UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Analysis of Torpedo Ladle Refractories Experiencing Premature Failure at the Spout

MSc (50/50) RESEARCH REPORT

Prepared by

Nichole Maistry

447939

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School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, South Africa

Supervisor: Josias van der Merwe

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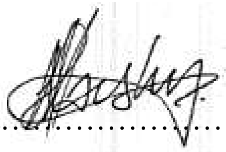
Declaration

I, Nichole Maistry, declare that this dissertation is my own unaided work, except where references were made and were probably acknowledged. It is being submitted to the Degree of Masters of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other university



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Abstract

In recent years, it was found that torpedo ladle refractories, specifically at the spout area, experience premature failure. This has an adverse effect on the cost and efficiency of the process as torpedoes are removed from service at more frequent intervals. The objective of this research was to determine the factors that contribute to decreased torpedo life. Thus, refractory design, installation method and effect of operations were examined. Subsequent investigations were conducted for deviations noticed in procedures. This included evaluation of torpedoes that were removed from service with unsatisfactory campaign tonnages, in terms of molten metal mass, shell temperature, and tap to tap and residence. Furthermore, bricks from a failed torpedo were examined to determine the failure mechanisms experienced. It was found that the thermal and chemical properties of the brick are suitable for the temperature and chemistry it is exposed to as heat losses are minimal and corrosion is controlled. One of the major problems identified was spalling, which is caused by overfilling of torpedoes and long tap to tap times, resulting in rapid brick removal. The next problem was stress cracking as a result of incorrect mortar application, which occurs when the expansion due to thermal cycling cannot be accommodated. Incorrect mortar application also resulted in metal and slag penetration through the joint. When metal penetration occurs, the metal remains in the area it penetrated. The metal expands and contracts during operation, causing further cracking in the brick. The final problem experienced was skull formation, which is attributed to high tap to tap and residence times, as well as low molten metal temperatures. The brick was also subjected to XRF, XRD and SEM/EDS analysis. XRF analysis shows a decrease in the Al_2O_3 content and an increase in the CaO content at the hot face. The MgO and SiO2 content remain relatively unchanged. There is a 1.4% decrease in the alumina content and 0.6% increase in CaO content, which indicates that there is a small degree of dissolution that takes place, indicating that the refractory has good slag resistance. From the cold to hot face, XRD showed phases changes consistent with dissolution of alumina and iron infiltration. At the hot face, SEM/EDS analysis showed an increase in iron and other trace elements, and a decrease in aluminium and oxygen, indicating slag and iron infiltration, and a small degree of corrosion of the refractory.

Dedication

To Dr Wesley Maistry,

Thank you for always believing in me and encouraging me to pursue excellence.

I miss you.

Acknowledgements

Completion of this research would not have been possible without everyone who assisted me through this journey. To my supervisors, Prof Josias van der Merwe and Warren Seegers, thank you for the guidance and support throughout my research. To ArcelorMittal Newcastle management, thank you for giving me the opportunity to conduct research at their facility. To Nicolene Taute, thank you for all the assistance provided during analysis. To Andre Greeff, from Delta Refractories, thank you for assistance with optical microscopy. To Dr Aheesh Ramsaroop, thank you for all the love and support.

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Chapter One: Introduction

Torpedo ladles transport molten metal from the blast furnace to the steel plant for subsequent processing. The torpedo is manufactured from steel, which is lined with refractories. The refractories make the vessel suitable for hot metal transportation as they protect the shell by reducing the impact when molten metal is being poured into the torpedo, reducing the abrasion caused by the hot metal, and preventing thermal shock from occurring during filling and emptying of the torpedo.

In recent years, ArcelorMittal Newcastle has been experiencing a decrease in the life of the torpedo refractory lining, which is determined by the cumulative tonnage of molten metal it transports. Most frequently, failure occurs in the spout area. Unfortunately, the reasons for early failure are unknown. There are various factors that may decrease the life of the refractory layer, which include refractory properties, method of installation, blast furnace activities and tapping of torpedoes at the steel plant (Anand, 2015).

Torpedo ladle refractories may experience several failure mechanisms, which include thermal wear, oxidation, chemical wear, thermal shock and mechanical wear. The areas of concern are the slag line, where chemical wear may occur due to corrosive slag, as well as the mouth area, which may experience mechanical wear due to the impact on the refractory during pouring, agitation during transport and tapping of the hot metal, or thermal shock as a result of filling and emptying or overfilling of the torpedo. These mechanisms can be accelerated when the refractory does not meet the required specification, or when installation and operational procedures are followed incorrectly, ultimately leading to premature failure (Bhatia, 2011). However, there is no specific literature regarding failure occurring at the spout area. Premature failure of a torpedo lining has a significant, negative financial impact, thus, it is important to understand which factors have a major effect on the life of the torpedo. Thus, further investigation on practices and procedures, as well as the properties of the refractories will reveal the causes of premature failure, and how they can be mitigated.

1.1. Problem Statement

The life of the refractory lining in torpedo ladles, specifically at the spout, has decreased in recent years. This results in adverse effects on the torpedo shell, such as weak spots and burn through. The torpedo then needs to be removed from service and undergo repairs prior to its planned reline date. This has a negative financial impact on the business, as well as the efficiency of the process as more frequent failures result in fewer torpedoes in operation.

1.2. Research Questions

The research questions that will be investigated include:

- Is the refractory brick suitable for the temperature and slag chemistry that it is exposed to?
- Does the installation process follow the company procedure and standard refractory installation practices?
- How do operations and any deviations from procedure influence the life of the refractory?
- What are the causes of decreased life of torpedo ladle refractories?
- How can the life of torpedo ladle refractories be improved?

1.3. Research Objectives

The aim of this research is to study the premature failure at the spout area of torpedo ladles. This aim will be achieved through the following objectives.

1. Verify whether the refractory brick is suitable for the temperature and slag chemistry that it is exposed to.
2. Determine if the installation process adheres to the company procedure and standard refractory installation practices.
3. Assess how the refractory life is influenced by operations and any deviations from the procedure.
4. Identify the causes of decreased life in torpedo ladle refractories.
5. Make recommendations on how to improve the life of torpedo ladle refractories.

1.4. Approach

The refractory properties, installation and operations have a significant effect on the refractory performance; therefore, the research was conducted in various stages. The thermal properties of the refractories were investigated, by determining the temperature profile through the torpedo wall. A corrosion analysis was then performed to determine how the slag and refractory react. The installation process, filling of torpedoes and tapping of molten metal was observed and evaluated against the procedure. Deviations were further investigated by comparing molten metal masses, shell temperatures, tap to tap and residence times to the industry standard. Finally, bricks from a torpedo that was removed from service before the end of its campaign life were analysed macroscopically, microscopically and chemically, to determine the damage experienced by the brick and the extent of corrosion.

Chapter Two: Literature Review

2.1. Refractories

Refractories are ceramic materials that are able to withstand high temperatures, chemical attack and mechanical damage. They are used in high temperature corrosive environments to prevent heat loss and damage to the shell of the structure.

2.1.1. Corrosion of refractories

Corrosion, in terms of refractories, is defined as refractory wear due to loss of thickness and mass from the hot face as a result of chemical attack by a corrosive fluid, whereby the corrosive fluid and the refractory react, to achieve chemical equilibrium in the area of contact between the fluid and the refractory (Brosnan, 2004).

In order to fully understand the corrosion process, it is important to use a phenomenological approach, which views corrosion as both a chemical and physical process, together with phase diagrams (Brosnan, 2004).

2.1.2. Classification of refractories

Refractories may be classified into three categories; chemical composition, method of manufacture and physical form (Sarna, 2017).

2.1.2.1. Chemical composition

Refractories are separated based on their chemical behaviour when exposed to slag. They are categorized into acid, basic and neutral refractories (Brosnan, 2004). In reference to corrosion chemistry at elevated temperatures, an acidic material is characterised by an excess of silica content when compared to basic materials, usually CaO. Thus, neutrality will be achieved when the CaO/SiO_2 ratio is 1.0.

The type of refractory required depends on the chemical characteristics of the vessel (Brosnan, 2004). Acid refractories are described as “compatible” with acid slags, and basic refractories “compatible” with basic slags, where compatibility implies that there will be no reaction between mineral phases at elevated temperatures. Thus, when refractory and slag are not compatible, corrosion reactions occur as a result of the system trying to achieve compatibility by moving towards equilibrium.

Acid refractories experience attack from alkalis, or basic slags (Brosnan, 2004). An acidic refractory will contribute SiO2 in the corrosion reaction. They are used for acidic slags and atmospheres. Acidic refractories include silica, zirconia and aluminosilicate.

Basic refractories experience attack from acidic slags, however, they are stable when exposed to alkaline slags, dusts and fumes at high temperatures (Brosnan, 2004). Therefore, they are used for furnace linings, which have an alkaline environment, such as non-ferrous metallurgical processes. A basic refractory will contribute CaO or MgO in the corrosion reaction. Basic refractories include magnesia (caustic, sintered and fused magnesia), dolomite (sintered and fused dolomite) and chromite.

Neutral refractories are chemically stable when exposed to both acids and bases (Brosnan, 2004). Thus, they may be used for an acidic or basic slag or atmospheres. Neutral refractories include carbon graphite, chromites and alumina. Graphite is the least reactive and often used in metallurgical furnaces where the oxidation process can be controlled.

2.1.2.2. Method of manufacture

There are five possible methods of manufacture for refractories; dry press process, fused cast, hand moulded, formed (normal, fired or chemical bonded) and unformed (monolithic – plastics, ramming mass, gunning, castable and spraying) (Sarna, 2017).

Fusion cast and/or bonded bricks are used for the working lining, which is placed in front of a safety lining, or sometimes directly against the shell (Brosnan, 2004). Monolithics may be thick- or thin- wall applications. Thick-wall applications have a lining thickness of ≥ 75 mm, whereas thin-wall applications have a lining thickness of < 25 mm.

2.1.2.3. Physical form

Refractories may also be categorized by their physical form (Sarna, 2017). These include shaped and unshaped refractories. Shaped refractories are known as refractory bricks, and unshaped refractories refer to monolithic refractories

Bricks may have standard or special shapes. Standard shapes, which include straights, arches wedges and keys, are produced by most refractory manufacturers, and they are usually used for kilns and furnaces. They are mostly made via machine pressing; therefore, the properties are expected to be uniform throughout the brick. Special shapes are made for specific vessels. They are usually hand-moulded, thus, a variation in properties is expected.

Unshaped refractories do not have a definite form. They are given their shape when they are applied, forming a lining free from joints. They include plastic refractories, ramming mixes, castables, gunning mixes, fettling mixes and mortars.

2.1.3. Selection of refractories

Selection of refractories is important to lengthen life of the refractory and improve productivity of the vessel (Bhatia, 2011). The primary considerations are operating parameters and wear pattern, which is the typical way a refractory is worn during use.

There are five factors that influence the choice of refractory: area of application, type of refractory, operating conditions, quality of refractory and workmanship.

2.1.3.1. Area of application

There are four aspects that need consideration:

a) Thermal performance

   Thermal performance of refractories is extremely important. If the operating temperature exceeds the refractory rating, the refractory may soften, causing rapid erosion, and eventually, failure (Bhatia, 2011). If temperature fluctuations exceed the specified range, the refractory may undergo thermal shock, which compromises the integrity of the lining. Thus, during the design process, thermal factors must be carefully evaluated to prevent premature failure of the refractory, and there is limited scope to make changes to the vessel design and configuration after initial design and installation has been completed.

   Furthermore, if the thermal performance of the refractory is poor, it will cause the torpedo shell to exceed its critical temperature. This causes a loss of tensile and yield strength (Furtado & May, 2004). The shell also experiences excessive creep as a result of cyclic thermal stresses, which leads to thermal fatigue cracking. The cracks will develop in high stress areas, resulting in creep deformation.

b) Mechanical and physical properties

There are three major physical issues experienced during refractory service: physical shock and mechanical stress, thermal stress and refractory wear (Bhatia, 2011).

Since refractory materials are usually brittle and weak in tension, they may experience failure as a result of sudden or cumulative physical shock and mechanical stress (Sarna, 2016). Thus, it is essential that the refractory has excellent mechanical strength.

The entire refractory lining is subjected to thermal stress (Bhatia, 2011). The lining must have thermal resistance, expansion relief, prevent cracks and eliminate built-in barriers. Thus, it is critical to understand thermal stresses, and how they can be improved.

Refractories frequently experience wear as a result of being exposed to molten metal, slag or gas (Bhatia, 2011). Wear should be uniform; however, it is not always the case. More severe wear is experienced at the slag/metal interface, joints between the sidewall and floor, and thin spots as a result of poor installation.

c) Chemical characteristics

Chemical attack occurs when the refractory is exposed to gases, such as steam, hydrogen, carbon monoxide, acid and alkali slag, and sulphurous gases, which weaken the lining (Bhatia, 2011). Chemical characteristics should be a determining factor in selection, however, in some cases, physical properties may be considered to be more important, especially load bearing strength. Therefore, both physical and chemical properties must be compatible with the operating conditions and nature of the process.

d) Costs

This includes initial installation, maintenance and repairs, and replacement costs. Durability must be weighed against cost and ease of installation, as it is often the case that monolithics are wrongfully chosen over brick (Bhatia, 2011).

2.1.3.2. Type of refractory

Refractories are quasi-brittle material at room temperature, but they have viscous behaviour at elevated temperatures (Bhatia, 2011). Due to variations in microstructures, they have varying strengths. They are susceptible to high temperature creep, and they have a high elastic modulus, which makes them prone to failure under thermal stresses. Therefore, to ensure good service life, different types of refractories will be required in different areas depending on the required properties of the refractory, as shown in Table 1 (Sarna, 2017).

Table 1: Properties of various refractory types

Type of refractory	Composition	Properties
Silica	> 93% SiO_2	Spalling resistance, high refractoriness, high temperature strength, flux and slag resistance
High alumina	> 45% Al_2O_3	Withstands high temperatures, good corrosion and wear resistance
Magnesite	45-50% MgO 50-55% CO_2	High melting temperature, resists alkali slag attack
Forsterite	60-70% MgO 15-20% SiO_2	Good refractoriness, high temperature strength, basic slag erosion resistance. thermal stability
Dolomite	25-45% MgO 35-65% CaO	Good refractoriness, thermal stability, slag resistance
Magnesite chromite	> 60% MgO 8-18% Cr_2O_3	High service temperature, resist basic slags, spalling resistance
Chromite-magnesite	42-50% MgO 15-35% Cr_2O_3	Resist corrosive slags and gases, high refractoriness
Zirconia	> 65% ZrO_2	High strength, low thermal conductivity, low reactivity

		with liquid metals and molten glasses
Silicon carbide	50-90% SiC	High melting point, good thermal conductivity, spalling resistance, high hardness and stiffness, corrosion resistance
Carbon	3-30% C	Suitable for high reducing environments, high thermal conductivity, high refractoriness, thermal stability, non-wettability by slag

2.1.3.3. Operating conditions

The properties and specifications of the refractory must suit the operating conditions of the process to prevent rapid damage to the refractory (Bhatia, 2011). When there are changes in the product chemistry, it may adversely affect the refractory. Thus, it is essential to change the refractory material or configuration. However, this type of damage is difficult to isolate as failure may take place a while after damaged has occurred.

2.1.3.4. Quality of refractory

Refractories play a pivotal role in the performance, safety and efficiency of thermal vessels (Bhatia, 2011). To determine the life of refractory, similar length of service should be reached repeatedly. When the service life is less than expected, it indicates a refractory problem such as corrosion, excessive cracking, partial melting and degradation, mechanical damages, among others. For critical applications, it is important to evaluate a material from experience, rather than using its data sheet. Furthermore, properties should be reviewed regularly and changed, if necessary.

2.1.3.5. Workmanship

Correct installation of refractories must be given the same importance as selecting the correct material (Bhatia, 2011). If there is poor compaction, it may lead to low density areas and voids. These areas are weak spots that are susceptible to attack by molten metal or slag. To achieve the expected life, there are some guidelines to follow, such as using correct dimensions of bricks and monolithics, and maintaining proper expansion joints. They include:

a) Bond

This refers to an arrangement where there are staggered joints between the bricks (Bhatia, 2011). This improves stability in construction and ensures air tightness. In cases where there is high wear due to a high volume of molten metal, slag or gas moving at high velocities, regular maintenance is expected to be done to the hot face, thus, it is built separately from the main wall.

b) Wall thickness

Wall thickness is important for structural stability (Bhatia, 2011). To ensure good stability, the thickness should be at least 230 mm. Thinner walls require anchors when built higher than one metre. Metallic sheets with anchorage arrangements can be used for basic refractories as it improves stability of the wall. These types of walls should also have a sliding arrangement to prevent damage to the refractory during thermal cycling.

c) Joints

Joint are used to assemble bricks together but they are also responsible for absorbing thermal expansion and limiting the stress within the refractory wall (Bhatia, 2011). There are two types of joints: mortared joints and dry joints. A mortared joint is a material with a matrix and voids, which is granular in nature, whereas a dry joint is without mortar. Joints behave differently at different temperatures; at room temperature, the compressibility of the joint is approximately 20%, but at 1200°C, it increases to about 50%.

d) Mortar joints

They provide improved stability as they have uniform bedding throughout the joint, which accounts for size variations and warpages (Bhatia, 2011). Mortar joints should be approximately 1 mm along the length of the brick. The chemical and physical properties of the mortar should match that of the brick. Mortar should be workable to ensure good construction. It is extremely important that mortar should emerge from the edges when one brick is placed against the other. This indicates that the joints are full and there are no gaps present.

e) Expansion joints

Since refractories expand when they are heated, provisions should be made during construction to allow for expansion to occur without inducing stresses that may result in failure (Bhatia, 2011). These provisions must be made according to the expansion characteristics of the refractory. Experience has shown that at least half of the theoretical expansion must be catered for; the remainder will be absorbed by mortar or dry joints.

f) Structural support

Refractories are usually installed within a steel shell or structural framework (Bhatia, 2011). The structure should not get overheated as it may cause the shell to deform, thus, sufficient insulation must be installed where overheating may be expected. Good brickwork together with proper size and location of expansion joints, the rise of an arch and correct wall thickness are important to ensure good service life. If the installation, drying and sintering instructions are not followed, it may lead to premature failure.

2.2. Production of molten iron

The blast furnace is responsible for the production of liquid iron (Anand, 2015). This is facilitated by chemical reaction processes that occur within the blast furnace. The quality of the hot metal has a significant influence on subsequent processes, ultimately influencing the quality and price of the final product.

There are several operations that occur within the blast furnace process. The blast furnace is a chemical reactor where the reduction of ferrous oxides occurs. The iron-making process is a counter flow gas/solid reactor. It involves the charging of raw materials, which includes ferrous raw materials, fluxes, and coke, at the top of the blast furnace shaft. Simultaneously, hot air is blown in from the bottom, via the tuyeres, to ignite the coke, which then provides hot gases for the reduction process. The raw materials move downwards as the reduction gases move upwards through the raw materials. These gases have two functions: to pre-heat the charged materials and to facilitate chemical changes within the charge. Carbon monoxide, specifically, has a higher affinity to oxygen in iron ore than iron, thus, reduces iron ore to elemental iron in its liquid form. The fluxes that are present in the raw materials melt to form a liquid slag. Molten metal and slag is then tapped from the furnace. Slag is separated from molten metal, by means of a skimmer, due to the difference in density. Unfortunately, the skimmer experiences wear and failure, causing slag to sometimes report to the torpedo ladle.

Figure 1 shows the process of production of hot metal at the blast furnace. There are several operations that occur within the blast furnace process. The blast furnace is a chemical reactor where the reduction of ferrous oxides occurs (Anand, 2015). It is a hermetic stave cooled shell, which is lined with refractories to provide resistance to high temperatures. The raw materials are transferred from the stock house to the blast furnace, where ferrous oxides are converted to hot metal and slag (ArcelorMittal, 2006). This process begins at the stock house, where screening and batching of raw materials occurs, after which they are conveyed to and charged at the blast furnace top. External combustion stoves pre-heat cold blast air, from the blower hous

Figure 1: Blast furnace process (Gravita, 2018)

a the tuyeres, to react with the raw materials to produce hot metal. Pulverized coal is also injected into the furnace, together with hot blast air, allowing for partial replacement of metallurgical coke. When the raw materials have been converted to hot metal, the cast house manages the hot metal and slag tapped from the furnace. This involves separation and handling of the hot metal and slag, where hot metal is tapped into torpedoes and slag reports to the slag granulation plant. The slag granulation plant involves the online granulation of the molten slag after separation from hot metal. Dewatering and transportation also occurs. Quenching and cleaning of the by-product blast furnace gas occurs at the gas cleaning plant, to make it suitable for use as a fuel in steel making.

2.2.1 Blast furnace slag

Blast furnace slag is a non-metallic by-product generated during the production of molten iron (Sarna, 2013). It primarily consists of silicates, aluminosilicates and calcia-alumina-silicates. The impurities from iron ore, ash from coke and coal, and calcium and magnesium oxides from fluxes report to the slag. Majority of the sulphur is also absorbed in the slag. Slag makes up 20-35% of blast furnace production, and it is used to manufacture cement and other construction materials.

The chemical composition of blast furnace slag depends on the composition of the burden materials and the fractions in which they are charged. The slag contains four major oxides, Al_2O_3, CaO, MgO and SiO_2, which usually constitutes 95% of the total composition. The other elements include sulphur, iron, manganese, alkalis and other trace elements. Blast furnace slag composition is given in Table 2.

Table 2: Typical blast furnace slag composition

Component	Range (%)
SiO_2	30.5 - 40.8
CaO	30.9 - 46.1
CaO (free)	0.3 - 2.4
Al_2O_3	5.9 - 17.6
MgO	1.7 - 17.3
FeO	0.1- 4.7
Fe_2O_3	1.5 - 3.8
MnO	0.1-3.1
Mn_2O_3	0.01 - 0.28
TiO_2	0.1 - 3.7
Na_2O	0.1 - 1.7
K_2O	0.1 - 1.5
Na_2O equivalent	0.2 - 2.6
SO_3	0 - 0.9
S	0.4 - 2.3
Insoluble residue	0.03- 4.1

2.2.1.1 Effect of slag viscosity on corrosion

Slag viscosity significantly affects slag penetration and refractory dissolution. Slag viscosity is inversely proportional to the rate of refractory wear. Thus, a more fluid slag will cause increased penetration, which increases the potential for corrosion (Lee & Zhang, 2004). This occurs when the slag viscosity decreases as there is an increase in wetting between the refractory and slag, which results in increased wear due to penetration (Svantesson, et al., 2020).

During the corrosion process, dissolving of the refractory may result in an increase or decrease in slag viscosity. Slag viscosity has an inverse relationship with temperature (Lee & Zhang, 2004). When the dissolution causes an increase in viscosity, mass transport through the next melt layer will be slower. This occurs due to progressive saturation of the melt layer, which results in diffusion control and/or indirect dissolution. When there is an increase in viscosity, diffusion through the refractory increases rapidly, thus, there is no formation of a saturated layer, resulting in no reaction control, also known as direct dissolution. Thus, an increase in operating temperature may cause a change from indirect to direct dissolution.

2.3. Torpedo cars

Torpedo ladles weigh 250 tons when unfilled, and have a capacity of 200 - 250 tons. They are responsible for transporting molten iron from the blast furnace to steel making. (ArcelorMittal, 2006).

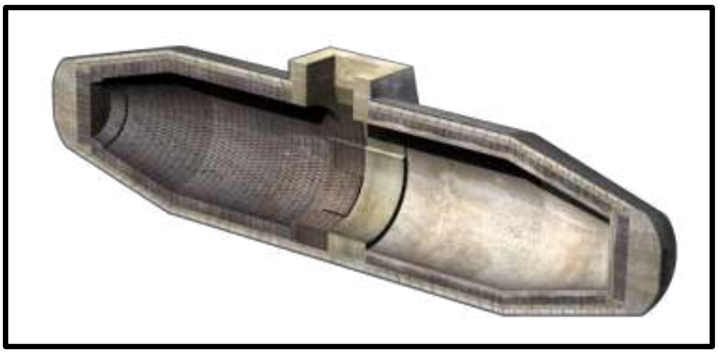


Figure 2: Cross-section of a torpedo ladle (Vesuvius, 2022)

The structure of the torpedo is shown in Figure 2. The outer layer of the torpedo is known as the shell, which is manufactured from steel. When the shell is exposed to elevated temperatures, it experiences a loss in strength and stiffness (Baetu, et al., 2016). The inner layer, which is the lining, is made of refractory bricks. The conical part is the venturi, and the cylindrical part is the barrel. The mouth is found on the upper side of the barrel, and hot metal, which is above a temperature of 1400°C, is poured into the torpedo via the mouth directly onto the charge pad, where the thickness of the refractory lining is considerably larger.

2.3.1 Torpedo car refractories

Torpedo cars are lined with refractories to protect the torpedo shell from impact and thermal shock (Anand, 2015). There are various factors that adversely affect the refractory lining, which include hot metal temperature, slag chemistry, metallurgical treatments, residence time of the hot metal inside the torpedo, transportation time and thermal cycling rates. Thus, the refractory lining must possess excellent thermal shock, abrasion, and impact and corrosion resistance. The lining is relined when it has been thinned down or worn away due to erosion, which is a result of thermo-mechanical shock when hot metal is tapped into the torpedo (Isei, et al., 2009). The service life of the torpedo is dependent on the refractory thickness in two critical areas where high erosion occurs. These areas include the slag zone/line area, which is shown in Figure 3, where the refractory is eroded by slag floating on the hot metal, and the metal impact area, which is located at the bottom of the torpedo.

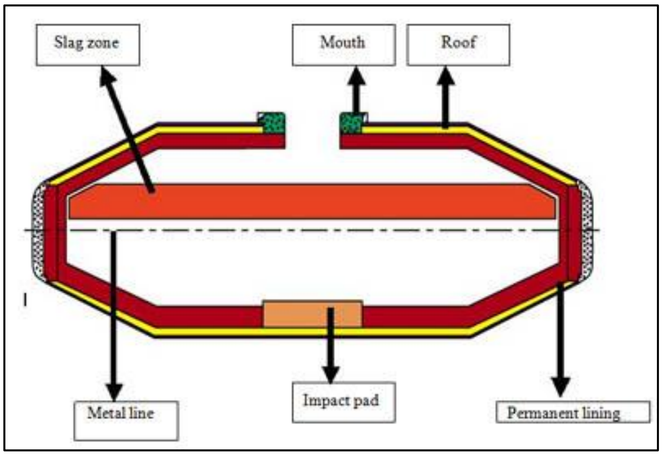


Figure 3: Schematic diagram of torpedo ladle (Champion Ceramics, 2015)

2.3.1.1. High stress areas in torpedo ladles refractories

There are specific areas in the torpedo ladle that experience high stresses, which include the impact area, metal zone, slag line, and mouth area (Gupta, 2017).

a) Impact area

The impact area, which is found at the base of the torpedo, experiences severe mechanical stress and thermal stress as a result of molten metal being directly poured onto the area during filling. The force of the impact is dependent on the height from which the molten metal stream falls and the quantity of material tapped, and the degree of thermal stress depends on the difference in temperature between the torpedo and molten metal.

b) Metal zone

This is the area that is in contact with molten metal, thus, it experiences stress during filling and emptying due to the weight of the material. It may also experience chemical wear if the molten metal is not compatible with the refractory.

c) Slag line

Located above the metal line, it is usually exposed to reactive and, sometimes, aggressive slag, which causing chemical stress due to corrosion of the refractory by slag. The slag line is a result of slag that is tapped into the torpedo, together with liquid iron. Due to the difference in density, the slag always sits in the same area, and due to corrosive slag, wear is more severe in this area.

d) Mouth area

The mouth area experiences mechanical stress in the form of abrasion due to the flow of molten metal. It also undergoes thermal stress due to thermal cycling during and after emptying of the torpedo.

2.3.1.2. Technical Development

Fired bricks containing alumina and silica have always been used in the ironmaking industry. They are suitable for torpedo ladle cars, even today, provided that desulphurization does not take place within the vessel (Blumenfeld, 2014). Fireclay bricks were used in the beginning; however, aluminosilicate refractories have been developed as manufactures are able to synthesise mullite to optimize refractory properties (Sadik, et al., 2014).

As a result of desulphurization taking place inside the torpedo, there have been various stages of development for torpedo refractories (Ito & Inuzuka, 2008). As problems were recognised, the need for improvement arose. The first types of refractory bricks were high-grade chamotte brick. Unfortunately, due to the increased CaO content in the slag. This caused the slag to react with the SiO_2 and Al_2O_3 in the chamotte brick, forming low melting point products, such as anorhite. Formation of these products caused the refractory to weaken, which resulted in a reduction of intervals between repairs by half (Ito & Inuzuka, 2008).

An Al_2O_3-SiC-C brick was then developed to improve the life of the refractory. The alumina content was increased to improve the corrosion resistance. Carbon was added to improve resistance to spalling and slag infiltration, and SiC was added to prevent the oxidation of carbon (Ito & Inuzuka, 2008).

Initially, worn torpedo linings were repaired during intermediate repairs, which were done by spraying an Al_2O_3-SiO_2 material. The next step was to accelerate the deaeration of the coating material by applying vibration to improve its durability, which is known as the vibro-trowel coating method. Unfortunately, this process was extremely labour intensive and the adhesion of the coating was unsatisfactory. This was eventually replaced by a method known as shotcreting. Shotcrete, more simply known as sprayed concrete, is a cement-based mixture that is pneumatically sprayed onto a surface at high velocity. Shotcrete allows for the compaction to occur on the sprayed surface. The process involves mixing of the refractory material with water to form a slurry. The slurry is pumped to the nozzle, where it is mixed with a hardening agent and sprayed onto the surface, using compressed air, to form a refractory layer (Ito & Inuzuka, 2008).

2.3.1.3. Types of refractories found in torpedo ladles

The major components of refractories used in torpedo ladles in iron making are alumina and silica. Initially, fire-clay bricks were used, however, as there were changes in operations and slag and metal chemistry, the properties of the brick required improvement to prevent premature failure. Thus, bricks that are often found in iron-making torpedo ladles include high alumina, silica, and alumina-silicon carbide-carbon (ASC), if desulphurization takes place.

2.3.1.4. *Fire-clay brick refractories*

They consist of hydrated aluminium silicates with small percentages of other minerals (Bhatia, 2011). It characteristically has %SiO_2 < 78% and %Al_2O_3 < 44%. It is considered to be a versatile material as it is the least expensive and it is used in the iron and steel industry. Fire-clay bricks have a wide range of properties, thus, they have been classified into 4 types, based on their alumina-silica ratio. Table 3 shows the different types of fire-clay bricks together with their typical SiO_2 and Al_2O_3 content.

Table 3: Types of fire-clay bricks

Type	**%SiO_2**	**%Al_2O_3**	**%Other**
Super duty	49 - 53	40 - 44	5 - 7
High duty	50 - 80	35 - 40	5 - 9
Medium duty	60 - 70	26 – 36	5 - 9
Low Duty	60 - 70	23 - 33	6 - 10

Fire-clay bricks soften below their fusion temperature and deformation takes place under load. This is a slow, continuous process until there is a change in temperature or load. As a result, this type of refractory is not suitable for wide sprung arches in high temperature furnaces.

2.3.1.5. *High alumina refractories*

High alumina refractories contain more than 45% alumina and trace amounts of other materials (Bhatia, 2011). It is considered to be the most chemically stable materials as it possesses excellent hardness, strength and spalling resistance. It is insoluble in water and super-heated steam, as well as most inorganic acids and alkalis. It has an operating temperature of 1840°C and it shows good resistance to oxidising and reducing environments. Therefore, it is used extensively in high temperature processes.

The refractoriness of high alumina refractories increase with increasing alumina content (Bhatia, 2011), thus, they are classified based on their alumina content. Mullite usually contains 72% Al_2O_3 and 28% SiO_2. It has excellent volume stability and strength at elevated temperatures, as it remains in as a solid solution up to 1890°C. It is used for electric arc roofs, blast furnace and blast furnace stoves. Corundum consists of 99% Al_2O_3, and these refractories may be single phase, polycrystalline and alpha- alumina. They are economical to use in lower sections of soaking pits in steel making as they have good resistance to iron oxide slags.

2.3.1.6. Silica brick

Silica brick refractories contain minimum 93% SiO_2 (Bhatia, 2011). They show excellent mechanical strength at temperatures approaching fusion point, which is not the case with other refractories, such as alumina-silicate materials, that experience fusion and creep at temperatures lower than their fusion point. The disadvantage is its susceptibility to spalling at temperatures lower than 650°C. Temperature instabilities above this point do not influence the brick and it is considered to have good spalling resistance. It is suitable for contact with siliceous slags and areas that are exposed to constant high temperatures.

2.3.2 Torpedo handling practices

There are specific practices that must be followed to ensure minimum damage to the torpedo ladle and its refractories (Ministry of Steel, 2004). Prior to filling at the blast furnace, the torpedo should be placed with the spout directly below the chute. This is done to prevent overfilling of torpedoes, which may result in thermal shock of refractories at the spout area, as they are at lower temperature than the molten metal or the refractories in the lower section of the torpedo. If the torpedo is overfilled it is required to go to the pool bay to discard the excess material. This results in long residences times, which may result in skull formation. When filling the torpedo, the liquid level should be 250 mm from the top or the torpedo should be 90% full. However, for torpedoes that have undergone a reline, it is recommended to fill the torpedo to 50%, to prevent thermal shock and skull formation. Finally, the torpedo must always be transported in the upright position. This is done to prevent spillage when reporting to steel plant and overfilling at blast furnace.

Chapter Three: Methodology

There were different investigative methods that were used to accurately determine what factors contribute to increased wear in torpedo ladle refractories, specifically at the spout. The first step involved evaluation of the refractory brick, to determine whether its design is suitable for the temperature and slag chemistry that it is exposed to. Thus, heat transfer calculations to determine the theoretical heat profile of the torpedo vessel, which assists in determining the final temperature for the shell so that its behaviour during operation can be predicted. In addition, the corrosion potential of the system and viscosity of the slag was determined to assess the degree of attack on the refractory by slag.

The next step involved observation of the installation process to determine whether the correct process is followed, and note any deviations.

Operations were observed and evaluated, and they were compared to operating procedures as well as literature. This was done for pre-heating of the torpedo, filling of torpedo ladles with hot metal at the blast furnace and emptying of the torpedoes at the steel plant. To further evaluate operations, hot metal weights and tap to tap time trends for failed torpedoes were found.

Lastly, the refractory brick underwent macroscopic and microscopic evaluation, and x-ray fluorescence to determine how the refractory behaves during operation.

3.1. Heat profile of torpedo ladle

Heat transfer calculations were used to determine the shell temperature, to ensure that the maximum operating temperature is not exceeded, as well as the minimum thickness of the hot face at which the maximum operating temperature is exceeded, resulting in damage to the shell. There are three types of heat transfer that occur, namely:

a) Conduction is the direct transmission of heat through a substance when there is a difference in temperature (Incropera & Dewitt, 2002). Conduction is given by the equation:

$$Q = -kA\frac{dT}{dx}$$

… Eqn 1

Where:

Q = heat transfer (W)

k = thermal conductivity (W/m.K)

A = area through which heat is transferred (m^2)

b) Convection occurs when there is movement of molecules within fluids, which include gases, liquids and molten ore/metal (Incropera & Dewitt, 2002). Convection is given by the equation:

$$Q = hA(T_{hot} - T_{cold})$$

… Eqn 2

Where:

Q = heat transfer (W)

h = heat transfer coefficient ($W/m^2.K$)

A = area through which heat is transferred

T_{hot} = temperature of heat source

T_{cold} = temperature of surroundings

c) Radiation refers to the emission of energy, such as heat, as electromagnetic waves (Incropera & Dewitt, 2002). Radiation is given by the equations:

$$Q = \sigma . T^4 . A$$

… Eqn 3

Where:

Q = Heat transfer

Ơ = Stefan-Boltzman constant

T = temperature of heat source

A = area through which heat is transmitted

$$Q = \varepsilon . \sigma . A(T_{hot} - T_{cold})$$

… Eqn 4

Where:

ε = emissivity of material through which heat travels

T_{hot} = temperature of material through which heat travels

T_{cold} = temperature of surroundings

The heat profile was determined at the slag line, thus conduction and convection were considered. The assumptions that were made include:

- Steady state
- k_1, k_2, k_3 & k_4 are constant
- h is constant
- Torpedo shell and refractory thickness are constant
- No internal heat generation
- One dimensional heat transfer
- Heat flow in radial direction
- Area through which heats flows is constant
- Slag temperature is 1500°C
- Ambient temperature is 25°C
- Heat transfer is not affected by external forces

Conduction and convection equations were formulated, and they were added together to give the equation:

$$\frac{Q}{A} = \frac{T_o - T_a}{\left(\frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \frac{1}{h}\right)}$$

… Eqn 9

Once Q/A was calculated, it was used substituted into Eqn 8, Appendix 1, to determine the shell temperature.

The heat transfer equations were then used to determine the critical thickness of the hot face, at which the maximum shell temperature is exceeded, and the properties of the shell are compromised.

3.2. Analysis of corrosion potential

The major components in the refractory are alumina and silica, and alumina, calcia, magnesia and silica in the slag. Thus, to determine how the refractory is affected by slag, relevant ternary phase diagrams were used. In this case, the slag contained 10% MgO, thus, the Al_2O_3-CaO-SiO_2-10wt%MgO phase diagram was used as this would give a more accurate reflection compared to the standard Al_2O_3-CaO-SiO_2 phase diagram. The refractory and slag compositions were then plotted and joined to determine corrosion products.

3.3. Viscosity of slag

The viscosity of slag was calculated from 2010 – 2019 using Eqn 9, which is applicable for blast furnace slags at 1500°C (Chen, et al., 2014).

$$\text{Viscosity } (\eta) = 0.005 + 0.0262[SiO_2] + 0.0184[Al_2O_3] - 0.0172[CaO] - 0.0244[MgO]$$

… Eqn 10

3.4. Installation process

The installation process was observed to determine whether the refractories were installed according to the correct methods and design, identifying any deviations from the procedure. The process was observed from a platform looking into the torpedo.

3.5. Operations

3.5.1. Pre-heating of torpedoes

Burner temperature data was evaluated to determine whether adequate heating is achieved prior to being filled with hot metal.

3.5.2. Filling of torpedo ladles

Blast furnace operations, which include filling of the torpedoes, tilting over to a secondary torpedo and replacement of the full torpedo, were evaluated according to the operating procedures to identify any deviations. This was observed from a platform overlooking the tilter filling up the torpedo ladle.

3.5.3. Handling of torpedoes at steel plant

Tapping of hot metal form a torpedo into a hot metal ladle was observed, from the hot metal control room. The torpedo car is first weighed to determine the mass of the hot metal. At the torpedo tilting station, an empty hot metal ladle is placed on a transfer car, which moves the ladle into position. The torpedo car is then tilted, transferring the hot metal into the 170-ton hot metal ladle.

After tapping was completed, a visual inspection of the torpedo was conducted to determine if there were any deviations in comparison the operating procedure.

3.6. Testing of refractories

3.6.1. Macroscopic inspection

The refractories inside the torpedo ladle were visually inspected before breakout took place. After breakout, refractory samples were taken from the slag line. The samples were visually inspected, specifically looking at the hot face, slag infiltration, the application of mortar between the bricks, cracks and any other anomalies.

3.6.2. Microscopic inspection

Following the macroscopic inspection, the area of concern, which was the mortar joints of the refractory bricks, were studied under a microscope to determine how the mortar behaves during operation

3.6.3. X-ray fluorescence

The composition of the refractory material was determined using x-ray fluorescence. Four samples were taken along the refractory brick; one from the hot face, one from the cold face, and two in between, with the objective to confirm the original chemistry of the bricks and to determine whether any changes in chemistry occur during service. Each sample was pulverised (<200µm), roasted at 950°C for five hours, producing a 40 mm sample disc. The sample was then inserted into the XRF machine, where it was analysed. The XRF measurement time was 30 minutes, at a voltage of 20 kV and intensity of 1200 µA.

3.6.4. X-ray diffraction (XRD)

The phase composition of the refractory material was determined by x-ray diffraction. Three samples were taken from a used refractory brick; at the hot face, refractory-slag interface and cold face. Samples underwent grinding in a ball mill for 2 hours. The powder wa then transferred to a plastic sample holder, which subjected to XRD.

3.6.5. Scanning electron microscopy (SEM)

Three samples from a used refractory brick from a torpedo ladle that had experienced premature failure were analysed using scanning electron microscope, the Leo 1525 SEM with EDS analyser. The samples were taken at the cold face, refractory-slag interface and hot face, to determine the changes to the microstructure. Furthermore, changes in chemical composition, as well as the distribution of different elements present were determined using EDS. Each sample was analysed at 50x, 250x, 500x and 1000x magnification to study the microstructure, after which, SEM and EDS were combined to determine chemical analysis and elemental distribution.

Chapter Four: Results & Discussion

4.1. Heat profile of torpedoes

The torpedo shell is fabricated from EN10028, which is a heat resistant pressure vessel steel. The steel contains chromium and molybdenum to improve the heat and corrosion resistance, as well as weldability. It has a maximum operating temperature of 400°C, after which, the shell's properties begin to deteriorate. As seen in Figure 4, for a new torpedo, the average shell temperature should be 220°C, which is significantly lower than the maximum operating temperature. Furthermore, it can be seen that the average temperature of the back-up lining is 285°C, which is also below the maximum operating temperature, indicating that the chosen refractories have excellent thermal properties. Thus, the heat profile of the torpedo indicates that the material chosen for the refractory lining is suitable to prevent plastic deformation to the torpedo shell.

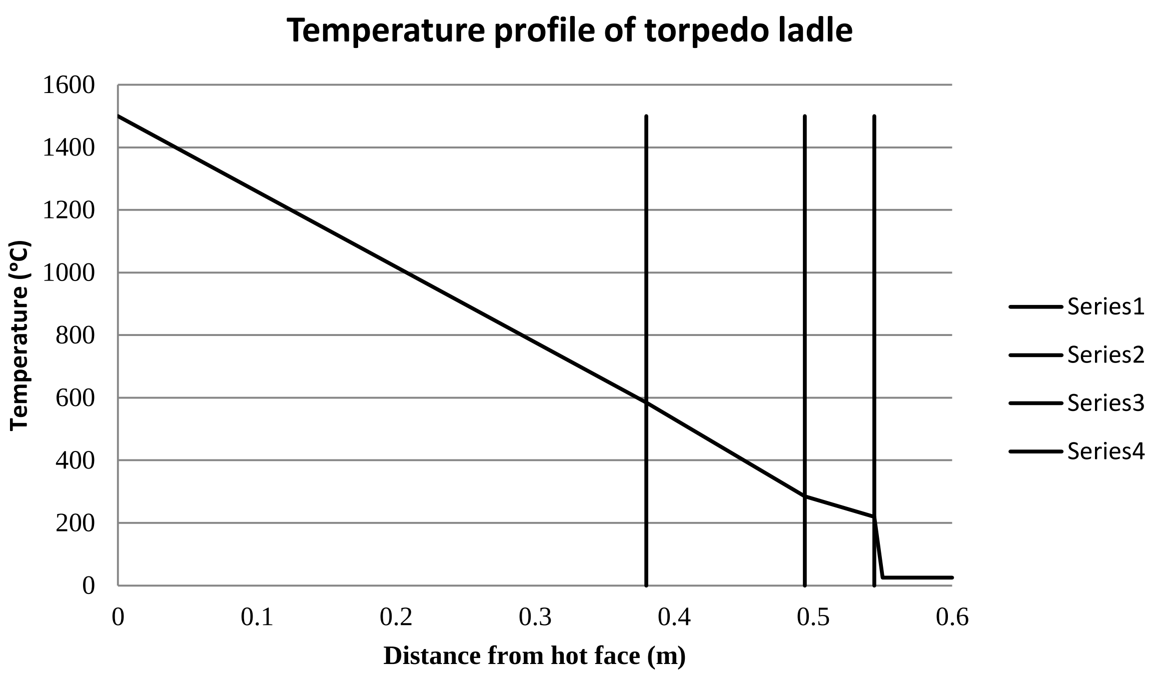


Figure 4: Temperature profile of torpedo ladle

However, due to wear and corrosion of the refractory, the thickness of the hot face gradually decreases. This is especially important for the slag line as corrosive slag results in a high erosion rate. The critical thickness was found to be 158 mm (Appendix 2). When the refractory has reached this thickness, the temperature of the shell has reached 360°C, which is considered to be critical, and the limit of thermal stability will soon be reached. According to Baetu, et al., when this occurs, the shell may experience degradation, chemical change and excessive creep. The tensile and yield strength are also lowered when exposed to high temperatures. This indicates that the material will experience plastic flow at lower loads, increasing its susceptibility to failure. In addition, the torpedo is subjected to thermal cycling as it undergoes constant filling and emptying of hot metal. This results in continuous expansion and contraction of the material, which induces thermal stresses, resulting in the formation of cracks. This occurrence is aggravated when the shell temperature exceeds it operating temperature, causing creep-fatigue cracking in high stress areas, resulting in creep deformation.

4.2. Corrosion analysis of the system

The molten metal does not contain any components that are expected to have a corrosive effect on the refractory. Thus, it is only responsible for high erosion rates at the impact area and at the top of the metal zone. The major components of the slag are Al_2O_3, CaO, MgO and SiO_2, which is in contact with a refractory whose major components are Al_2O_3 and SiO_2. The compositions of the slag and refractory in 2019 and 2010 are found in Table 4.

Table 4: Chemical composition of slag and refractory

Chemical composition		Major chemical compound			
		Al_2O_3 (%)	CaO (%)	MgO (%)	SiO_2 (%)
2019	Slag	16	34	10	37
	Refractory	56	0.4	0.3	41
2010	Slag	13	35	10	38
	Refractory	59	0.3	0.2	40

In 2010, torpedoes experienced good life, reaching campaigns of up to 400 000 tons. However, in 2014, the brick composition was changed, thus it is important to compare the degree of corrosion then and now to determine there has been an increase in the corrosion rate. Table 5 shows the chemical composition of the hot face brick in 2010 and 2014, as well as its apparent porosity.

Table 5: Composition and apparent porosity of hot face brick

Hot face brick	2010	2014
% SiO_2	39.7	41.2
%Al_2O_3	58.6	56.3
%CaO + %MgO	0.5	0.7
Apparent porosity	14.7	7.7

Each system was evaluated using the Al_2O_3-CaO-SiO_2-10%MgO ternary phase diagram, as shown in Figure 5 (a) and (b).

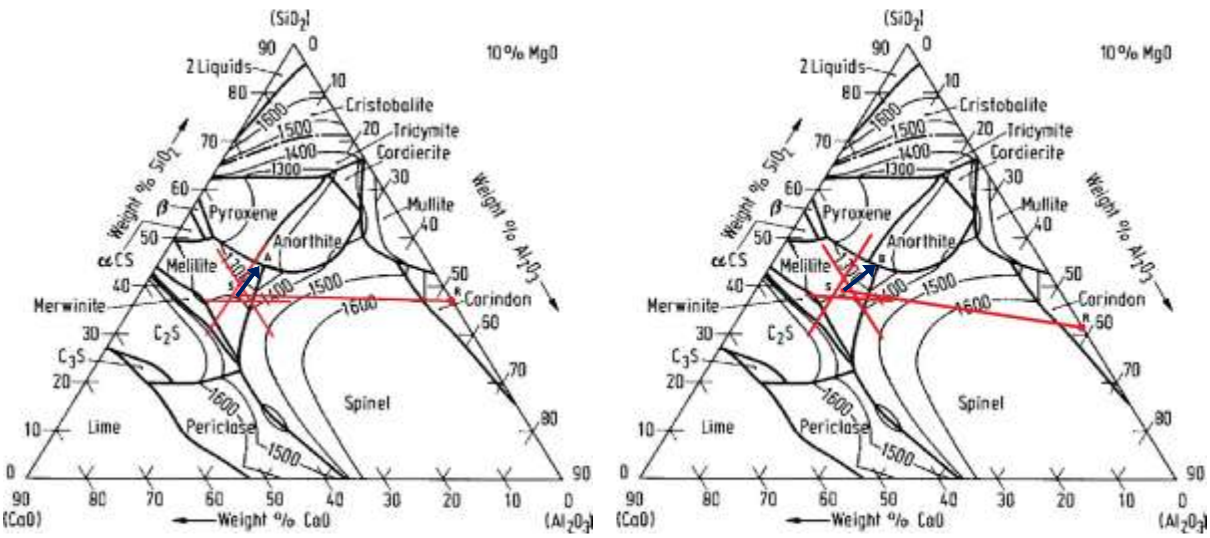


Figure 5: Al2O3-CaO-SiO2-10%MgO Ternary phase diagram showing slag and refractory interaction in (a) 2019 and (b) 2010

In Figure 5 (a), the refractory composition is represented by point R and the slag by point S. When the bulk composition is plotted, a triangle is formed due to other chemical species that are present in the slag. The triangle represents possible slag composition. At the slag-refractory interface, the composition move towards the slag from the refractory. Since the slag is not saturated with Al_2O_3, there will be dissolution of Al_2O_3 into the slag. Thus, the composition at the hot face will have a lower Al_2O_3 content. As dissolution occurs, the composition of the slag moves towards the ternary eutectic at point A, at which it becomes saturated with Al_2O_3. The reaction rate at the interface is not uniform. The reactions begin to slow down as the temperature decreases and slag viscosity increases, as a result of temperature losses and increasing alumina content in the slag. When saturated, diffusion of CaO into the refractory takes place. At point A, precipitation of the corrosion product occurs.

The corrosion analysis corresponds to literature (Brosnan, 2004) as the slag and refractory are not considered to be compatible. There is a significant difference between the %Al_2O_3 in the slag and refractory. This implies that dissolution of alumina will occur at the refractory-slag interface. It may react with CaO and MgO as both components are not present in the refractory, and precipitation of both anorthite and spinel should occur. However, at 1500°C, CaO is more reactive than MgO, this it is expected that precipitation of anorthite will occur as only small amount of slag enter the system. This liquidus is below 1300°C, which is a low melting point phase that may be removed with molten metal. When compared to 2010, the Al_2O_3 composition in the brick was higher and the slag had a lower Al_2O_3 composition, which indicates a lower slag viscosity and it is less saturated with Al_2O_3. As a result, the extent of corrosion is greater in 2010, thus, the decrease in torpedo life cannot be attributed to corrosion. Furthermore, in both cases, the degree of corrosion is small due to slag being present in small amounts, thus exposure the slag should not have a detrimental effect on the brick as the change in Al_2O_3 content should not be too large, which will be confirmed by the chemical composition in Section 4.5.3. Furthermore, literature (Brosnan, 2004) states that slag corrosion rates increase with increasing apparent porosity. Thus, the decrease in apparent porosity in the brick decreases its susceptibility to corrosion.

4.2.1. Effect of slag viscosity

The average viscosity for each year is shown in Figure 6. Data was analysed for slags produced during 2010-2019.

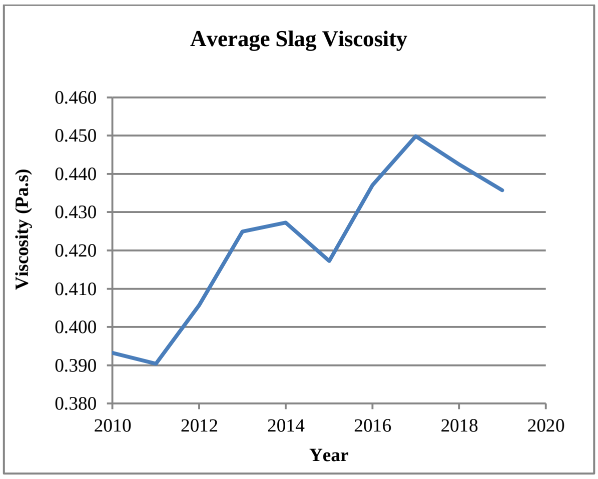


Figure 6: Average slag viscosity

Over the 10 year period, there has been a gradual increase in the slag viscosity. This is due to the increasing Al_2O_3 content in the slag. Since literature (Lee & Zhang, 2004) states that slag viscosity is inversely proportional to corrosion rate, an increasing viscosity indicates that there should be a decrease in corrosion rate of refractories. This occurs due to the slag becoming less fluid, decreasing penetration. Thus, the decrease in torpedo life is not a result of the change in slag viscosity.

4.3. Installation of refractories

The installation of the refractory lining for a torpedo was observed to determine whether it was built according to the ArcelorMittal SA, Newcastle Works procedure. There are a few critical steps that were followed correctly. The first was laying of the first refractory bricks. The refractory lining inside a torpedo ladle consists of two layers; the back lining and the hot face. The ladle was first lined with a back lining, which began at the centre of the torpedo, where one line of bricks was laid along the entire length of the barrel section. This is done to ensure that incorrect building of refractories does not occur. After the first line was installed, the refractories were built away from the centre, up to the sides of the barrel.

The next critical step was filling the area where the 114 mm barrel back lining and 51 mm cone back lining meet with a refractory castable of quality similar to the back lining brick. Due to a difference in thickness, it is important to level the difference to prevent corking at a later stage.

Another important step is corking of the back lining, which takes place before completing the roof of the barrel section. Unlike the floor of the ladle, the roof does not have a brick back lining. Instead, the brick lining is replaced with refractory concrete. This process is known as corking, and it is extremely critical. If done incorrectly, metal penetration may occur when the hot face has worn. At the spout, there are bolts securing the cast iron spout to the ladle. In this area, the entire cavity was corked carefully to minimize metal penetration.

The final step in the process was to cast the spout. A former, which was used to cast the spout, was installed in the spout area. The former was first oiled with a release agent to facilitate easily removal after casting. If the former is not oiled sufficiently, it may stick to the castable and break it. A high quality castable was used to fill the former, which was further vibrated by means of electrical vibrators to achieve the correct height. Once completed, the newly casted spout set for at least 24 hours before the former was removed. Care was taken to remove the former carefully to prevent the formation of cracks inside the torpedo and the spout.

Furthermore, few deviations were noticed. The procedure states that an inspection must take place after the back lining is installed, and again, when the hot face has been installed. Unfortunately, no inspections were done, which leaves room for error during the installation process, and no corrections can be made after the entire torpedo has been built. The other anomaly that was noticed was the application of mortar to bricks. The mortar was only applied on the edges of the brick and pressed down. The application was also noted to be uneven. According to literature (Bhatia, 2011), mortar must be applied evenly, to the entire surface of the brick, which must emerge when pressed down, removing all excess mortar and ensuring the width of joint at 1 mm. Incorrect application results in poor allowance for expansion, resulting in stress cracking of the brickwork or open spaces in joints, which may allow for liquid metal or slag penetration. In addition, if there are spalling cracks present, penetration may occur inside the crack, accelerating the crack propagation, which eventually causes pieces of the brick to break off.

4.4. Observation and evaluation of operations

4.4.1. Pre-heating of torpedoes

The information available for pre-heating of torpedoes only indicates burner temperature when there is a torpedo placed under it. The temperature is controlled by a system that causes the burner to trip when the temperature is below 800°C. As a result, the problem is rectified immediately, and there are no anomalies in the information. However, it does not indicate whether all burners were operational. The need for burners depends on blast furnace production. Thus, a higher production will require more torpedoes to be under burners. When burners are taken out of operation, it may force a torpedo that has not undergone preheating to report to the blast furnace for molten metal transport. Due to the extreme change in temperature, the bricks experience thermal shock during filling of the torpedo. This causes stress within the refractory as a result of a sudden volume change. These stresses lead to cracks, which propagate rapidly due to the brittle nature of refractories.

4.4.2. Filling of torpedo at blast furnace

ArcelorMittal iron making practices state that, at the blast furnace, each cast takes approximately two hours, and approximately 45 minutes to fill one torpedo, depending on the blast volume. Thus, when one torpedo has been filled, the tilter is moved to the second torpedo and the filled torpedo is replaced by an empty one. Furthermore, literature dictates that the level of molten metal inside the torpedo should be 250 mm from the roof or it should be 90% full. The torpedo level is determined by visual inspection. Unfortunately, this is not an accurate method, which may cause the level to vary from torpedo to torpedo. This may result in over-filling of torpedoes, which causes thermal shock of bricks in the spout area as it is cooler than the rest of the torpedo. Overfilling may also result in molten metal overflowing out of the torpedo through the spout, causing erosion of the spout castable, burn through of steel shell and damage to the rails and tilting cables.

4.4.3. Tapping of torpedoes at steel plant

Torpedoes filled with hot metal were received by the steel plant, where it is prepared to be tilted to pour the hot metal into the ladle. When the ladle was placed into position below the torpedo, the torpedo was tilted until hot metal started flowing out. The flow must be controlled, by titling the torpedo back and forth, to ensure the hot metal stream is not too wide. A wide stream can cause material to be tapped over the sides of the ladle or onto the splash shield, which may result in material loss, burning of cables and lost production time. The tonnage being tapped into the ladle was monitored using a scale, which counts down to zero. As the target was approached, tapping was slowed down by tilting the torpedo upwards. When tapping was completed, the torpedo was tilted upwards until there was no hot metal flow.

According to the ArcelorMittal SA, Newcastle Works operating procedure, upon completion of tapping, the torpedo must be returned back to its upright position. In this case, the torpedo was tilted approximately 30° towards the ladle. This has adverse effects on the torpedo, as well as subsequent filling at the blast furnace. Since torpedoes hold more hot metal than hot metal ladles, the torpedoes often contain hot metal when they are tilted up. This may cause thermal shock to the bricks present around the spout, as they are only meant to be in contact with the hot metal during pouring, and not for extended periods of time. As a result, the bricks in the spout area are weakened as spalling may occur. Continuous brick removal in this area will cause metal penetration, which may burn through and cause premature failure of the vessel. Skull formation may also occur at the spout when the torpedo is tilted. Skulls in torpedoes are formed when metal or slag attaches to the refractory wall and builds up gradually, which is a result of too low temperatures. Since the refractories in the spout area are colder than the molten metal and the lower section of the torpedo, solidification may occur. Skull formation is unwanted as it reduces the working volume of the vessel, it contributes to heat losses as energy is consumed when the skull begins to melt after being filled with molten metal and it causes refractory removal together with the skull. Furthermore, if the torpedo is sent back to the blast furnace in the tilted position, it makes filling difficult as the opening has been narrowed. It also gives a false sense of the torpedo level, depending on the view, resulting in overfilling, which may cause thermal shock, or insufficient filling of the torpedo, which has an adverse effect on productivity and may contribute to skull formation. It was also observed that there are instance where there is molten metal remaining in the torpedo when it is sent back to the blast furnace, which contributes to skull formation as the material has sufficient time to solidify before it is filled again.

4.4.4. Evaluation of operations

Due to the anomalies observed at the blast furnace and steel plant, torpedoes that completed campaigns with less than satisfactory cumulative tonnages were investigated further. Molten metal mass, shell temperature data and tap to tap and residence times for specific campaigns were analysed.

From 2010 to 2019, there were four torpedoes that were removed from service that did not reach the desired campaign mass. Table 6 shows the mid- and full campaign masses, which are expected to be 150 000 and 300 000 tons, respectively.

Table 6: Mid- and full campaign molten metal masses

Torpedo No.	Campaign duration	Mid-campaign mass (tons)	Full campaign mass (tons)
5	12/2014 - 08/2015	145 250	266 485
1	11/2014 - 07/2016	161 119	270 179
7	01/2016 - 11/2016	-	169 500
2	06/2018 – 08/2019	-	185 645

The molten metal mass was investigated to determine if overfilling takes place. Overfilling causes contact between slag and bricks that are not meant to be in contact molten metal, which contributes to spalling as a result of rapid temperature changes. Figure 7 (a) to (d) shows the molten metal masses for torpedoes that experienced short life after its mid-campaign reline.

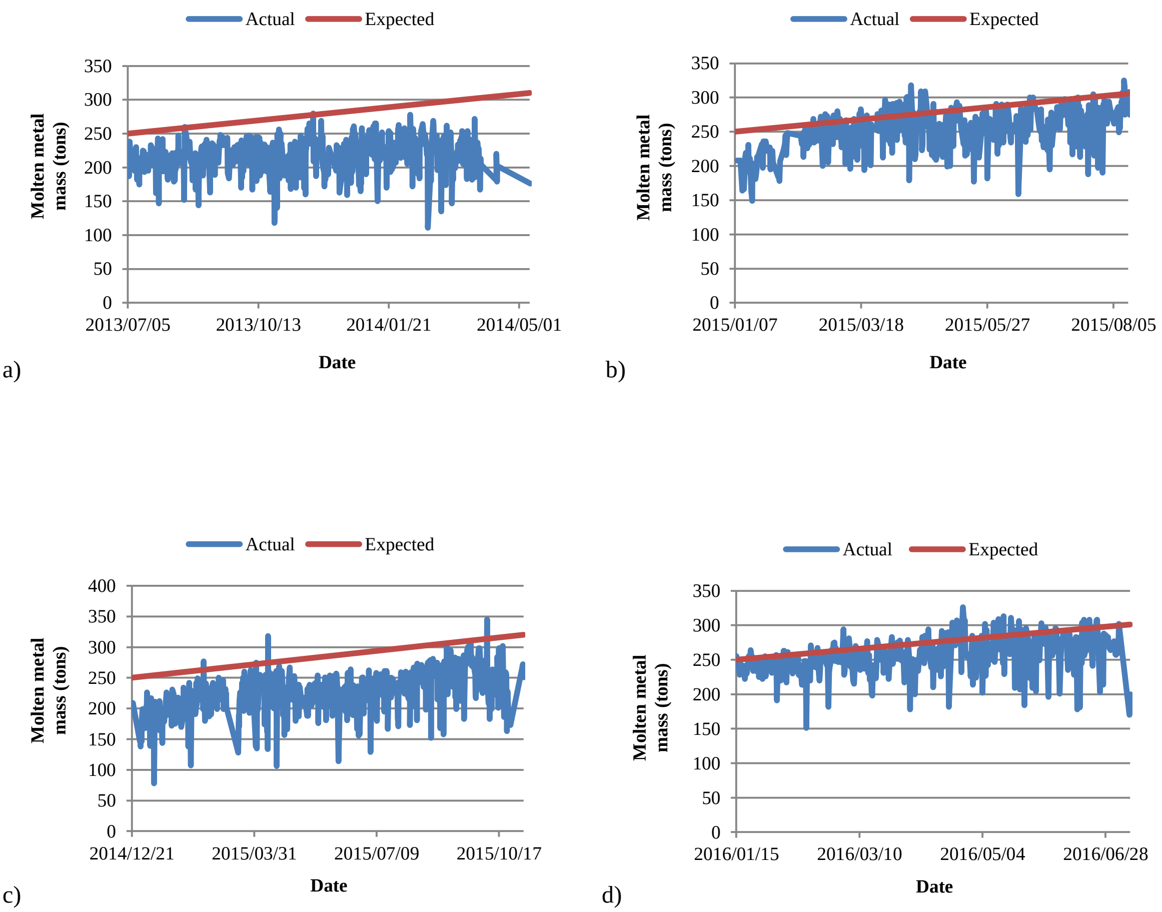


Figure 7: Molten metal mass for (a) Torpedo no. 5 during mid-campaign, (b) Torpedo no. 5 during full campaign, (c) Torpedo no. 1 during mid-campaign, and (d) Torpedo no. 1 during full campaign

The mass of liquid iron is expected to increase during the campaign life of the torpedo due to an increase in volume as the refractory is worn away. The red line represents the expected molten metal mass during the campaign. For both torpedoes, as shown in Figure 7 (a) and (c), the actual masses before the mid-campaign reline were equal to or below the expected mass, which resulted in a good mid-campaign life. However, Figure 7 (b) and (d) show that after the mid-campaign reline was completed, actual masses frequently exceed the expected mass, which lead to shortened campaign lives. Thus, in keeping with literature (Ministry of Steel, 2004), overfilling of torpedoes has an adverse effect on the life of the torpedo.

Figure 8 (a) and (b) represents the molten metal mass for torpedoes that have been removed from service for a full reline after they have exceeded their mid-campaign life.

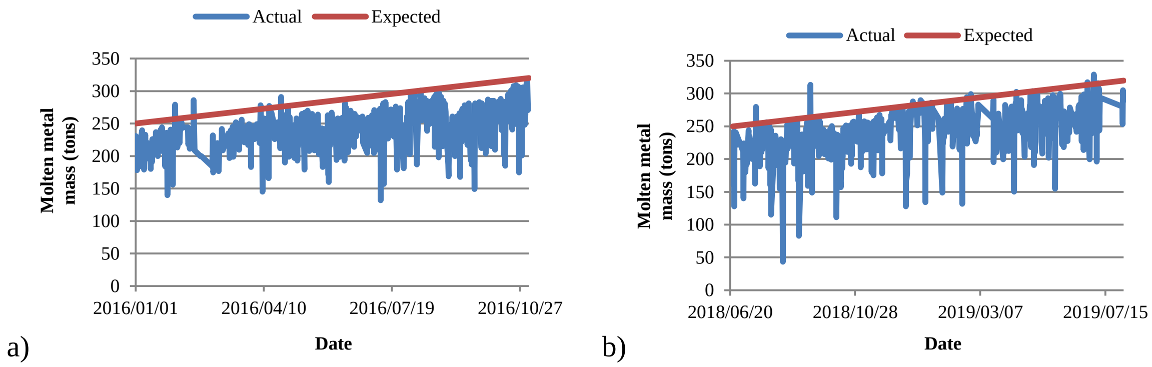


Figure 8: Molten metal mass for (a) Torpedo 7 and (b) Torpedo 2

For both torpedoes, the molten metal mass does not exceed the expected mass, which indicates the torpedoes were not removed as a result of damage caused by overfilling. Thus, the shell temperature was investigated. Figure 9 (a) and (b) shows the maximum shell temperature of the torpedo, as determined by thermal scanning.

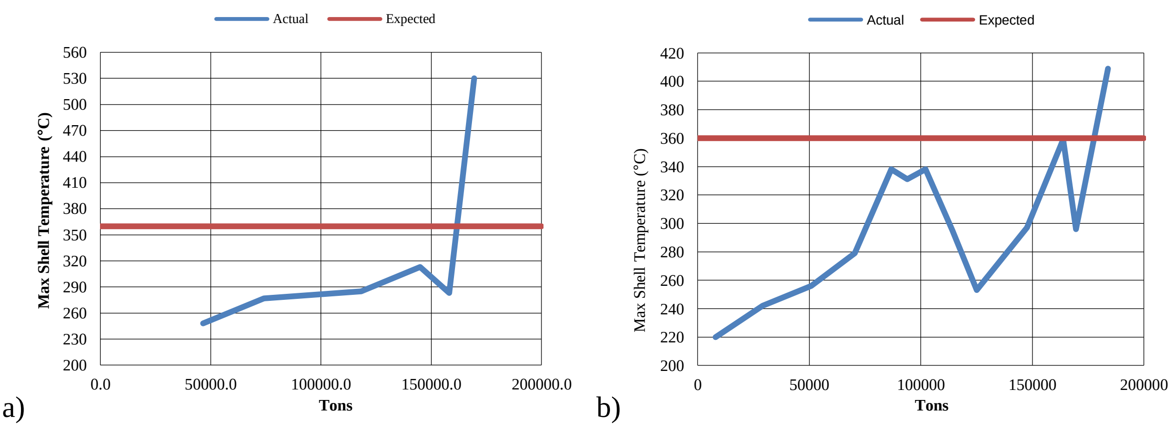


Figure 9: Maximum shell temperature of (a) Torpedo 7 and (b) Torpedo 2

Thermal scanning of torpedoes, which is also known as condition monitoring, is a form of predicative maintenance, which involves monitoring of the shell temperature at specified intervals, to identify significant changes indicative of developing faults. Typically, an increase in shell temperature implies a loss in refractory thickness. The maximum shell temperature of the torpedoes increase significantly after the mid-campaign life is reached. It is recommended that the torpedo does not remain in operation for too long once it has exceeded 150 000 tons. At this point, the refractories have been worn significantly, therefore, it is important to use with caution. The final temperature of both torpedoes is greater than the expected, indicating that there are weak spots on the torpedo shell. Weak spots may arise due to severe refractory wear in certain areas, or if spalling occurs and pieces of brick are removed during operation. Due to these weak spots, the properties of the shell are compromised, which is in agreement with literature (Baetu, et al., 2016), thus, it was necessary to remove the torpedoes from service, to prevent burn through of the shell.

There were also seven instances where a full reline was required as a result of skull formation. Table 7 shows torpedoes that were removed from service due to skull formation.

Table 7: Torpedoes removed due to skull formation

Torpedo No.	Campaign duration	Full campaign molten metal mass	Residence time of molten metal in torpedo	Last tap to tap time	Molten metal weight	Molten metal temperature
13	02/2010 - 01/2011	186 367	02:24:02	11:44:33	69	1446
1	07/2011 - 01/2014	288 608	01:29:10	05:45:25	245	1462
3	12/2014 - 12/2016	255 054	04:15:51	18:26:15	76	(Not available)
1	01/2017 - 05/2017	41 984	03:52:51	18:07:07	229	(Not available)
5	11/2015 - 05/2017	237 417	03:54:54	13:11:30	215	(Not available)
6	05/2017 - 11/2017	223 123	02:31:58	05:28:15	250	1320
7	09/2018 - 11/2018	90 241	189:58:53	08:32:30	0	1462

The residence time of the molten metal inside the torpedo is 2 - 4 hours and the maximum tap to tap time, which is the time taken from emptying the torpedo until it is filled with molten metal, is 9 hours. The last tap to tap time for torpedoes 13, 3, 1 (2017) and 5 (2017) exceed nine hours. When the torpedo takes a long time to return to the blast furnace, the torpedo does not have time to stand under the burner to pre-heat, which causes the refractories in the torpedo to cool down. When molten metal is tapped into the torpedo, it causes the molten metal temperature to decrease. When the solidification temperature is reached, skull formation occurs. Therefore, the longer the standing time, the more likely it is that skull formation will occur. Furthermore, when torpedoes are not completely emptied, the material remaining inside the torpedo solidifies once it reaches the blast furnace, resulting in larger skulls being formed. Torpedo 13 had a molten metal mass of 69 tons, which indicates that skull formation may have occurred during the previous trip. Further investigation revealed that the previous trip had a tap to tap time of 11:03:40 and the molten metal temperature was 1358. Filling a torpedo that has cooled down with molten metal of a low temperature is likely to result in skull formation. The final molten metal mass was 235 tons, which is lower than the average, indicating that a portion of the material solidified prior to tapping at steel plant. Torpedoes 3 and 7 experienced high residences times of molten metal inside the torpedo. After four hours, further heat loss causes solidification of the material, forming skulls. Torpedo 3 had a molten metal mass of 76 tons, which indicates that solidification of material took place before the torpedo was emptied, thus only a small tonnage was still liquid. Torpedo 7 had a residence time of 189 hours and a molten metal mass of 0, which indicates that all the material inside the torpedo solidified before it was ready to be tapped at steel plant. The hot metal temperature for torpedo 6 was 1320°C, and at this low temperature, the allowable heat loss is limited, thus, solidification occurs more rapidly.

4.5. Analysis of refractory brick

4.5.1. Macroscopic Evaluation

Prior to breakout, the refractory bricks were inspected while they were still installed in the torpedo, which is shown in Figure 10.

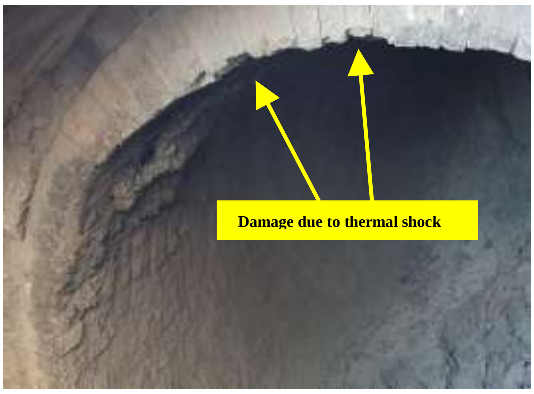


Figure 10: Refractory bricks inside torpedo ladle

The bricks at the top of the torpedo are much longer than those found at the slag line or in the metal zone. This is expected as the torpedo is considered to be full when the molten metal level is at 250mm from the top, thus, the roof is not in direct contact with the molten metal. However, some bricks have experienced some damage to the hot face. The damage is non-uniform, thus, it is likely due to an undesirable condition, such as overfilling or improper heating of torpedoes. It can be seen that the hot face of some bricks have broken off completely. This indicates that the brick may have experienced thermal shock, causing the brick to fracture. This is typically a result of overfilling of the torpedo. Figure 11 shows the refractory bricks present on the upper arch.

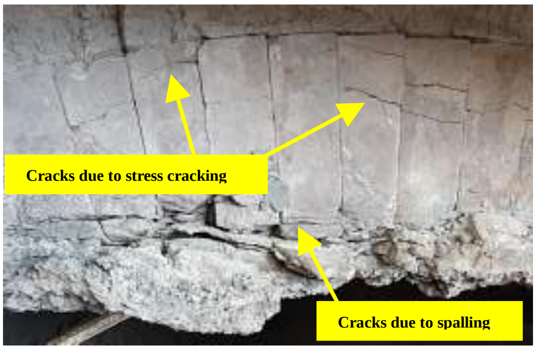
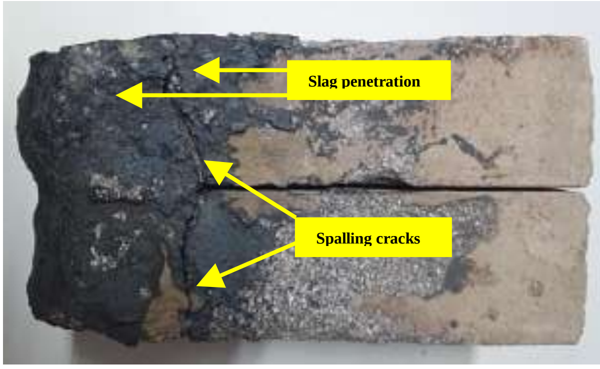
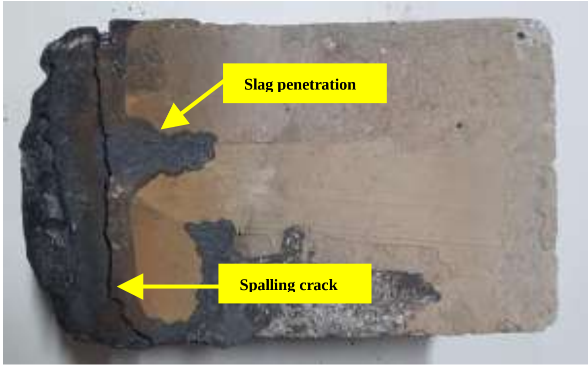


Figure 11: Upper arch of torpedo ladle

Cracks are visible towards the hot face and cold face. The cracks closer to the hot face appear to be a result of spalling. Uneven expansion and contraction within the refractory is caused by rapid temperature changes. This generates internal stresses and strains, which eventually cause cracks to appear and propagate. The cracks present at the back are due to stress cracking. The cold face of the brick is not exposed to temperature that can cause thermal shock. Thus, as stated in literature (Bhatia, 2011), this is a consequence of improper installation as it occurs when joints are too tight, which does not cater for expansion, thus the bricks experience excessive stress, causing them to crack.

Further inspection was conducted on bricks that were taken from the slag line. Figure 12 (a) and (b) show the top and side view of the bricks.





a) b)

Figure 12: Spalling cracks and slag penetration shown from (a) top view and (b) side view

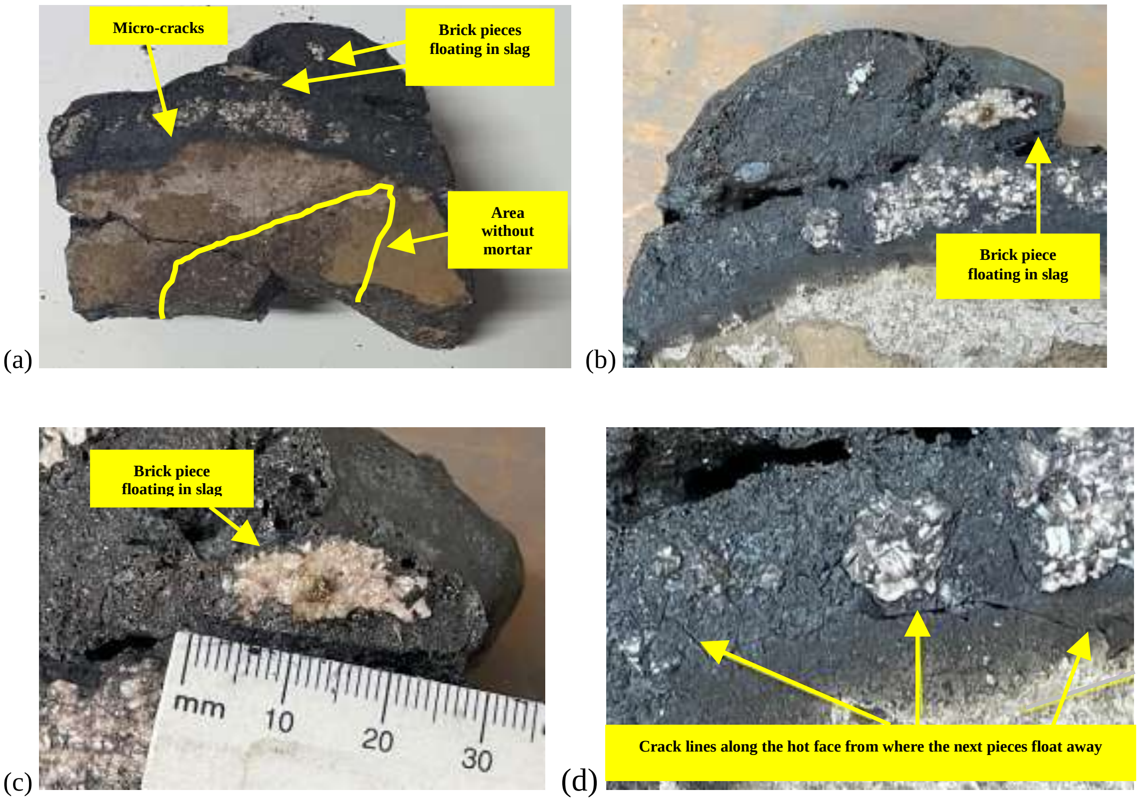
The cracks are clear and well defined and they are evidence of spalling. Other than overfilling, spalling may also occur as a result of inadequate pre-heating or standing too long at steel plant. The darker areas close to, around and behind the spalling cracks indicate that slag has entered and reacted with the brick. There is also slag penetration inside the crack, as shown in Figure 13.

Figure 13: Slag penetration inside spalling crack

Figure 14 shows the cold face of the bricks, which are in a good condition as there is no evidence of severe damage.

Figure 14: Cold face of the brick

Figure 15 (a) - (f) shows sections of a bricks that was removed from the slag line, which shows a few problems that occur within the refractory brick.



(e) 

(f) 

Figure 15: Problems occurring within refractory brick: (a) Evidence of micro-cracks, brick pieces floating in slag and area without mortar, (b) Brick piece floating away in slag, (c) Length of brick piece floating in slag, (d) Cracks along hot face, (e) Area of brick not covered by mortar, and (f) Area of brick not covered by mortar.

There are large pieces that have spalled off the hot face of the brick that can be seen floating in the slag, which is shown in Figure 15 (a) and (b). The brick appears to be unreacted, which indicates that the brick has good slag resistance. However, due to spalling, the pieces of brick may be removed during operation, which, as seen in Figure 15 (c), is at least 20 mm. Removal of such large pieces will cause rapid deterioration of the brick. Micro-cracks are also visible, which are likely initiated due to spalling or when the brick is penetrated with slag, which may react with the refractory, forming products that have a higher expansion coefficient. They also indicate the next pieces that will be removed by the slag. When these cracks propagate, it results in material loss. Figure 15 (a), (e) and (f) shows areas on the brick that are not covered by mortar. This indicates that the application of mortar during installation is incorrect. The purpose of the joint is to accommodate expansion and contraction during operation, without causing damage to the brickwork (Bhatia, 2011). When there are opened spaces in the joint, liquid metal or slag may penetrate it, which expands and contracts during operation, causing further damage to the brick as the degree of expansion cannot be accommodated. Thus, improper mortar application may also lead to stress cracking in the brickwork.

Figure 16 (a) - (c) show evidence of slag penetration and attack, specifically along the mortar joint and through cracks via the joint.

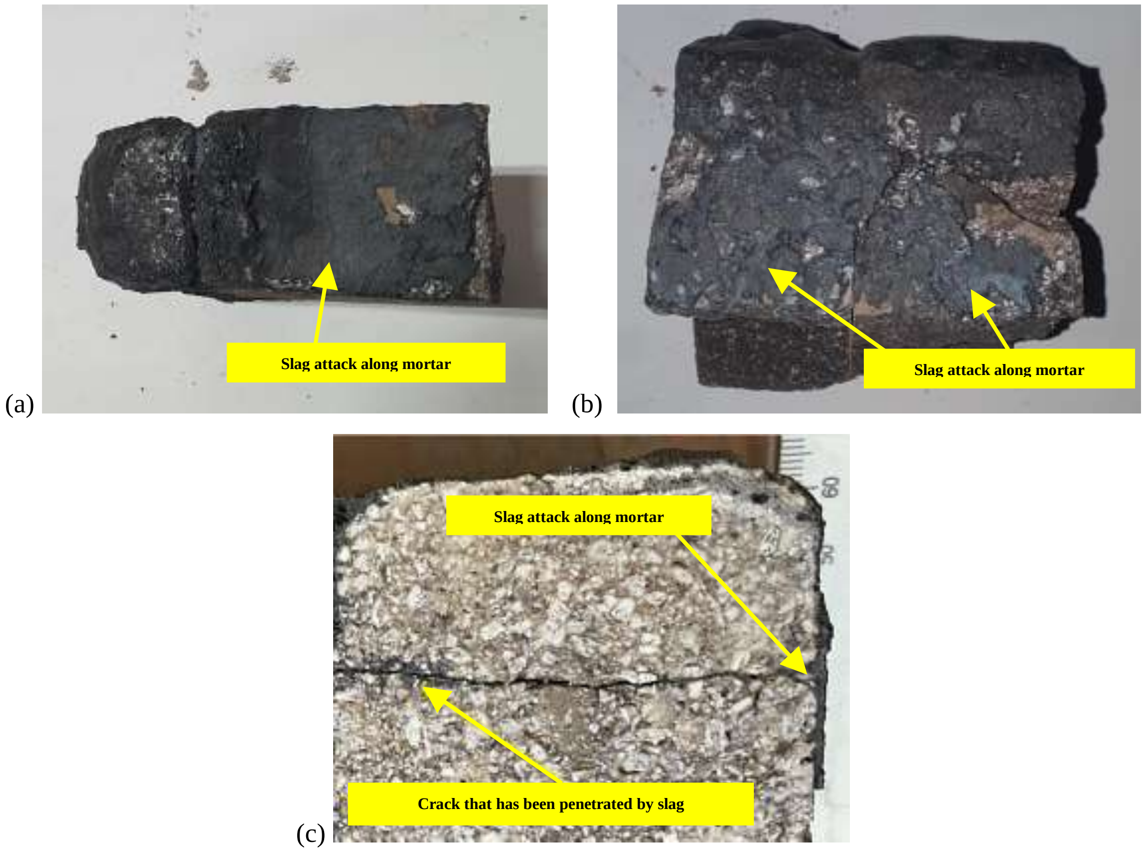


Figure 16: Slag penetration and attack of (a) mortar joint, (b) mortar joint, and (c) mortar and crack via joint

The rule of thumb for mortar selection is, to select a material of superior quality to the brick. Even though the mortar used in this application has a high alumina content, it contains 7% impurities, such as TiO_2 and Fe_2O_3, which may make it more susceptible to slag attack. Furthermore, when there are areas that are not covered by mortar, the joint may be penetrated far deeper than the hot face. This also allows slag to enter between spalling cracks and penetrate from within, as shown in Figure 16 (c). The brick is still is good condition, thus, penetration probably occurred through the crack, via the joint. Slag penetration and attack is evident by the darker coloured area on either side of the crack. This speeds up crack propagation, and ultimately, material removal. Metal penetration may also occur, however, it does not react with the refractory brick. Thus, the metal remains between the crack and the joint, as shown in Figure 17 (a) - (c).

Figure 17: Metal penetration of refractory evident (a) as a metal chip, (b) between a crack, and (c) as a metal plate

Due to poor mortar application and thermal expansion of the hot face of the brick, there is sometimes iron penetration through the joint. The metal expands and contracts during operation as it exposed to a wide range of temperatures. Upon expansion, new cracks may develop and existing crack may propagate, increasing the frequency of material loss. Since penetration of joints, either by slag or metal, adversely affects the effect the brickwork's ability to accommodate expansion, this may also contribute to the stress cracking experienced by the bricks.

4.5.2. Microscopic analysis

Since most evidence was gathered via macroscopic inspection, the only area that required microscopic inspection was the mortar joints. The mortar joints were studied at a magnification of 10x. Figure 18 (a) shows a mortar joint, and Figure 18 (b) shows a mortar joint that has been penetrated and chemically attacked by slag.

(a) 

(b) 

Figure 18: Micrographs of (a) unpenetrated and (b) penetrated mortar joints

There are three important things to note about the mortar joints. Firstly, the mortar joints are not uniform. Joints are required to be 1mm; however, it can be seen in Figure 18 (a), the joint are noticeably thinner in some areas. This has a strong influence on whether the torpedo brickwork is able to accommodate expansion without causing damage. Uneven joints may decrease the ability to accommodate expansion, leading to stress cracking. The second problem is that there is slag penetration and chemical attack of the mortar joint, as shown in Figure 18 (b), which may result in products that either have higher expansion coefficients, which impose more stress and strain on the brick, or those that have lower melting points, which result in material removal with liquid slag. The area of attack shows open spaces, which implies that there was removal of material due to liquid formation. In comparison to the brick, the mortar also contains a higher percentage of impurities, which includes titania, iron oxide, calcia, magnesia, sodium oxide and potassium oxide. The brick has 0.5% impurities, whereas, the mortar has 7.0% impurities. Higher impurity content is associated with strong flux action at high temperature as they reduce high temperature resistance, causing production of liquid phase. Finally, on the right side of the joint in Figure 18 (b), between the mortar and the brick, there is a darker area. This indicates that there is poor bonding between the brick and mortar in that area. This is a result of improper installation. It is important for mortar to be mixed correctly, to be free from impurities and to be applied uniformly to the entire surface area of sides that make contact with already installed bricks. Mortar that is too dry or applied incorrectly may result in a weak bond, making the mortar susceptible to metal or slag penetration.

4.5.3. XRF analysis

The sample brick that was used was 280 mm in length. It was divided into four sections, and a representative sample from each section. This shows the change in composition along the refractory brick, as shown in Figure 19.

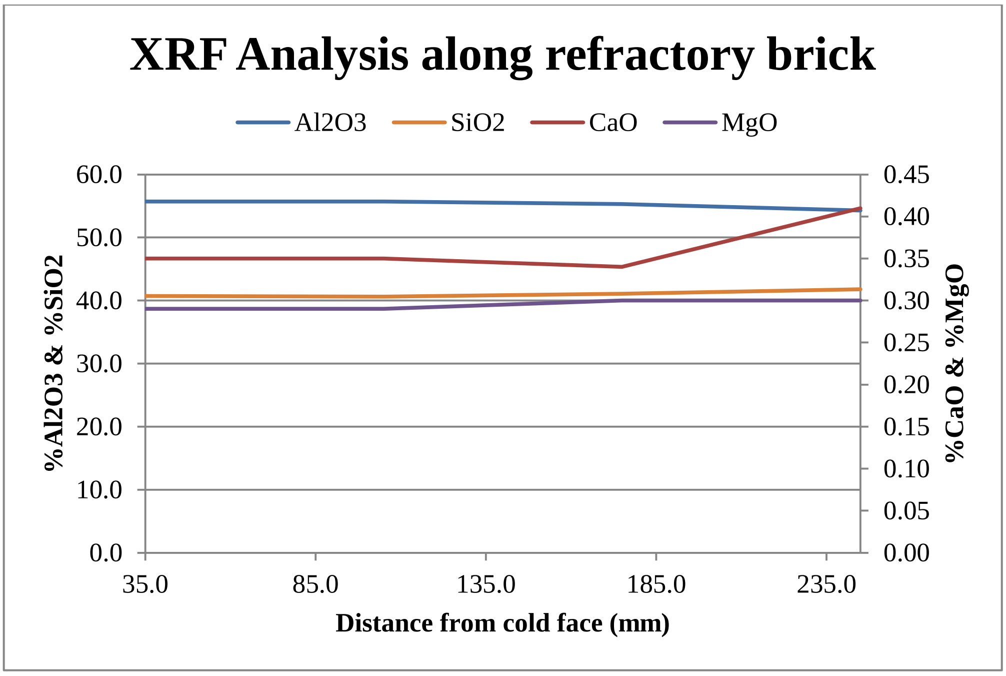


Figure 19: XRF analysis of refractory brick

The $\%Al_2O_3$ and $\%SiO_2$ in the original refractory, which is found at the cold face, was found to be 55.7% and 40.7%, respectively. This composition confirms that the actual brick composition corresponds to the specification provided by the supplier. At this composition, the phases present are mullite and cristobalite, which remains as a solid solution up to 1587°C, thus, the refractory is suitable for the environment it is exposed to. The XRF analysis shows that the brick composition remains relatively the same until the hot face is reached. There is a decrease in the Al_2O_3 content and an increase in the CaO content. The MgO and SiO2 content remain relatively unchanged. This confirms that the alumina in the refractory brick reacts with the calcia in the slag, which is in accordance with literature (Brosnan, 2004). The slag is not saturated with Al_2O_3, thus, the slag consumes the refractory. This causes the dissolution of Al_2O_3 into the liquid slag, which will continue until the slag has been saturated or the solidification temperature of the corrosion product has been reached. Thus, dissolution will cease when equilibrium of the system has been achieved. There is a 1.4% decrease in the alumina content, which indicates that there is a small degree of dissolution that takes place, thus, the corrosion of the system is controlled. At the same time, CaO enters the refractory system, which results in infiltration of slag and corrosion of the refractory. Brosnan further states that CaO causes the solidus temperature of the hot face of refractory to decrease. This leads to liquid formation if the new solidus is below the molten metal temperature. However, in this case, the increase in CaO content is only 0.6%, indicating that the refractory has good slag resistance. However, torpedoes are used on a continuous basis, thus, dissolution of the refractory will occur whenever the torpedo is filled, resulting in refractory loss.

4.5.4. XRD Analysis

Table 8: XRD Analysis of used refractory brick

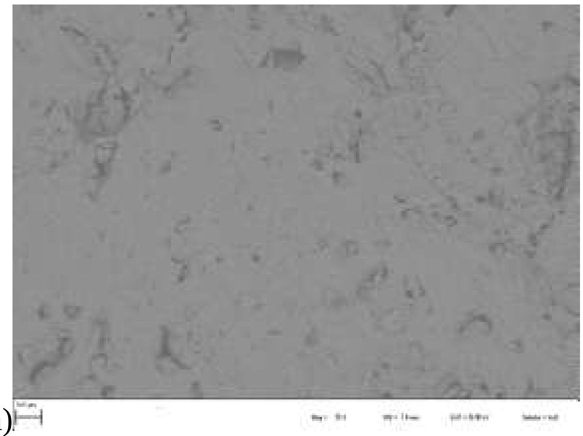
Mineral	Formula	Cold face	Interface	Hot face
Mullite	$3Al_2O_3.2SiO_2$	87.3	74.1	64.1
Quartz	SiO_2	1.3	0.2	0.5
Cristobalite	SiO_2	0.2	4.3	5.7
Cordierite	$Mg_2Al_4Si_5O_{18}$	0.2	2.1	0.2
Tridymite	SiO_2	0.1	1.3	0.9
Hematite	Fe_2O_3	N/D	N/D	1.1
Iron	Fe	N/D	0.7	2.3
Hercynite	$FeAl_2O_4$	N/D	2.6	N/D

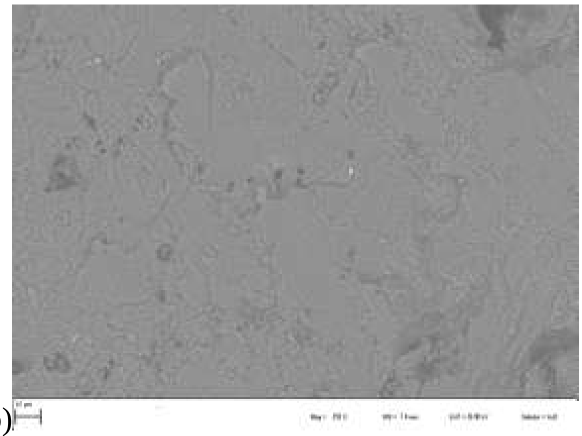
Amorphous	Glassy	10.9	14.8	25.3

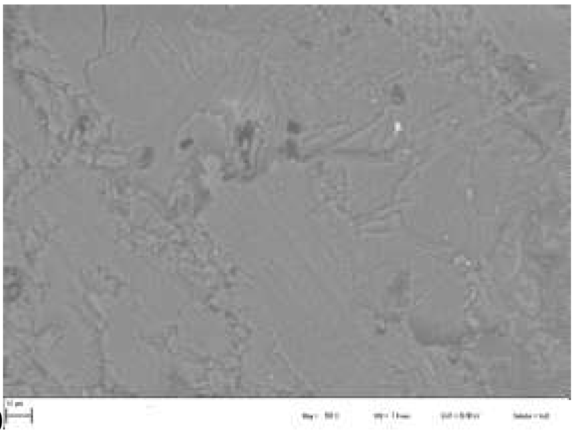
Table 8 shows the phase composition of a use refractory brick at the cold face, refractory-slag interface and hot face. There is a decrease in the composition of mullite and an increase in the composition of the glassy phase, as we move from the cold face towards the hot face. This confirms that there is dissolution of alumina into the slag, and formation of the spinel phase, as predicted by the corrosion analysis of the system. It was also observed that there was an increase in the compositions of cristobalite and tridymite. Figure 5 shows that these phase are present at the SiO_2 apex, and they are both not possible products of corrosion. Their presence may be due to slag infiltration, causing it to solidify in the brick matrix, or inclusions. Hematite and iron are not detected in the cold face, but are present in the hot face. This indicates that there is no corrosion reaction, instead there is iron infiltrating the refractory brick, which solidifies in the brick matrix. Lastly, hercynite and cordierite have an elevated composition at the refractory-slag interface. These compounds are low melting compound products, which usually dissolve into the molten metal. Its presence may be due to infiltration and solidification of these products into cracks formed due to thermal shock.

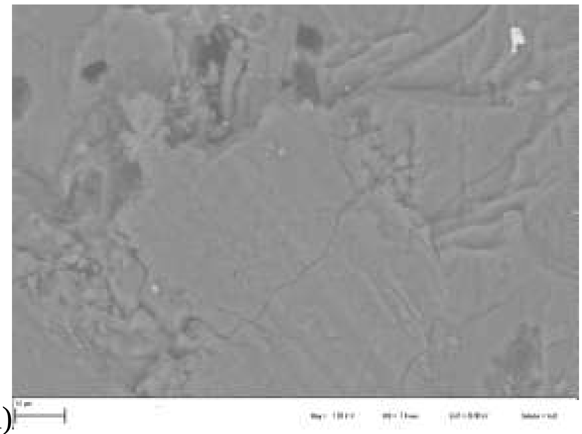
4.5.5. SEM Analysis

Three samples were analysed using SEM/EDS techniques. Figures 21, 22 and 23 are photomicrographs of the cold face, refractory-slag interface and hot face, respectively. Table 9 shows the elemental distribution of each sample.

a) 

b) 

c) 

d) 

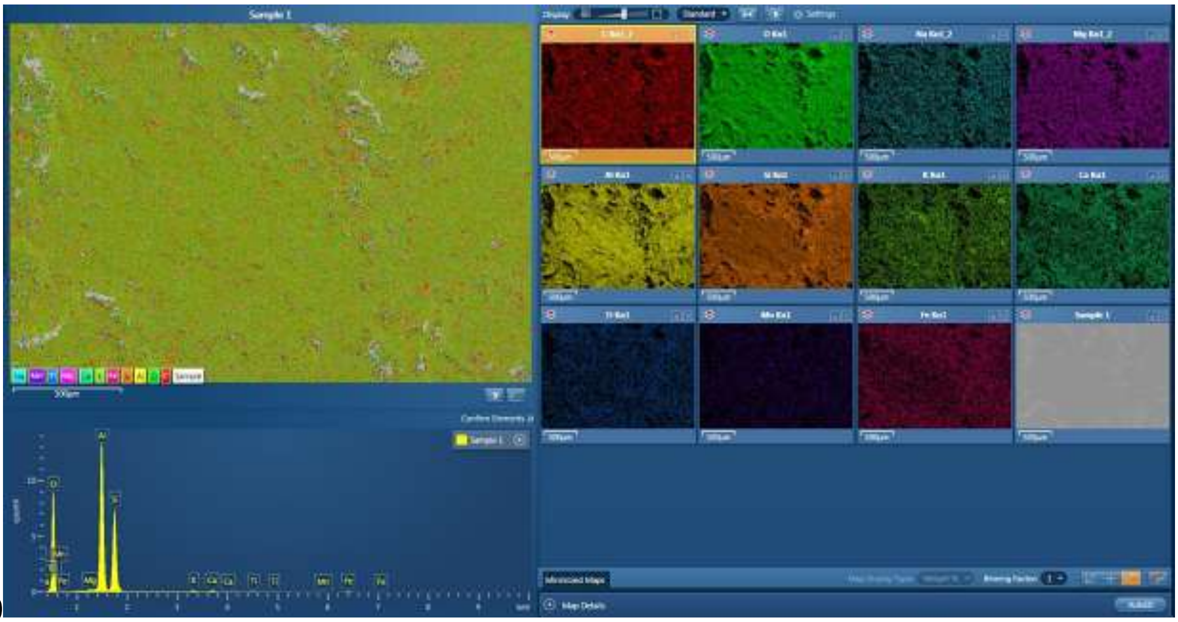
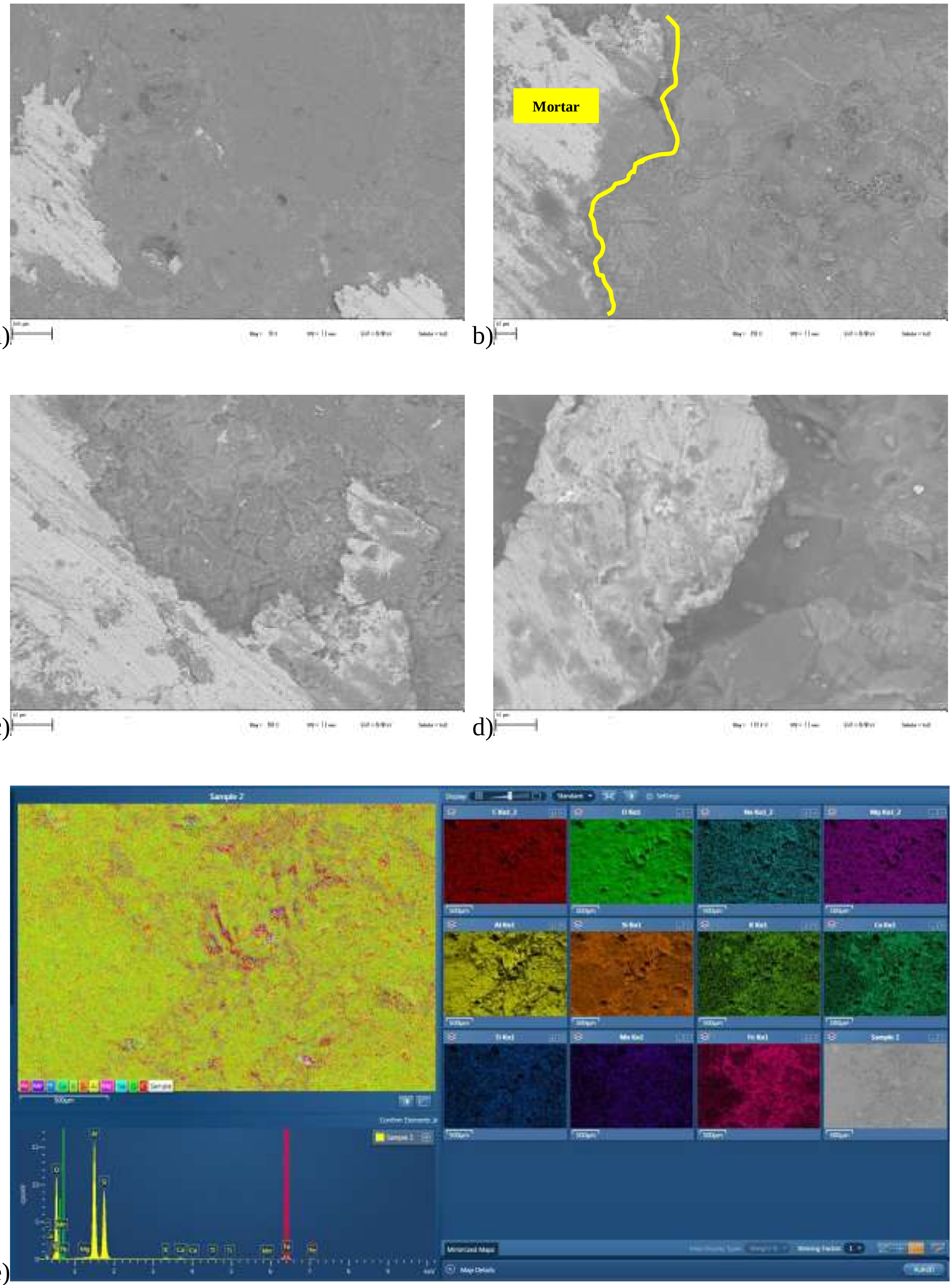
e) 

Figure 20: SEM images of cold face a) at 50x magnification, b) at 250x magnification, c) at 500x magnification, d) at 1000x magnification, and e) with EDS

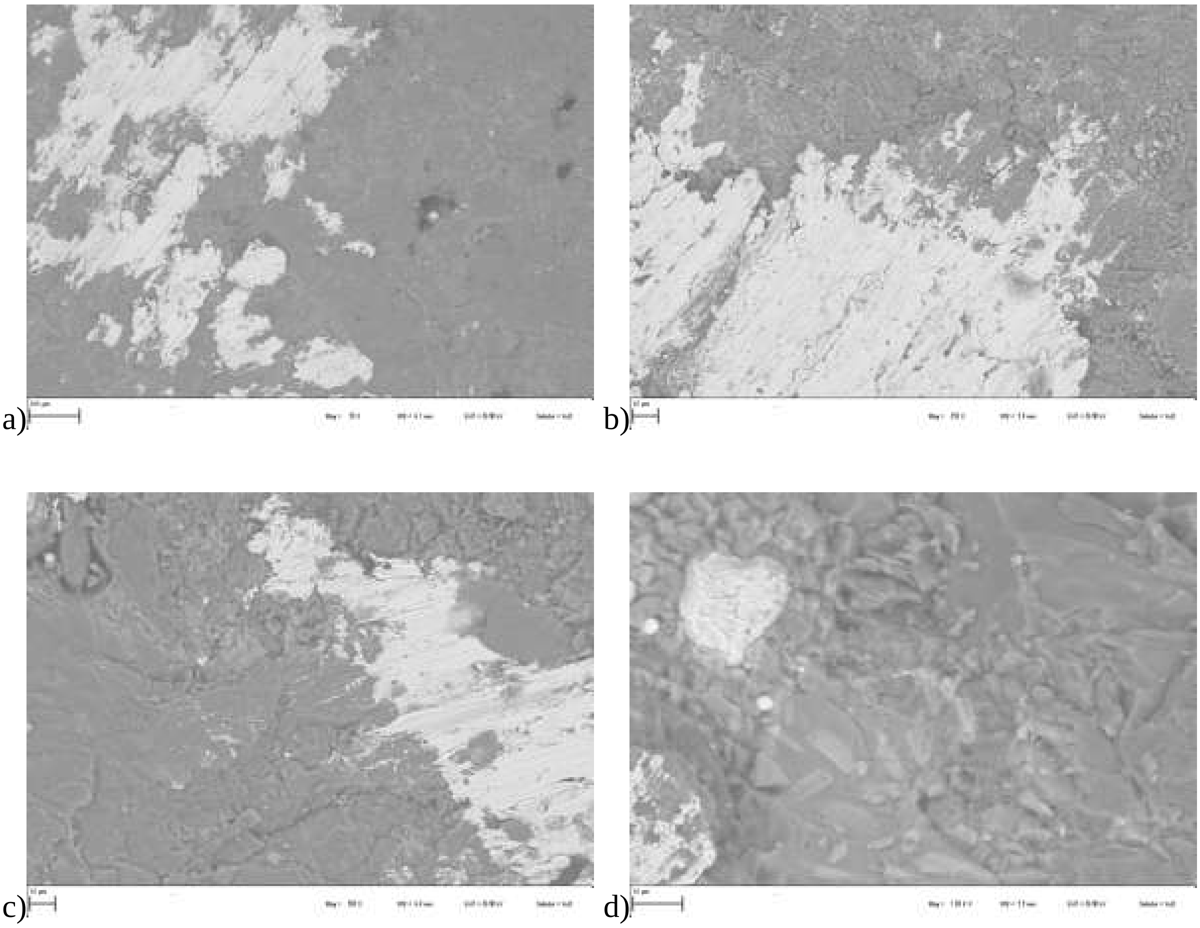
In Figure 20 a), it can be seen that the image is mostly one shade of grey. The homogeneous appearance indicates that the cold face is unreacted. The darker areas result from damage to the brick, where material has been removed. As the magnification of the brick increases, as seen in Figures 20 b) & c), the damage to the brick is more visible. Cracks are also seen in Figure 20 d). Figure 20 e), the SEM image with EDS of the cold face, shows the elemental distribution of the cold face, which mostly comprises of aluminium (Al), silicon (Si) and Oxygen (O) and other trace elements. This shows that the cold face has had little or no change from its original state.



a) b) c) d) e)

Figure 21: SEM images of refractory-slag interface a) at 50x magnification, b) at 250x magnification, c) at 500x magnification, d) at 1000x magnification, and e) with EDS

Figure 21 a) is mostly one shade of grey, with two distinct lighter areas. Since heavier elements appear lighter in SEM images, this indicates the presence of iron. In Figure 21 b) and c), the iron can be seen on a layer of mortar, thus, the amount of iron may be less than it appears to be. Figure 21 d) shows an enhanced image of the brick where there are some lighter spots, which may indicate some iron infiltration. Figure 21 e) shows the elemental distribution of the refractory-slag interface, which mostly comprises of aluminium (Al), silicon (Si) and Oxygen (O) and other trace elements, however, there is now a small, but significant amount of iron (Fe) present. This shows that the interface is subjected to elemental changes due to iron infiltration in areas where the brick has been damaged.



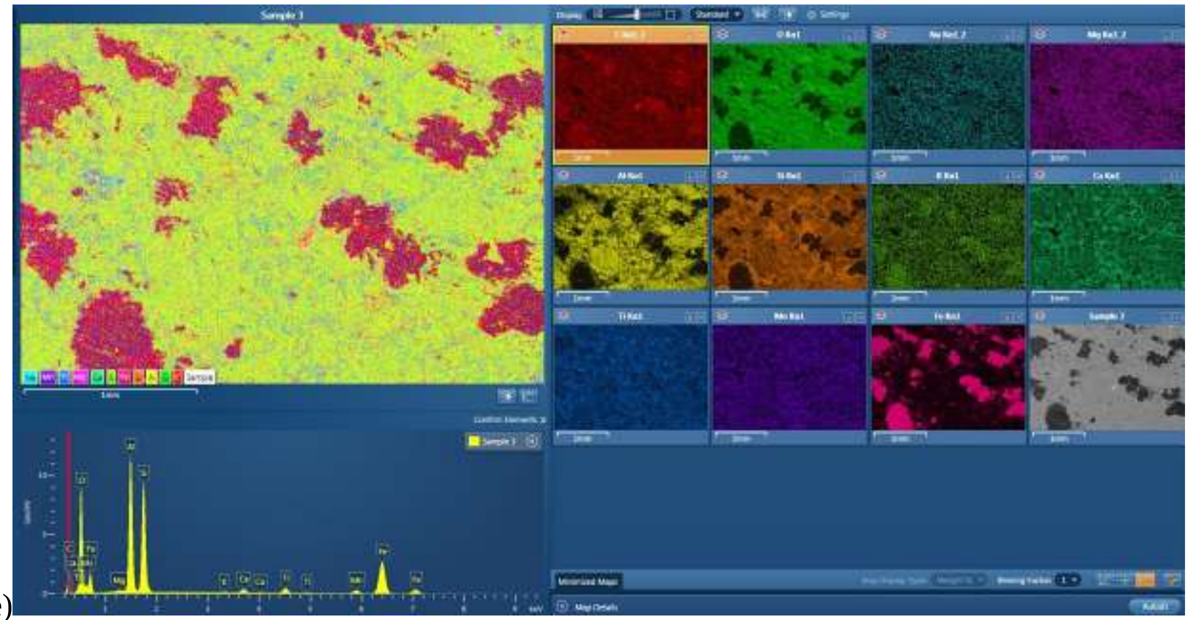
e) 

Figure 22: SEM images of hot face a) at 50x magnification, b) at 250x magnification, c) at 500x magnification, d) at 1000x magnification, and e) with EDS

Figure 22 a) has more lighter areas than the cold face and interface, indicating that there is a higher presence of iron at the hard face. This is due to iron infiltration, and enhanced in improper operating conditions that promote skull formation. Figures 22 b), c) and d), the iron can be seen on a layer of mortar, as well as in the brick matrix. Figure 21 e) shows the elemental distribution of the hot face, which mostly comprises of aluminium (Al), silicon (Si) and Oxygen (O), however, the amount of trace elements and iron (Fe) has increased significantly. This indicates that there is iron and slag infiltration, and possibly some degree of corrosion at the hot face.

Table 9: Summary of elemental distribution (EDS)

Sample	Element									
	O	Mg	Al	Si	K	Ca	Ti	Mn	Fe	Total
Cold face	63.5	0.1	20.9	14.7	0.2	0.2	0.1	0	0.3	100
Interface	62.5	0	20.1	14.7	0.2	0.3	0.1	0.1	2	100
Hot face	54.3	0.2	18	15.9	0.1	0.5	0.9	0.9	9.3	100

Table 9 shows the elemental distribution of the cold face, refractory-slag interface and hot face of a used refractory brick. From cold face to hot face, there is a decrease in aluminium and oxygen, which indicates a loss in alumina at the hot face, as a result of alumina dissolution. There is also an increase in silicon, confirming the loss of alumina, and in calcium, indicating that slag infiltration. There is a 9% increase in iron, indicating iron infiltration at the hot face, but it may be limited to mortar and cracks caused by spalling.

Chapter Five: Conclusion

The purpose of this research was to determine the factors that contribute to decreased torpedo ladle life as a result of experiencing premature failure of refractories, specifically in the spout fractory design, installation, and operations, and torpedo life may decrease rapidly when problems exist in more than one of these areas.

To evaluate the design of the refractory, the temperature profile of the torpedo wall and the corrosion behaviour of the system were investigated. The temperature profile indicates that the expected shell temperature is 220°C, and the critical thickness of the refractory, which is when the shell temperature exceeds is operating temperature, is 121 mm. This implies severe refractory wear must occur to reach the critical thickness. Thus, the thermal properties of the brick make it suitable for the temperature it is exposed to. When the refractory is exposed to slag, corrosion takes place. However, due to slag being present in small amounts, severe refractory loss cannot be due to slag attack. The degree of corrosion has also decreased since 2010, where campaigns of up to 400 000 tons were achieved. This is due to the increase in slag viscosity and improved compatibility of the refractory-slag system, which causes a decrease in the corrosion rate. This indicates that the refractory had good slag resistance and it was confirmed by a 1.4% and 0.6% change in %Al2O3 and %CaO, respectively, in the hot face composition.

During the installation process, there were a few steps that were followed carefully. However, there were also some deviations that were observed. Inspections that were required upon completion of the back lining, and again upon completion of the hot face, were not conducted. This can result in errors during building that cannot be corrected due to the torpedo being completely built. The other problem was incorrect application of mortar, which was only applied to the edges of the brick. This leads to open spaces in the joint, which may be penetrated by metal or slag. Mortar was also applied unevenly, resulting in insufficient allowance for expansion, which causes stress cracking of bricks, which weakens the refractory lining.

There are three major processes that occur during operations: preheating, filling of torpedoes at blast furnace and tapping of molten metal at steel plant. No issues were found with preheating, however, there is no record of burner availability. When burners are not operational, torpedoes that are below the required temperature are forced to report to blast furnace. When the molten metal is tapped, the refractories undergo thermal shock. Another problem regarding filling of torpedoes, is that the molten metal level is checked visually, which can result in overfilling. Overfilling may cause spalling of bricks in the spout area, or the torpedo may overflow, causing damage to the spout castable and steel shell. At steel plant, a factor that adversely affect the lining were not returning the torpedo to its upright position after tapping into the hot metal ladle. The capacity of the torpedo is greater than the hot metal ladle; therefore, material remains in the torpedo after the hot metal ladle is full. After tapping, the torpedo was titled up, 30° from the upright position. This causes thermal shock and skull formation at the spout, which is only meant to have molten metal contact during pouring, and the temperature of the refractories at the spout is also lower that the molten metal and lower section of the torpedo.

Due to the anomalies observed during operations, molten metal mass, shell temperatures and tap to tap and residence times for torpedoes that performed unsatisfactorily were investigated. Evidence of overfilling, which is associated with spalling, correlates with decreased campaign life. There was also evidence of high shell temperatures, which occurred suddenly, indicating that due to sudden refractory loss, possibly due to spalling, there are weak spots in the shell. At this temperature, the shell properties are weakened, increasing the risk of burn through. There were also torpedoes that were removed from service due to skull formation, which is caused by long tap to tap times, high residence times and low molten metal temperature.

Finally, refractory samples from a torpedo removed from service were analysed. Macroscopic inspection revealed that spalling occurs in refractories in the roof area, which is due to overfilling and improper handling at steel plant. There is also evidence of micro-cracks, which are initiated by spalling. As a result, there are pieces of brick floating in slag, indicating that chunks of refractory are removed periodically. Slag penetration was found to be limited to the surface of the refractory, confirming low corrosion rates. However, there was slag penetration inside spalling cracks, which may have entered through open spaces in joints, which is cause by improper mortar application. Further investigation of the mortar joint also revealed that joints are uneven, which results in limited allowance for expansion, causing the brickwork to experience stress cracking, and there were areas of the brick that were not covered in mortar, causing metal penetration through joints, which expands and contracts with thermal cycling, causing bricks to crack as the internal stresses are increased. The brick was also subjected to XRF, XRD and SEM/EDS analysis. XRF analysis shows that the brick composition remains relatively the same until the hot face is reached. There is a decrease in the Al_2O_3 content and an increase in the CaO content. The MgO and SiO2 content remain relatively unchanged. There is a 1.4% decrease in the alumina content, which indicates that there is a small degree of dissolution that takes place, thus, the corrosion of the system is controlled. The increase in CaO content is only 0.6%, indicating that the refractory has good slag resistance. From the cold to hot face, XRD analysis revealed a decrease in mullite, indicating dissolution of alumina into the slag. There is an increase in iron and hematite, suggesting iron infiltration. There is also an increase in cristobalite and tridymite, which are not expected corrosion products, thus, they may be inclusions or due to slag infiltration. At the interface, there were elevated amounts of hercynite and cordierite, which may be due to formation of these low melting compound products infiltrating cracks, caused by thermal shock, and solidifying. They are not present at the hot face as they dissolve into the molten metal. SEM/EDS analysis showed no elemental changes to the original brick. However, from the cold to hot face, there was an increase in iron and other trace elements, and a decrease in aluminium and oxygen, indicating slag and iron infiltrations, and a small degree of corrosion of the refractory.

Therefore, decreased torpedo life is attributes to numerous factors. The major problems that exist are improper mortar application during refractory installation and slag attack of joint, spalling due to overfilling and long tap to tap times, stress cracking due to improper mortar application and skull formation due to long tap to tap and residence times.

Chapter Six: Recommendations

To improve the life of the torpedo, it is recommended that the inspections must be done during installation to ensure that mortar is applied correctly and any other necessary corrections can be made before the torpedo has been built, and deviations cannot even be identified. A new mortar should also be tested. It should be manufactured with a different binder, as phosphate bonded mortars may perform better, and contain less impurities. A level detector should be installed at the blast furnace to prevent the problem of overfilling. Long tap to tap pose problems due to the decrease in refractory temperature, which may cause thermal shock or skull formation, thus, heat losses can be minimized by placing lids on torpedoes. However, if lids are difficult to remove and replace, there is a risk of them being used incorrectly or not at all. In that case, a ceramic blanket should be considered, which only needs to be placed as it disintegrated when the torpedo is filled or tapped. Minimizing heat losses may increase the maximum residence time in the torpedo, preventing skull formation.

Torpedoes often experience the above problems when there are frequent changes in production and torpedoes are not added or removed from service on time. Therefore, further study should be conducted to develop a system to determine the required number of torpedoes that need to be in operation depending on the blast furnace production and processing capabilities of the steel plant.

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Appendix 1: Calculation for temperature profile through torpedo wall

Heat transfer calculations:

$$T_o - T_1 = \frac{Q.\ x_1}{A.\ k_1} \qquad \text{Eqn. 4}$$

$$T_1 - T_2 = \frac{Q.\ x_2}{A.\ k_2} \qquad \text{Eqn. 5}$$

$$T_2 - T_3 = \frac{Q.\ x_3}{A.\ k_3} \qquad \text{Eqn. 6}$$

$$T_3 - T_a = \frac{Q}{h.\ A} \qquad \text{Eqn. 7}$$

$$Q/A = \frac{T_o - T_a}{[(x_1/k_1)+(x_2/k_2)+(x_3/k_3)+(1/h)]} \qquad \text{Eqn. 8}$$

$$= 5576.089467$$

Parameters used to calculate shell temperature:

Temperature			Thickness			Thermal Conductivity			Heat transfer		
To	1500	°C									
T1	585.49	°C	x1	0.38	m	k1	2.317	W/mK			
T2	286.21	°C	x2	0.114	m	k2	2.124	W/mK			
T3	220.64	°C	x3	0.05	m	k3	17.9087	W/mK	h	22.7	W/m2.K
Ta	25	°C									

Q/A was substituted into Eqn 4 to determine shell temperature.

Parameters used to calculate minimum thickness:

Temperature			Thickness			Thermal Conductivity			Heat transfer		
To	1500	°C									
T1	994.74	°C	x1	0.121	m	k1	2.317	W/mK			
T2	476.93	°C	x2	0.114	m	k2	2.124	W/mK			
T3	400.00	°C	x3	0.05	m	k3	17.9087	W/mK	h	22.7	W/m2.K
Ta	25	°C									

The goal seek function was used to determine the minimum refractory thickness at 400°C.

Appendix 2: Calculation of slag viscosity

Slag viscosity was calculated using:

$$\text{Viscosity } (\eta) = 0.005 + 0.0262[SiO_2] + 0.0184[Al_2O_3] - 0.0172[CaO] - 0.0244[MgO]$$

…Eqn 6

Slag viscosity was calculated for the period 2020-2019:

	Al2O3	CaO	MgO	SiO2	Viscosity
2010	13.28	34.69	10.51	38.05	0.393
2011	13.13	35.09	10.14	37.97	0.390
2012	13.46	34.56	9.92	37.76	0.406
2013	13.87	34.61	9.31	37.67	0.425
2014	13.64	34.79	9.35	38.09	0.427
2015	13.82	34.64	9.61	37.72	0.417
2016	14.56	34.08	9.61	37.59	0.437
2017	14.93	33.75	9.78	37.76	0.450
2018	15.51	33.56	9.91	37.07	0.443
2019	15.95	33.74	9.92	36.63	0.436