paint removal on other objects. Electrochemical stripping is discussed in more detail in Volume 1 of the SSPC Painting Manual.

10. Film Thickness

It is essential that ample coating be applied after blast cleaning to adequately cover and protect the peaks of the surface profile. The method of measuring dry film thickness (DFT) described in SSPC-PA 2, "Measurement of Dry Coating Thickness with Magnetic Gages," takes into account the effect of surface profile so that the measured DFT is approximately the thickness of the coating over the peaks. Thus, the depth of the surface profile should be considered in determining the amount of coating to be applied. For example, if a 50 micrometer (2 mil) DFT is desired, it will require a larger volume of paint to fill the valleys in a 75 micrometer (3 mil) profile than to fill the valleys in a 25 micrometer (1 mil) profile and still have 50 micrometers (2 mils) over the peaks. Because of the existence of rogue peaks, a greater coating thickness may need to be specified when coating deeper profiles.

11. Consensus Reference Photographs

Note that consensus reference photographs, when used in conjunction with SSPC surface preparation standards, give only an approximation of the final surface condition, because the consensus reference photographs are based on one specific set of steel conditions and cleaning operations. These conditions will not be identical to the conditions faced on other projects. It is cautioned, therefore, that any consensus reference photographs should be considered a supplement to, and not a substitute for, surface preparation standards. The use of consensus reference photographs in conjunction with SSPC standards is required only when they are specified in the procurement document covering the work. It is suggested, however, that consensus reference photographs be specified in the procurement document. Although they will not precisely match the appearance of the steel on every project, they are a valuable aid in establishing the general appearance described by the surface preparation standards, and are especially useful in depicting the relative differences between the various grades.

Even when consensus reference photographs are included in the procurement document, however, it must be recognized that the written standards prevail.

SSPC has consensus reference photographs for degrees of blast cleaning (SSPC-VIS 1), for the amount of rust on a painted surface (SSPC-VIS 2), for hand and power tool cleaning (SSPC-VIS 3), for waterjetting (SSPC-VIS 4), and for wet abrasive blast cleaning (SSPC-VIS 5). Some SSPC consensus reference photographs are jointly issued with NACE (SSPC-VIS 4 and VIS 5) or ASTM (SSPC-VIS 2). Other associations, such as ISO, as well as individual companies, have visual standards. The following sections summarize the SSPC consensus reference photographs.

11.1 SSPC-VIS 1, "GUIDE AND REFERENCE PHOTOGRAPHS FOR STEEL SURFACES PREPARED BY DRY ABRASIVE BLAST CLEANING": SSPC-VIS 1 provides standard consensus reference photographs for seven rust conditions (pre-blast conditions) and five degrees of blast cleaning thoroughness. End conditions corresponding to SSPC-SP 5, 6, 7, 10 and 14 are depicted over four initial unpainted conditions and three painted conditions. SSPC-VIS 1, which contains the actual photographs, is a separate publication (SSPC #02-12); however, a written "Guide to SSPC-VIS 1" is included in this volume. The appendix of SSPC-VIS 1 includes supplementary photographs depicting the appearance of white metal surfaces prepared from alternative non-metallic and metallic abrasives. Additional photographs show the effect of profile height, viewing angle, and diffusion of light.

11.2 SSPC-VIS 2, "STANDARD METHOD OF EVALUATING DEGREE OF RUSTING ON PAINTED STEEL SURFACES": This standard defines a rust grade scale which goes from 10 (no rust) to 0 (totally rusted). SSPC-VIS 2 defines three rust distributions:

- General Rust – consisting of various size rust spots randomly scattered over the surface
- Spot Rust – where the rusting is concentrated in a few large spots
- Pinpoint Rust – where each rust spot is very small and scattered across the surface.

SSPC-VIS 2 consists of 27 color photographs depicting rust grades 1 to 9 for each rust distribution. The photographs were subjected to computer analysis to ensure they illustrate the percentage of rust defined in the written standard. For each color photograph, there is a corresponding black and white image showing only the rusted area. The written description and the black and white images are contained in this volume, and are identical in technical content (though not format) to ASTM D 610. In addition to the text and the black and white images reproduced in this volume, the separate publication SSPC-VIS 2 includes a full color set of 27 photographs that show rust staining and represent a more realistic picture of the painted surface

11.3 SSPC-VIS 3, " GUIDE AND REFERENCE PHOTOGRAPHS FOR STEEL SURFACES PREPARED BY HAND AND POWER TOOL CLEANING": SSPC-VIS 3 provides consensus reference photographs for four grades of hand and power tool cleaning (SSPC-SP 2, 3, 11, and 15) of seven initial conditions of steel (four unpainted and three painted surfaces). The tools used to clean these surfaces include hand and power wire brushes, sanding discs, and non-woven abrasive discs. Needle guns and/or rotary flap peen assemblies were used to create the profile in the surfaces cleaned to SSPC-SP 11 and SP 15.

While a guide to the VIS 3 standard is included in this volume, the color photographs are only available as a separate supplement. Written standards are the primary means to determine conformance with cleaning requirements; photographs should not be used as a substitute for the written standards.

11.4 SSPC-VIS 4/NACE VIS 7, "GUIDE AND REFERENCE PHOTOGRAPHS FOR STEEL SURFACES PREPARED BY WATERJETTING": SSPC-VIS 4 provides consensus reference photographs for six rust conditions (pre-blast conditions) and four degrees of cleaning by waterjetting. End conditions corresponding to SSPC-SP 12: WJ-1, WJ-2, WJ-3, and WJ-4 are depicted over two initial unpainted conditions and four painted conditions. Three levels of flash rusting after cleaning are depicted for two initial rust conditions cleaned to two degrees of waterjetting cleanliness (WJ-2 and WJ-3). SSPC-VIS 4, which contains the color photographs, is a separate publication (SSPC #01-05); however, a written "Guide to SSPC-VIS 4" is included in this volume.

11.5 SSPC-VIS 5/NACE VIS 9, "GUIDE AND REFERENCE PHOTOGRAPHS FOR STEEL SURFACES PREPARED BY WET ABRASIVE BLAST CLEANING": SSPC-VIS 5 provides consensus reference photographs for two rust conditions (C and D) and two degrees of wet abrasive blast cleaning (SSPC-SP 6 and SP 10). Three levels of flash rusting after cleaning are depicted for the two initial rust conditions. SSPC-VIS 5, which contains the color photographs, is a separate publication (SSPC #01-06); however, a written "Guide to SSPC-VIS 5" is included in this volume.

11.6 ISO PICTORIAL STANDARDS: The International Organization for Standardization (ISO) in conjunction with Swedish Standards Institution (SIS) has issued a booklet of reference photographs (ISO 8501-1:1988/SIS SS 05 59 00) depicting the appearance of surfaces prepared by hand and power tool cleaning, abrasive blast cleaning (four degrees) and flame cleaning. The methods of cleaning are depicted over various rust grades of unpainted steel. ISO 8501-2 depicts a similar set of surfaces where the substrate was previously painted steel.

11.7 OTHER PHOTOGRAPHIC STANDARDS: The Production Technical Society (Japan) has printed color illustrations of wash primed and zinc-rich primed steel before and after weathering and re-cleaning. The photographs of the Shipbuilding Association of Japan illustrate the appearance of painted, unpainted, welded, and flame-cut steel before and after various degrees of damage or weathering.

British standard BS 7079 Part A1 is equivalent to ISO 8501-1 (unpainted steel) and BS 7079 Part A2 is equivalent to ISO 8501-2 (previously painted steel).

11.8 PROJECT PREPARED STANDARDS: Prepared steel will often appear different from the photographic standards due to variations in initial surface conditions, abrasives being used, and so forth. Because of difficulties in comparisons, it is sometimes recommended that the contractor prepare blast cleaned samples representative of the steel to be blasted which, by mutual agreement of the owner and the contractor, are representative of the required surface cleanliness and appearance. Suggested dimensions of the reference steel panels are approximately 15 x 15 x 0.5 cm (6 x 6 x 3/16 inch) minimum. The blast cleaned panels should be completely protected from corrosion and contamination, and maintained as reference standards for the duration of the project. As an alternative to test panels, portions of the structure being prepared can be used.

12. Other SSPC Surface Preparation Documents in This Volume

12.1 SSPC-TR 1/NACE 6G194, "JOINT TECHNOLOGY REPORT ON THERMAL PRECLEANING": Thermal precleaning is used in conjunction with other surface preparation methods, such as abrasive blast cleaning, to remove soluble salts from the pits of heavily corroded steel. The oil and gas industry as well as the rail car industry use thermal precleaning extensively. This report describes the parameters used for dry heat and wet heat. It also lists methods for verifying the surface cleanliness.

12.2 SSPC-TR 2/NACE 6G198, "JOINT TECHNICAL REPORT ON WET ABRASIVE BLAST CLEANING": This document covers procedures, equipment, and materials involved in a variety of air/water/abrasive, water/abrasive, and water-pressurized abrasive blast cleaning systems. Various types of wet blast systems are described and compared. SSPC-TR 2 discusses selection of abrasives, water delivery systems, inhibitors, and equipment operation and maintenance. (See Section 8.2.)

12.3 SSPC-TU 2/NACE 6G197, "INFORMATIONAL REPORT AND TECHNOLOGY UPDATE: DESIGN, INSTALLATION, AND MAINTENANCE OF COATING SYSTEMS FOR CONCRETE USED IN SECONDARY CONTAINMENT": This report covers the design, installation, and maintenance of polymeric coating systems that are applied and directly bonded to concrete in secondary containment applications. This report is intended to inform manufacturers, specifiers, applicators, and facility owners who are required to contain chemicals and/or protect concrete in these applications.

A chemical resistant coating is often applied to concrete to extend the service life of the secondary containment structure and properly contain the chemicals. This report focuses on those aspects of the design, materials, and procedures that are specific to coating for concrete in secondary containment applications, making reference to other publications when appropriate. While there are numerous successful commercial products and designs for containment of chemicals, this report focuses on concrete structures that are coated with thermoset polymer coating systems. Other potentially effective containment systems, such as acid-resistant brick and thermoplastic liners, are not described in this report.

12.4 SSPC-TU 4, "FIELD METHODS FOR RETRIEVAL AND ANALYSIS OF SOLUBLE SALTS ON SUBSTRATES": This technology update describes methods for estimating the amount of soluble salt on a surface. Two types of retrieval methods, the cell method and the swabbing or washing method, are applicable to field retrieval. The "total" extraction method involves immersion of the surface in boiling water and, hence, is useful only in a laboratory.

SSPC-TU 4 gives detailed procedures for obtaining a liquid sample and for analyzing it to determine the level of soluble salt. Test kits are available to simplify the extraction and analysis. The SSPC standard on waterjetting, SSPC-SP 12, defines three levels of soluble salt contamination or non-visible surface cleanliness.

12.5 SSPC-TU 6, "CHEMICAL STRIPPING OF ORGANIC COATINGS FROM STEEL STRUCTURES": This document defines chemical strippers and discusses their use for removing conventional organic coatings from steel structures. Chemical stripping involves application of a chemical to existing paint, allowing it to dwell for a period of time to attack the organic binder, removing bulk paint/stripper residues, and properly cleaning the steel substrate prior to repainting. This technology update describes methods used to identify the type of stripper that will work most effectively, and typical application and removal options. It also presents containment and disposal options for stripper wastes. Chemical stripping is also discussed in Volume 1 of the SSPC Painting Manual.

13. Non-SSPC Cleaning Standards

The recommendations, standards, and guides of a number of other associations reference the SSPC surface preparation standards, including: American Association of State Highway and Transportation Officials (AASHTO); American Institute of Steel Construction (AISC); American Iron and Steel Institute (AISI); American Petroleum Institute (API); American Railway Bridge and Building Association (ARBBA); American Water Works Association (AWWA); Canadian Institute of Steel Construction (CISC); Painting and Decorating Contractors of America (PDCA); Steel Plate Fabricators Association (SPFA);

and the Texas Structural Steel Institute (TSSI). They are also used by many state highway departments and other federal, state, and local agencies.

Governmental agencies have been active in preparing good surface preparation specifications, but most of these deal with thin metal and do not particularly apply to structures. The US Army Corps of Engineers Civil Works Division has issued CW-09940, "Guide Specifications for Painting Hydraulic Structures and Appurtenant Works." This specification covers the cleaning and treating of structural steel as well as the application of paint and the paints to be used. It makes use of the SSPC surface preparation standards.

Federal Specification TT-C-490, "Chemical Conversion Coatings and Pretreatments for Ferrous Surfaces (Base for Organic Coatings)," covers various types of surface preparation and pretreatments.

For internal use, the U.S. Department of the Navy, Naval Sea Systems Command, has prepared Chapter 631, "Preservation of Ships in Service (Surface Preparation and Painting) NAVSEA-S9086-VD-STM-OOOC/H-631," which includes surface preparation standards in addition to painting specifications and paint systems. Detailed specifications for pickling are included.

The International Organization for Standardization (ISO) has included written definitions and photographs depicting the appearance of uncoated steel surfaces cleaned by flame cleaning (ISO 8501-1:1988). This book also includes photographs for uncoated steel surfaces cleaned by hand and power tools and by abrasive blasting. A parallel standard ISO 8501-2 depicts degrees of cleaning over previously painted surfaces.

The British Standards Institution standard BS 7079:Parts A1 and A2, "Preparation of Steel Substrates Before Application of Paints and Related Products" is essentially equivalent to ISO 8501-1 and ISO 8501-2.

14. Surface Preparation of Concrete for Coating

14.1 INDUSTRY STANDARDS: There are several relatively new SSPC publications for surface preparation and coating of concrete included in this volume:

- SSPC-SP 13/NACE NO. 6, "Surface Preparation of Concrete"
- SSPC-TU 2/NACE 6G197, "Informational Report and Technology Update: Design, Installation, and Maintenance of Coating Systems for Concrete Used in Secondary Containment"
- SSPC-TR5, "Design, Installation, and Maintenance of Protective Polymer Flooring Systems for Concrete"
- SSPC-PA 7, "Applying Thin Film Coatings to Concrete"

  SSPC-TU 10, "Procedures for Applying Thick Film Coatings and Surfacings Over Concrete Floors"
- SSPC publication #04-03 "Surface Preparation and Coating of Concrete" is a compilation of SSPC documents taken from Volumes 1 and 2 of the SSPC Painting Manual, The Inspection of Coatings and Linings, and SSPC 2003 technical presentations.

The International Concrete Repair Institute (ICRI) has defined nine concrete profiles, thirteen methods of achieving them, and five different coating thickness ranges. ICRI has also developed a set of rubber replica specimens for the nine different profiles. These rubber replicas and the accompanying document, ICRI Guideline No. 03732, "Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays," are available from SSPC. NACE and ASTM have also issued standards on surface preparation, repair, coating, and inspection of concrete. These are referenced in the SSPC documents listed above.

14.2 METHODS OF CLEANING CONCRETE: Concrete may be cleaned by many of the same methods used to clean steel for painting. However, care must be exercised so as not to damage the concrete surface. Concrete may be cleaned with detergent/power washing, alkaline or steam cleaning, chemical cleaning, abrasive blasting, high-pressure water cleaning, or mechanical cleaning with pneumatic tools, scarifiers, grinders, and scabblers. Efflorescence must be removed from cementitious surfaces by dry wire brushing or other mechanical means before any washing occurs. Water will merely dissolve the efflorescence and force it into the concrete.

15. Surface Preparation of Other Metallic Surfaces

15.1 ALUMINUM: Because aluminum is soft and chemically reactive, special precautions must be exercised when preparing an aluminum surface for painting. Chipping hammers and scrapers tend to gouge the soft aluminum. Wire brushes work well on aluminum, but they must have stainless steel bristles, not carbon steel or copper. Abrasive mats, paper, and cloths can be used to remove corrosion products or to feather the edges of intact paint. However, these materials should not be used on any other type of surface to prevent cross contamination of the aluminum. Aluminum wool may also be used for cleaning.

Abrasive blast cleaning can be performed on aluminum if the abrasive and blasting pressure are chosen correctly. The most common situations are 80-grit aluminum oxide (alumina, corundum, or emery) or garnet at 410 - 480 kPa (60 - 70 psi). Ferrous abrasives should never be used. Alternative media for cleaning aluminum include pliant media (sponges), plastic pellets, agricultural abrasives (corn cobs, walnut shells, peach pits), glass beads, sodium bicarbonate (baking soda), and carbon dioxide (dry ice). Chemical stripping has been used on aluminum in situations where blasting is not feasible. Care must be exercised to use a striper that does not attack the aluminum.

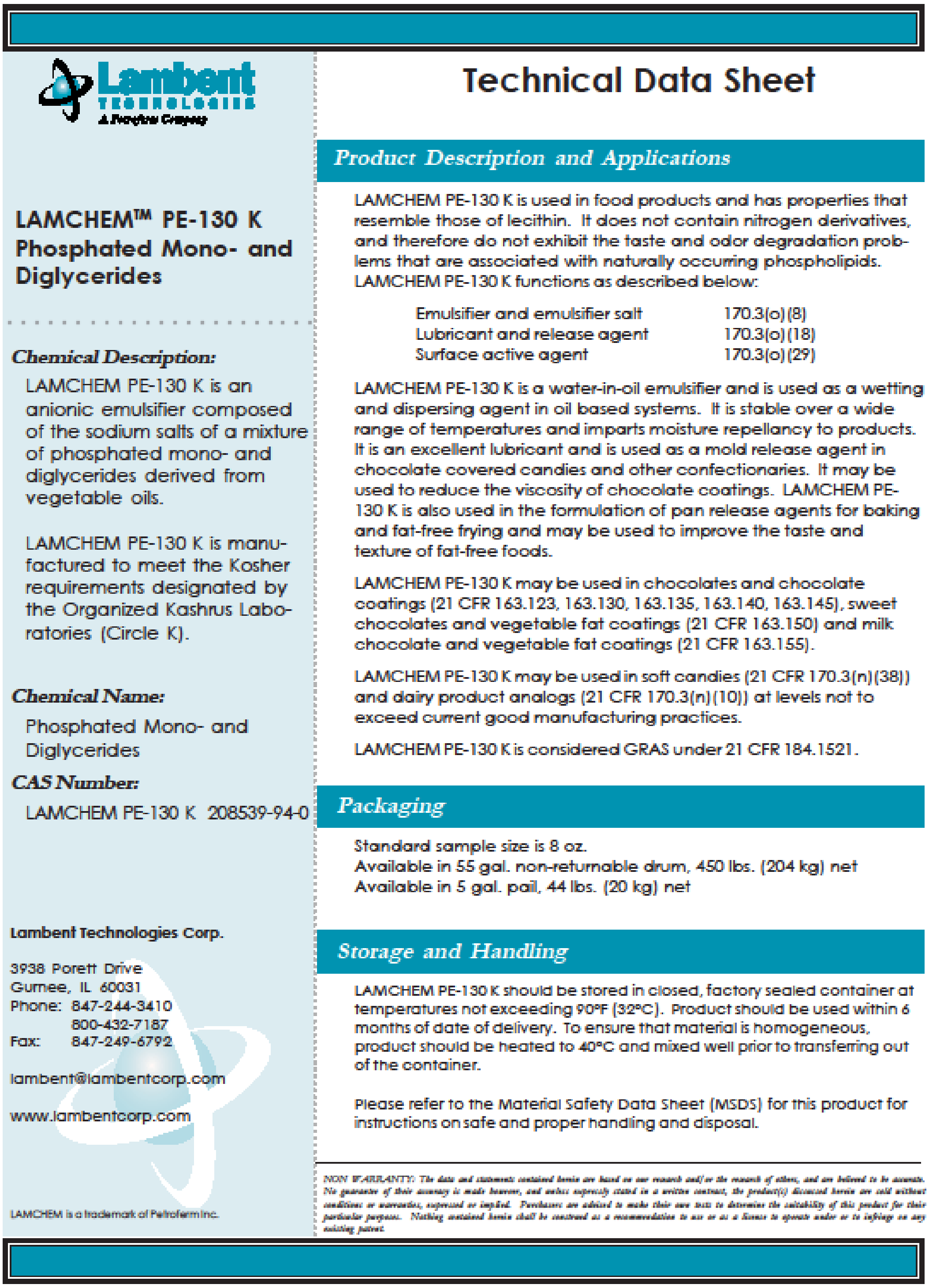
Waterjetting provides another option for cleaning aluminum. Usually, if a profile is desired and an existing profile does not exist, abrasive is added to the water. Because aluminum is a soft metal, high-end ultra-high pressure waterjetting can impart a profile without an abrasive, although it will appear differently from a profile created using abrasives.

15.2 STAINLESS STEEL: As with aluminum, care must be taken to avoid contaminating the stainless steel with carbon steel or iron. Hence, common steel shot and grit are not used to blast stainless steel. A hard non-metallic abrasive such as aluminum oxide or garnet is commonly used. Because stainless steel is hard, reducing the blast pressure is not necessary.

The most common painting problem associated with stainless steel is lack of adhesion. Some contribute this to the protective oxide film that forms on the surface. A blast profile increases the effective surface area to promote chemical bonding. An acid-etching vinyl butyral wash primer, SSPC-Paint 27, is sometimes used to promote adhesion.

15.3 COPPER ALLOYS: Most copper, bronze, or copper alloy substrates come in the form of pipes, valves, pumps, strainers, heat exchangers, and statues. As with all metallic surfaces, solvent cleaning is the first step in surface preparation. Usually, the only method specified for these alloys is hand or power tool sanding using abrasive cloths, belts, or pads.

Appendix L: Corrosion Inhibitors' Data Sheet



Technical Data Sheet

LAMCHEM™ PE-130 K
Phosphated Mono- and Diglycerides

Chemical Description:

LAMCHEM PE-130 K is an anionic emulsifier composed of the sodium salts of a mixture of phosphated mono- and diglycerides derived from vegetable oils.

LAMCHEM PE-130 K is manufactured to meet the Kosher requirements designated by the Organized Kashrus Laboratories (Circle K).

Chemical Name:

Phosphated Mono- and Diglycerides

CAS Number:

LAMCHEM PE-130 K 208539-94-0

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www.lambentcorp.com

LAMCHEM is a trademark of Petroferm Inc.

Product Description and Applications

LAMCHEM PE-130 K is used in food products and has properties that resemble those of lecithin. It does not contain nitrogen derivatives, and therefore do not exhibit the taste and odor degradation problems that are associated with naturally occurring phospholipids. LAMCHEM PE-130 K functions as described below:

Emulsifier and emulsifier salt	170.3(o)(8)
Lubricant and release agent	170.3(o)(18)
Surface active agent	170.3(o)(29)

LAMCHEM PE-130 K is a water-in-oil emulsifier and is used as a wetting and dispersing agent in oil based systems. It is stable over a wide range of temperatures and imparts moisture repellancy to products. It is an excellent lubricant and is used as a mold release agent in chocolate covered candies and other confectionaries. It may be used to reduce the viscosity of chocolate coatings. LAMCHEM PE-130 K is also used in the formulation of pan release agents for baking and fat-free frying and may be used to improve the taste and texture of fat-free foods.

LAMCHEM PE-130 K may be used in chocolates and chocolate coatings (21 CFR 163.123, 163.130, 163.135, 163.140, 163.145), sweet chocolates and vegetable fat coatings (21 CFR 163.150) and milk chocolate and vegetable fat coatings (21 CFR 163.155).

LAMCHEM PE-130 K may be used in soft candies (21 CFR 170.3(n)(38)) and dairy product analogs (21 CFR 170.3(n)(10)) at levels not to exceed current good manufacturing practices.

LAMCHEM PE-130 K is considered GRAS under 21 CFR 184.1521.

Packaging

Standard sample size is 8 oz.
Available in 55 gal. non-returnable drum, 450 lbs. (204 kg) net
Available in 5 gal. pail, 44 lbs. (20 kg) net

Storage and Handling

LAMCHEM PE-130 K should be stored in closed, factory sealed container at temperatures not exceeding 90°F (32°C). Product should be used within 6 months of date of delivery. To ensure that material is homogeneous, product should be heated to 40°C and mixed well prior to transferring out of the container.

Please refer to the Material Safety Data Sheet (MSDS) for this product for instructions on safe and proper handling and disposal.

NON WARRANTY: The data and statements contained herein are based on our research and/or the research of others, and are believed to be accurate. No guarantee of their accuracy is made however, and unless expressly stated in a written contract, the product(s) discussed herein are sold without conditions or warranties, expressed or implied. Purchasers are advised to make their own tests to determine the suitability of this product for their particular purposes. Nothing contained herein shall be construed as a recommendation to use or as a license to operate under or to infringe on any existing patent.

Lambent
TECHNOLOGIES
A Division of Petroferm Inc.

Technical Data Sheet

LUMULSE™ GML K
Glycerol Ester

Chemical Description:

LUMULSE GML K is glycerol monococoate prepared by the esterification of glycerine and coconut oil.

LUMULSE GML K is manufactured to meet the Kosher requirements designated by the Orthodox Union (OU).

Chemical Name:

Glycerol monococoate

CAS Number:

61789-05-7

Lambent Technologies

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LUMULSE is a trademark of Petroferm Inc.

Product Description and Applications

LUMULSE GML K is a multi-functional, oil-soluble emulsifier used in synthetic lubricants and plastic products. LUMULSE GML K provides lubricity and rust prevention in oils and is an anti-icing fuel additive. It may also be used in textile lubricants for synthetic fibers and spin finishes and as a solvent and mold release agent.

LUMULSE GML K may be used as an direct food additive as described in 21 CFR 184.1505, used as a component of adhesives intended for use in food packaging as described by 21 CFR 175.105, and used as a lubricant for textiles intended for use in food packaging as described by 21 CFR 177.2800.

Specifications	*Limits*
Appearance at 25°C (77°F)	Yellow solid
Acid Value, mg KOH/gram	7 max.
Alpha-Monoglycerides, %	35 min.
Free Glycerine, %	8 max.

Typical Properties

Color, Gardner	5
Iodine Value, cg Iodine/gram	7
HLB	3.0
Flash Point, COC, °C (°F)	192 (378)
Pour Point, °C (°F)	26 (79)
Density, lbs./gallon	8.0

LUMULSE GML K is soluble in ethyl alcohol, propylene glycol, organic solvents, vegetable and mineral oils. It is insoluble in water.

Packaging

Standard sample size is 8 oz.
55 gal. non-returnable drum, 420 lbs. (191 kg) net
5 gal. pail, 40 lbs. (18.2 kg) net

Storage and Handling

LUMULSE GML K should be stored in closed, factory sealed containers at temperatures not exceeding 90°F (32°C). Product should be used within two years of date of manufacture.

Please refer to the Material Safety Data Sheet (MSDS) for this product for instructions on safe and proper handling and disposal.

NON WARRANTY: The data and statements contained herein are based on our research and/or the research of others, and are believed to be accurate. No guarantee of their accuracy is made however, and unless expressly stated in a written contract, the product(s) discussed herein are sold without conditions or warranties, expressed or implied. Purchasers are advised to make their own tests to determine the suitability of this product for their particular purposes. Nothing contained herein shall be construed as a recommendation to use or as a license to operate under or to infringe on any existing patent.