Reducing zinc contamination in basic oxygen steelmaking dust

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by

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Abstract

Basic oxygen steelmaking (BOS) produces significant quantities of dust which are both rich in iron, and varied in composition, presenting either a potential recycling resource or disposal liability. In particular, the increasing use of galvanised steel in the automotive industry has resulted in larger quantities of galvanised scrap recycling during BOS manufacturing. The zinc from this scrap finds its way into the process dusts, contaminating them and causing difficulties in their recycling. The treatment of BOS dust via pyrometallurgical and hydrometallurgical processes has been researched extensively and proven to be difficult to be commercially successful.

The objectives of this study were to characterise the zinc contamination of BOS dust; assess the impact of charging different amounts of galvanised scrap and waste oxide briquettes (WOBs); and to analyse if zinc contamination can be reduced by holding galvanised scrap in a hot converter in an inert nitrogen atmosphere, prior to the hot metal addition, to volatilise the zinc. The impact of the different scrap charges and the success of holding the galvanised scrap were evaluated by measuring the mass and concentration of the zinc in the BOS dust extraction systems.

The finding of this work includes:

25% of the BOS dust has a coarse particle size and is predominantly made up of iron spheres with little zinc contamination suitable for recycling via the sinter plant.

Further physical separation of the fines section of the dust is not possible since the zinc oxide either attaches to the other particles or reacts with their surface.

Adding WOBs during the blow causes an increase of zinc contamination, especially at the later stages of the blow.

By holding the scrap for more than ten minutes in the nitrogen purged converter, approximately 50% of the zinc contained in the scrap is volatilised and can be diverted away using the secondary dust collection system. This resulted in halving the zinc contamination in the primary dust extraction system.

Charging the converter with a reduced amount of galvanised scrap makes it is possible to produce a dust with low zinc contamination which can be recovered through the sinter plant and blast furnace.

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Appreviations

BAP	Bath agitation system
BOS	Basic oxygen steelmaking
EAF	Electric arc furnace
hm	Hot metal
ICP	Inductively coupled plasma mass spectrometry
ID fan	Induced draft fans
OG	Off gas
PI system	Tata process information system
SEM	Scanning electron microscope
WOB	Waste oxide briquettes

1 Introduction

Over the years environmental awareness has dramatically increased in the steelmaking industry. Driven by environmental legislations and the economical need to recover in-process wastes, highly efficient gas cleaning systems and recycling options have been developed and researched. It is reported that environmental facilities account for more than 15 % of the steelmaking industries capital spending per year. (Szekely, 1995)

An integrated steelworks has a number of in-process waste streams of which material such as iron could be recovered. Those wastes or potential resource streams are usually in the form of dusts and slurries. The Basic Oxygen Steelmaking (BOS) process generates a considerable quantity of dust. The two conditions during the steelmaking process which cause the formation of the dust are temperature and turbulence. Temperatures in excess of 1600˚C cause tramp elements like zinc and lead to be volatilised, and turbulence created by oxygen injection causes some liquid steel droplets to be ejected into the gas phase. The dust material is transported away from the converter via an off gas system and later oxidises and condenses when the temperature starts cooling down in the pipe work.

This dust is predominately made up of iron units which can be recovered via the iron making process. However, zinc from the galvanised scrap used in the steel making process contaminates the BOS dust, restricting the amount of iron units that can be recovered. High zinc levels cause scaffold formation and subsequent production problems and thus has to be stockpiled. The treatment of BOS dust via pyrometallurgical and hydrometallurgical processes has been researched extensively and proven to be difficult to be commercially successful. Therefore there is a need for research to potentially separate the zinc from the iron units before the dust is formed.

The objectives of this study were to characterise the zinc contamination of BOS dust; assess the impact of charging different amounts of galvanised scrap; and to analyse if zinc contamination can be reduced by holding galvanised scrap in a hot converter in an inert nitrogen atmosphere, prior to the hot metal addition, to volatilise the zinc. The impact of the different scrap charges and the success of holding the galvanised scrap were evaluated by measuring the mass and concentration of the zinc in the BOS dust extraction systems.

Chapter 2 of this thesis gives an overall picture of the steel production and its dusts. It is described how the BOS process works and how the dust is formed. Also the off gas extraction system above the converter is explained

Chapter 3 deals with zinc contamination in the dust and possible ways to recycle or treat the dust. It explains what makes zinc in the dust problematic. Further it analyses and evaluates the different treatment options of the dust (physical separation, hydrometallurgy, pyrometallurgy).

In Chapter 4 the sampling procedure of the BOS dust is shown and explained. The flow patterns of the particles in the wet dust collection systems are predicted in order to create a sampling device which is capable to generate representative samples under isokinetic conditions.

In Chapter 5 the four different sampling trials are described. First the Hold trials which clarify if zinc can be volatilised in the hot converter prior to the blow, to prevent zinc contamination, second the Zero WOB trials, which establish the minimum amount of zinc is achievable in BOS dust. During this trial unexpected high dust masses were measured, therefore the third trial the Mass verification trial was performed in order to verify the dust levels. The forth trial was the Maximum WOB trial which analyses the impact of WOBs to the BOS dust zinc levels.

In Chapter 6 the data from all four trials was used to find correlations between the BOS process and dust production in order to explain the high dust masses during the Zero WOB trials.

In Chapter 7 the findings are discussed.

2 Steel production and its dusts

2.1 Global and European steel production

Steel is a principal material in modern society, being used in many different sectors, including construction, automobile, household or medicine. Global steel production heavily increased since 2000, rising from 849 million metric tonnes to 1414 million metric tonnes in 2010. The main reason is the increased steel production in China, reaching 626.7 million metric tonnes in 2010, contributing for 44.3% of worldwide steel production. In comparison, 172.6 million tonnes of steel were produced in the European Union in 2010 and 9.7 million tonnes solely in the UK. (World Steel Association, 2011)

Nowadays steel is primarily produced by two methods, the basic oxygen and the electric arc steelmaking process. In 2010, 70% of world steel was produced using the basic oxygen steelmaking process, and 28.8% using the electric arc process. The remaining share is produced by the outdated open hearth furnace process, found to some extend in India and countries of the former Soviet Republic. In the UK the majority of steel (75.4%) is produced using the BOS process, the rest being produced via electric arc furnaces. (World Steel Association, 2011)

2.2 BOS process

Steelmaking starts by charging iron ore, coke and limestone in a blast furnace, to produce so called "hot metal". The iron ore is initially bound with oxygen typically in the form of Fe_2O_3 or Fe_3O_4. Carbon monoxide in the blast furnace reduces the chemically bound oxygen in the iron ore transferring the iron to its elemental form. Herby carbon saturated iron is produced. Usual carbon level in the hot metal is between 4 and 5% (European commission, 2001).

The BOS process is then used to burn the carbon content down to 0.01 – 0.4% as well as to remove other impurities like silicon, manganese or phosphorus.

The BOS process consists of three main steps as seen in Figure 1. (Tata steel, 2015)

The first step is charging the converter with scrap and hot metal from the blast furnace. First the scrap is charged. Herby the converter gets tilted and a crane charges the scrap at ambient temperature into the converter. Usually a ratio of scrap to hot metal would be 20 to 80. In the case of the converters in Port Talbot this equals a 300 tonne hot metal charge and a 70 tonne scrap. After the scrap is charged the hot metal is poured into the converter. The charging process typically takes 5 to 10 minutes.

After charging, the 'blow' starts, when a water cooled lance blasts oxygen into the molten metal. Due to the oxygen injected into the hot metal, the impurities begin to oxidise and carbon monoxide is formed. This exothermic reaction increases the temperature of the liquid steel up to 1650°C.

After a blow time of approximately twenty minutes the steel is ready for the third step, tapping off. The whole sequence consisting of charging, blowing and tapping is called a 'heat' and takes approximately 45 minutes.

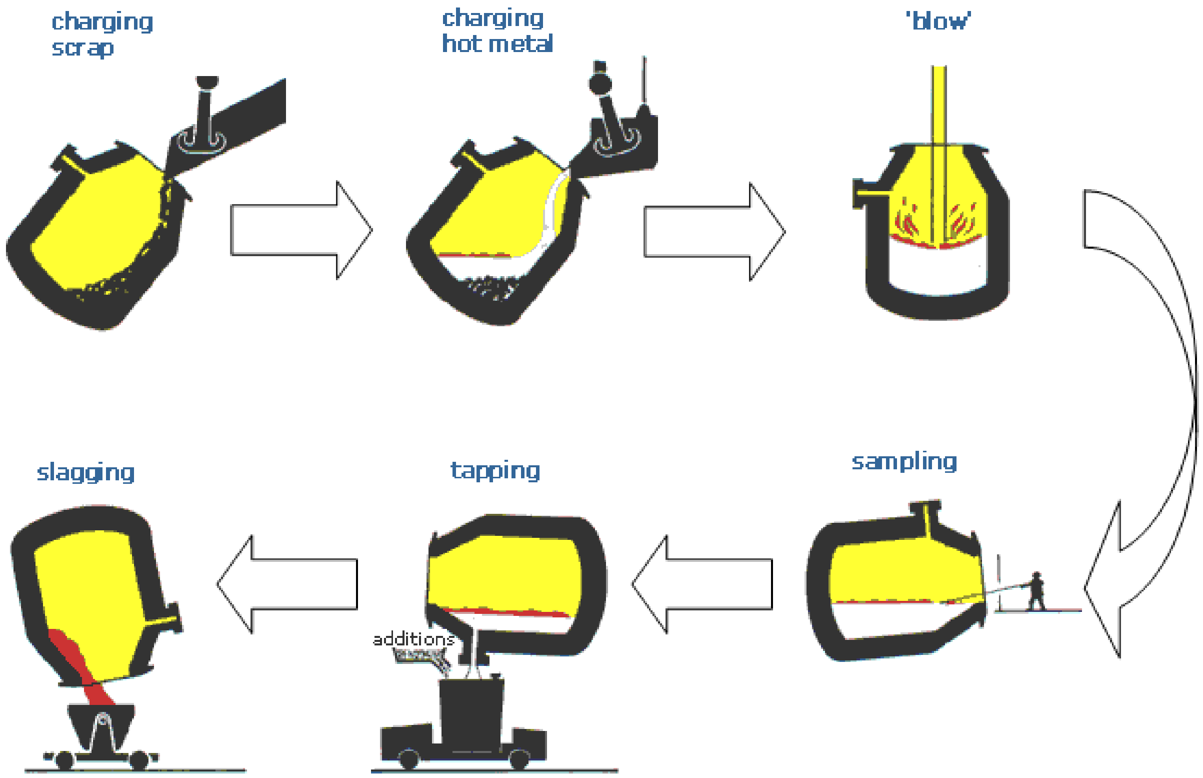


Figure 1: BOS process

2.3 BOS dust

2.3.1 Dust formation

The waste of the BOS process is widely referred to as dust, but technically it is “fume”. The term fume describes typically a solid metal oxide particle with a particle size below 1 micron. (Drinker & Hatch, 1936)

In 1944 brown fumes were described by (Kohlmeyer, 1944), which occurred during hot metal refining in a laboratory setting. In 1954 (Kosmider, Neuhaus, & Kratzenstein, 1954) analysed the dusts from a 20 tonne Bessemer converter, the predecessor of the basic oxygen converter. They concluded the causes of the dust emission to be evaporation of iron. This was confirmed by (Bogdandy & Pantke, 1958) in 1958. On year later (Knaggs & Slater, 1959) added that bursting CO bubbles in the melt may cause melt droplets to be ejected. This finding was strengthened by (Holden, 1959) who passed an oxygen stream in a laboratory setting over different liquid iron alloys. The typical fuming just occurred with liquid iron alloys which contained carbon. Also in 1959 (Turkdogan & Leake, 1959) performed laboratory experiments and identified evaporating iron and volatilisation of iron compounds as main source for the fuming. In 1966 (Morris, Riott, & Illig, 1966) described that the boiling of the carbon monoxide on the steel bath surface causes iron vaporisation and the CO bubbles bursting causes fine liquid metal ejection. In 1989 (Tsujino, Hirai, Ohno, Ishiwata, & Inoshita, 1989) made a large scale investigation and found out that in the initial stage of the blow CO bubble bursting is the dominant force of dust production. With the Carbon content in the melt declining over the blow period, less dust is produced in this way.

Therefore making vaporisation a more dominant dust generator in the later stages of the blow.

More recently various researchers have described the dust formation (Gritzan & Neuschutz, 2001), (Delhaes, Hauck, & Neuschutz, 1993), (Nedar, 1996), (Simonyan & Govorova, 2011) (Schuermann, Ploch, Pflipsen, & Herwig, 1995).

From the research done over the last years it can be summarized, the dominant dust generation mechanism is the ejection of fine metal and slag droplets caused by bursting of the film of CO bubbles in the melt. (Figure 2) (Reinke, Vossnacke, Schuetz, Koch, & Unger, 2001) describes how the bubble bursting and the creation of the jet droplets occur. The liquid bubble film bursts, and the film droplets drop back into the bath. A wave converges causing the liquid to rise, releasing the jet droplets. (Gleim, 1953)

Further contributors to dust generation are vaporisation and spitting of material and entrainment of fines during top charging.

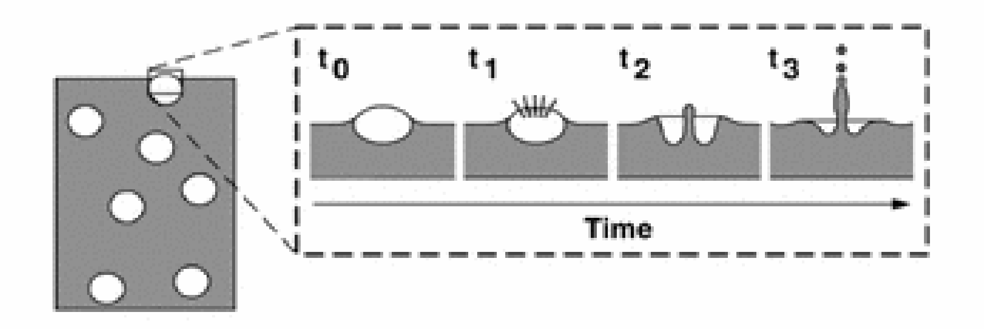


Figure 2: Droplet generation due to bubble bursting

During the BOS process zinc is effectively removed from the converter. The vast majority of zinc is liberated into the dust, causing final zinc levels of steel and slag to drop below 50 ppm. With its high vapour pressure at steelmaking temperatures, suitable thermodynamics for zinc dissolution and the high production rate of process gas, (Pluschkell & Janke, 1992), zinc effectively vaporises out of the melt.

2.3.2 Dust Extraction

During the BOS process, oxygen is blown into the converter and combines with carbon as well as other elements in the hot metal. During the process the gas production rate is 50-100 Nm^3/ tonne of steel (Industrial Efficiency Technology Database). The gas has a temperature of 1600°C a flow rate of 1000-2000 Nm^3/min and a dust content of 50-100 g/m3 (which is up to 1000 times the limit for discharge to the atmosphere). Typical composition of the gas by volume is CO, 55 to 60 %, CO^2, 12 to 18 %, oxygen, 0.1 to 0.3 % and rest is N^2, (Satyendra, 2015) making the gas toxic, flammable and potentially explosive.

The off gas (OG) system is designed to collect the waste gas safely and to cool, clean and dispose of it. A sketch of the system is shown in Figure 3 (Tata steel, 2008).

The first quencher after the turnover section mainly functions as a gas cooler as well as dust collector. The hot gas in the turnover section has a temperature of about 800 -1000°C. It is spray-cooled using water to about 60 -70°C. The water rate is altered to match the varying gas flow and is ideally 3.5 - 4.0 litre/m^3. The waste gas and the spray bulk water are then forced through the venturi scrubber where the pressure drop across it will create water droplets that serve to scrub the dirty gas. The schematics of a venturi scrubber are shown in Figure 4. (Alonso, Azzopardi, Gonçalves, & Coury, 2001)

The size of water droplets formed determines the size of dust particles scrubbed, low pressure drop will create large droplets which serve to remove coarser dust, and vice versa. A pressure drop of about 15 mBar will normally be achieved during the blow. In that way aound 80 - 90% of coarse dust in the gas is removed by the quencher unit.

The slurry formed at the first quencher unit is drained off through the primary separating elbow, where the agglomerated solids are trapped by a weir, and drop out and into the third floor seal tank before being drained back for water treatment.

Afterwards the gas is directed through the second venturi scrubber which is the main scrubbing unit. The main scrubbing unit creates a much higher pressure (140 mBar) drop to break up the bulk water into finer water droplets with higher kinetic energy to remove fine dust in the gas. At this stage the fine water droplets will remove almost all fine particles in the gas.

After the main scrubbing unit, the slurry water will be drained off through the secondary elbow, and will be collected in a slurry tank and then pumped back to the third floor seal tank to be fed to the water treatment plant while the gas is led to the demister which is a third scrubbing unit. The function of the demister is to remove particulates that might still be contained in the fine water droplets that flow along with the gas stream. Those particulates, if not removed, will contribute to stack emission. The particles collected from the demister are also fed to the slurry tank from the secondary elbow.

The ID fan provides suction power to pull the gas through all the section in the OG system.

The combined slurry from the OG system is then pumped outside of the BOS plant into a degritter, which removes the coarse particles with a steel chain, see Figure 5. (Water Institute of Southern Africa, 2002)

After the degritter the slurry is fed into a large clarifier vessel. The slurry in the water settles to the bottom of the vessel and a large rotating rake ensures that the slurry is collected and drawn towards the centre of the vessel, where it is piped to the slurry tank. The water is collected from the top of the clarifier into dust water collecting tanks, where a reservoir of cleaned water is held. This cleaned water is then pumped back to the venturi scrubbers and water sprays, completing the closed circuit dust collecting water system.

From the slurry tank, the slurry is pumped to the filter press, which is located next to the briquetting plant. The water is pressed out of the slurry to produce filtercake which still contains about 30% moisture. The filtercake is then left out in the open to dry to 15-20% moisture, after which it can be briquetted. Those Waste oxide briquettes (WOBs) can then be recycled into the BOS converter.

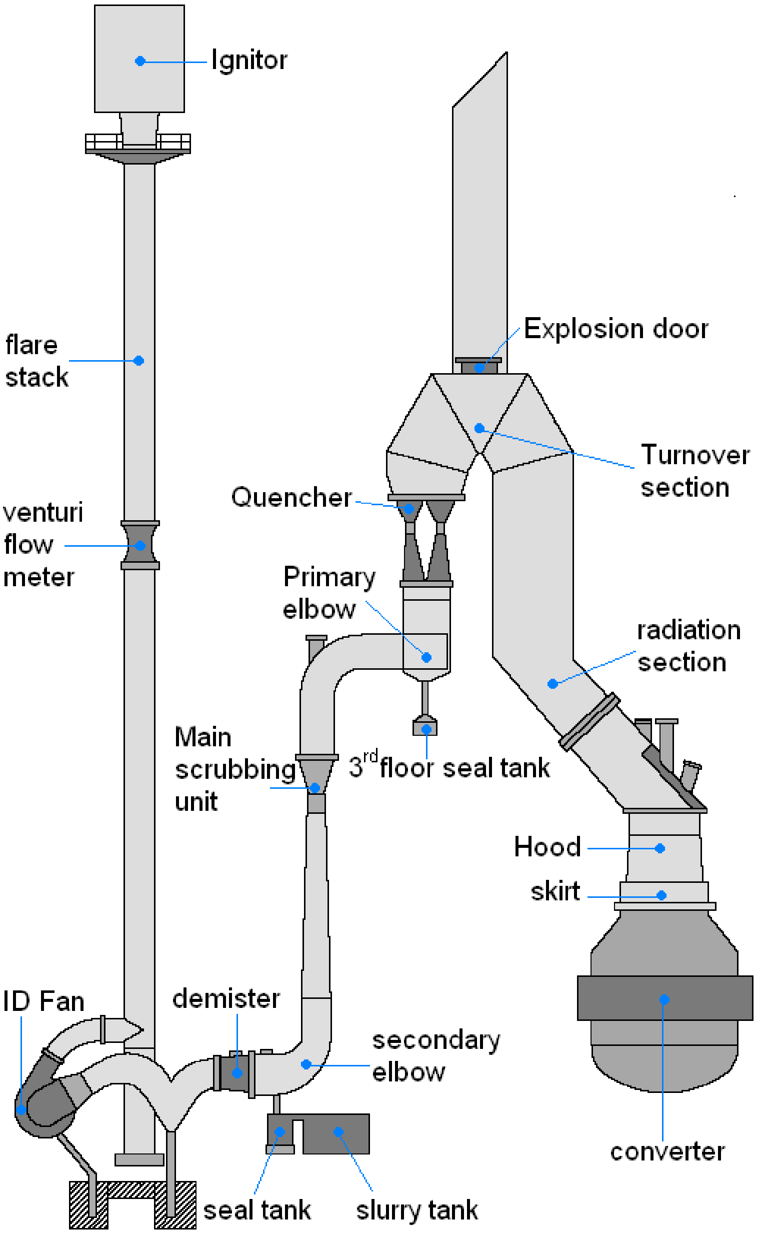


Figure 3: BOS Off Gas System

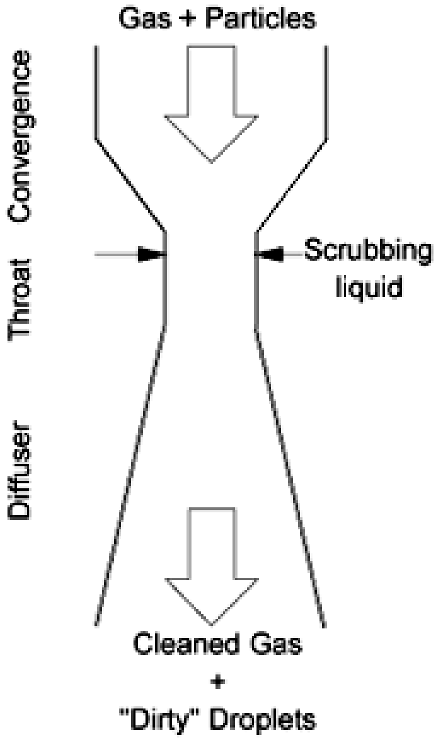


Figure 4: Schematics of a venturi scrubber

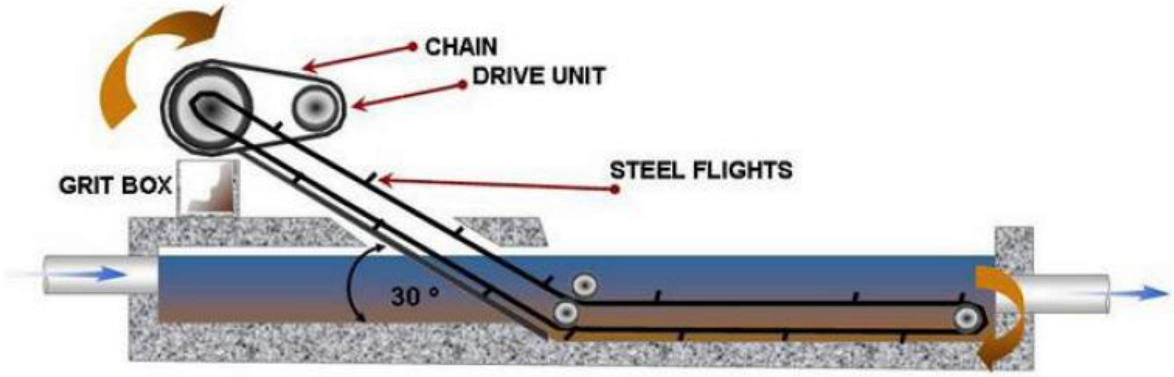


Figure 5: Schematics of the degritter

2.3.3 Characterisation of BOS dust

BOS dust is variable in terms of quantity, composition and particle size. The generation figures are descriped widely in literature including (European commission, 2001), (West, 1976), (Schaukens, 1997). Generally the dust generation ranges from 15 – 20 kg per tonne of liquid steel, with the majority being formed during the blow period.

The individual particle size is typically below 1 micron but the individual particles are predominately agglomerated. (Hogan, 1974)

The dust composition is highly variable, and is dependent on the converter charge, the type and quality of steel being produced and the period within a heat. For example dust produced at the start of the blow period shows higher zinc and calcium levels than at the end. A typical composition range for a BOS dust composite sample is shown in Table 1. This information has been collected from various researchers. (Afonina, Krichevtsov, Kulikova, Laletin, & Smirnov, 1980) (Hay & Rankin, 1994) (Holowaty, 1971) (Lee, Smith, & Nassaralla, 1997) (Pasztor & Floyd) (Ray, Chattopadhyay, & Ray, 1997) (Piddington, 2001)

The elements in the dust are present as simple metal oxide. The exceptions are sulphur and carbon which are in its elemental form. Iron is present as metallic iron, wustite (FeO), hematite (Fe_2O_3), and magnetite (Fe_3O_4). But magnetite is the most dominant form in the dust. In it Fe cations are replaced by zinc, magnesium, calcium and other elements. Zinc can be found as zincite (ZnO) or Franklinite ($ZnFe_2O_3$). (Krzton, 2010)

With BOS dust being such a variable material, the slurry created from the wet off gas system shows the same variations. The solids concentration of the slurry in Port Talbot ranges from 0.3 grams per litre during the charging process, up to 50 grams per litre at the start of the blow period. This change in solids concentration is reflected in the appearance of the slurry which varies in colour from fairly clear to dark black. In contrast to the solids concentration, the flow rate of the slurry stays relatively constant at several cubic metres per minute with flow velocities of approximately 3 metres per second.

Table 1: Anticipated composition for a typical BOS dust composite sample

Element	**Expected Range %**
Fe	50-80
Zn	1.7-6.5
Pb	0.2-1.8
Ca	3.0-8.8
Mn	0.4-2.2
Mg	0.2-5.0
Na	0.2-1.4
K	< 0.2
C	0.2-4.5
As	< 0.05
Cd	< 0.05
Si	0.02-3.8
Al	0.05-1.8
Cr	0.01-0.5
Cu	< 0.05
Ni	0.01-0.05
S	0.05-0.44

3 Zinc contamination and recycling

Zinc and steel are often found together. Zinc coatings on steel protect against corrosion and therefore lengthen the usability of steel. In Western Europe, 18 % of steel produced, is coated with zinc by galvanising (IZA Europe, 1999).

The increasing use of galvanised steel in the automotive industry has resulted in larger quantities of galvanised scrap recycling during BOS manufacturing. The zinc from this scrap finds its way into the process dusts and contaminates them.

3.1 Options without treatment

There are two options to directly recycle BOS dust within an integrated steelworks.

The first option is feeding it into the blast furnace. But zinc content in the dust restricts the amount which can be charged. Recycling of BOS dust with zinc levels above 0.2% exceeds a typical blast furnace limit of 0.3kg Zn/tonne of hot metal (Koros, Hellickson, & Dudek, 1995), Tata staff mentioned the zinc limit should not be higher than 0.5%. Other researchers state that steelmaking dust is suitable for recycling via the blast furnace if its zinc content does not exceed 1%. (Duyvesteyn & Jha, 1986) (Pugh & Fletcher, 1974) Zinc causes problems in blast furnace operation, including refractory failure or scaffold formation, which reduces furnace life and efficiency. It has also been reported that it can cause the coolers to break and it may block up the gas off take. (Nicolle & Lu, 1974)

Steelmaking dust with the mentioned low zinc levels gets agglomerated in order to handle, transport and eventually feed it into the blast furnace. The most used agglomeration techniques are pelletisation and briquetting.

The second option is recycling the dust back into the BOS converter. This implies that all the volatile dust components re-circulate, and with each circle the amount of re-circulating components will increase, which lowers the quality of the produced steel. (Hogan, 1974) Also the dust levels will increase which means an increased amount of energy is needed to melt the dust and an increased amount of reductant is needed. This will end up in increasing the cost of the steel produced. (Goldstein, Porter, & Keyser, 1982)

Direct selling of BOS dust to the zinc industry for recovery is no option, since the sinters which are used for smelting have much lower iron content (7-12%) and much higher zinc content (37-44%). (Zhao, 2013)

Direct disposal of dust is also no option. Chlorides and sulphates of heavy metals in dust are partly soluble in water, which possibly contaminates ground water if the dust is unprotected. Because of that, in the US, electric arc furnace dust is classified as hazardous material. (Goldstein, Porter, & Keyser, 1982) (Krishnan, 1983) In the UK the steelmaking dusts are not considered as hazardous waste but it is not guaranteed that it will stay like this in the future. The toxic elements in the dust which can be leached include lead, cadmium, hexavalent chromium and selenium. (Law, 1983) In the US where the dust cannot be used as landfill the cost for disposal are as high as 30 – 40 Dollars per tonne. (Hoeffer, 1994)

3.2 Physical separation

An option of treating steelmaking dusts is the use of physical separation. The objective hereby is to separating ferrous and non-ferrous components so it can be later treated by other technologies.

Since zinc is concentrated in the finer size fraction of dust a high iron, low zinc coarse fraction can be recovered. (Heijwegen, 1985) (Pazdej & Steiler, 1980)

A common practice is the recovery of coarse particles by either using a degritter or a hydrocyclone. The schematics of a hydrocyclone are shown in Figure 6. (Lenntech.com, 2015) The feed material enters the hydrocyclone through the inlet. Because of the circulating velocities an air core is generated in the middle of the hydrocyclone. Large and heavy particles will move to the wall of the cyclone and exit it via the underflow, whereas small and light particles will be dragged towards the air core and exit the cyclone via the overflow. In that way the feed material is separated into two fractions.

The BOS dust coarse dust fraction amounts to less than 40% of total dust. (Piret & Castle, 1990) In Port Talbot this fraction is approximately 20 %. Zinc content of this material is less than 1%, thus recyclable via the blast furnace. But most of remaining dust is stockpiled.

Gravity methods are due to fine particles unsuitable. (Pazdej & Steiler, 1980)

Magnetic separation has also been looked at. The zinc ferrite is paramagnetic and the zincite is diamagnetic, whereas the magnetite is ferromagnetic. Therefore it is theoretically possible to separate the fractions. The problem is the electrostatic attraction of the particles which makes wet magnetic separation necessary. However zincite is attached to iron and manganese particles which makes it impossible to recover a non magnetic zinc rich product. (Hogan, 1974)

In summary due to the fine particle size and the way zinc and iron are present in the dust, physical separation methods have not played a major role.

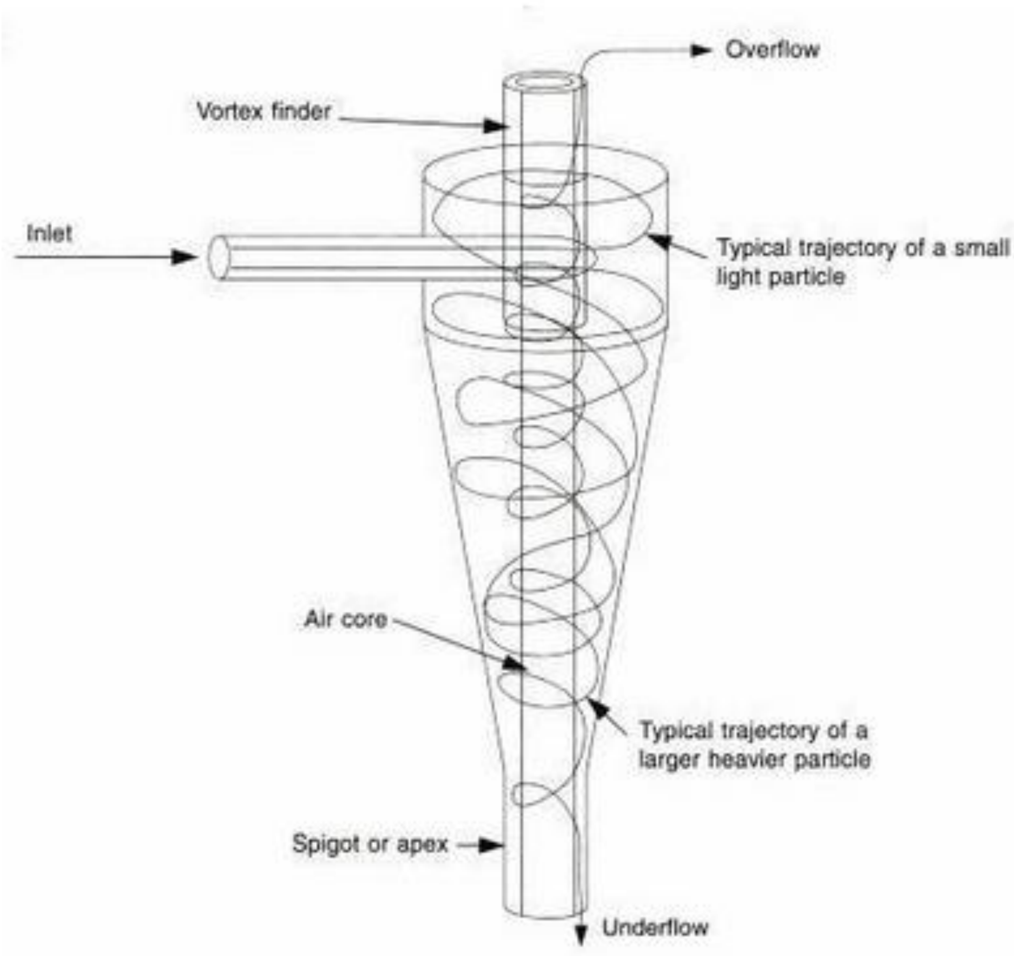


Figure 6: Schematics of a Hydrocyclone

3.3 Hydrometallurgical processing

Hydrometallurgical processing in the context of steelmaking dust treatment is typically called process leaching. It describes to selectively convert species into a soluble form by using a liquid chemical reagent. The resulting aqueous solution is later treated with chemical or electrochemical methods in order to recover or separate the metals.

A vast amount of research based on leaching technologies in combination with steelmaking dust has been done. (Nyirenda, 1991)

Since energy consumption in process leaching is much lower compared to the high temperature processes, researchers have been looking for economical feasible leaching processes which do not require the large feed material throughput as seen with the high temperature processes. The primary aim for a leaching process is to generate a residue which is non toxic and can be disposed as normal waste.

An example of a hydrometallurgical process would be leaching with sodium hydroxide:

The process dissolves the zinc and lead oxides in the dust using a sodium hydroxide (NaOH) solution (95°C, 1–2 hours, 8-10 M). With these conditions 85-90% of zinc can be extracted. (Pooley & Wheatley, 1990)

The chemical principle is seen in the following equation:

$$ZnO_{(solid)} + 2NaOH_{(aqueous)} <-> Na_2ZnO_{2(aqueous)} + H_2O$$

The advantage of the process is that hardly any iron goes into solution. The disadvantage is that the later solid liquid separation is problematic due to the fine particles of the flue dust and the viscosity of the sodium hydroxide. This problem was overcome by the so called Cardiff process which uses a high intensity magnetic field and a filter press to separate the magnetic particles from the leachate. (Pooley & Wheatley, 1990)

But as of today the author in not aware of any hydrometallurgical processes used in commercial dust treatment facilities.

3.4 Pyrometallurgical processing

Those technologies are based on high temperature (excess of 1100°C) reduction volatilisation. As reductants solid carbonaceous materials or gases are used. There are different pyrometallurgical processes used in industry today, which are all varying in three main aspects:

1. Heat generation
2. Recovery of volatilised material
3. Charging of the furnace

The basis of all pyrometallurgical processes is reducing the metal components from the feed material to its metallic form and volatilisation of volatile elements for example zinc.

Reduction means specifically the removal of oxygen from the metal oxides. In that way for example Fe_2O_3 is reduced using CO gas to Fe, as seen in the following equation:

$$Fe_2O_3 + 3CO <-> 2Fe + 3CO_2$$

Zinc present in the feed material as ZnO will be reduced to gaseous zinc, zinc present in other forms for example $ZnFe_2O_4$ will be reduced to gaseous zinc and Fe_3O_4.

In this way at least 90% of zinc and lead in the feed material are volatilised, as well as other unwanted elements.

As a reducing agent typically carbon is used. For the reducing agent it is necessary to have a higher affinity to the oxygen compared to the metal the oxygen is initially bound to.

In 1974 (Higley & Fukubayashi, 1974) described that 98% of zinc could be removed from loose electric arc furnace dust, using temperatures of 1050-1150°C with 10% coke added. (Dressel, Barnard, & Fine, 1974) did similar work, using pre-reduced pellets of electric arc furnace dust and BOS dust, and achieved 99% zinc removal at temperatures of 850-1000°C.

After reducing the feed material the volatilised materials need to be recovered. This can be done in two ways:

- The volatilised material is transported away by an off gas system, cools down, oxidises and is collected using filtering equipment. (Bounds & Pusateri, 1988)

- The volatilised material is transported away by an air tight off gas system, preventing it to oxidise and using a condenser for collection. (Pedersen, Aune, & Cundall, 1990)

The advantage of the pyrometallurgical processes is the production of an inert slag, which prohibits leaching from any residual toxic elements. Therefore the inert material can be utilised for road construction etc. The disadvantage of pyrometallurgical processes is that the iron rich inert slag can still not be recycled back into the iron and steelmaking process due to impurities like sulphur and copper. (Maczek & Kola, 1980) This means that any revenue from the process is generated by the zinc recovery from the feed material. Typically a feed material of 20-25 % zinc is needed to make the process feasible. (Metal Price Report, 1990) The economics further determine that the process has to be done on a large scale. The fixed costs of the processes stay relatively constant no matter what the capacity of the plant is. Therefore larger plants are in favour to smaller operations. (Nyirenda, 1991) states that the most used pyrometallurgical process, the waelz kiln process, is uneconomic for plants which produce less than 50000 tonnes of a feed material with 15% zinc per year. (Kola, 1990) states that a typical pyrometallurgical treatment charge in Europe for steelmakers is 30 – 50 Dollars per tonne of dust.

Below the most established pyrometallurgical process, the Waelz kiln process is described in greater detail:

A schematic of the process can be seen in Figure 7 (Steel dust recycling, 2015).

This process was initially used from the 1920s onwards to recover metal oxides from ores. It has been then adapted for the steel industry. As feed material, a minimum of 20 % zinc content needs to be charged to be economical feasible. The reduction volatilisation is conducted in rotary kilns up to 3m diameter and 40m length. The dust is blended with coal or coke fines, limestone and sand, and pelletised. Then the mixture is heated up to 1200 - 1300°C. At this temperature zinc and lead and other unwanted elements get reduced by excess carbon and volatised. The vapours are re-oxidised and removed via an off gas system. The Waelz kiln process is capable of volatising over 95% of Zinc in the feed and its off gas contains only 2-3% iron. (Kern, Joo, & Gee, 1988) This process generates two products:

First the mixed oxides, which require further processing to separate valuable zinc and lead. Secondly and iron rich slag, which contains 40 – 50% iron. But recovery of the iron units is unfeasible due to contamination by copper and sulphur. However the slag is inert, therefore can be used as subsurface material for road building.

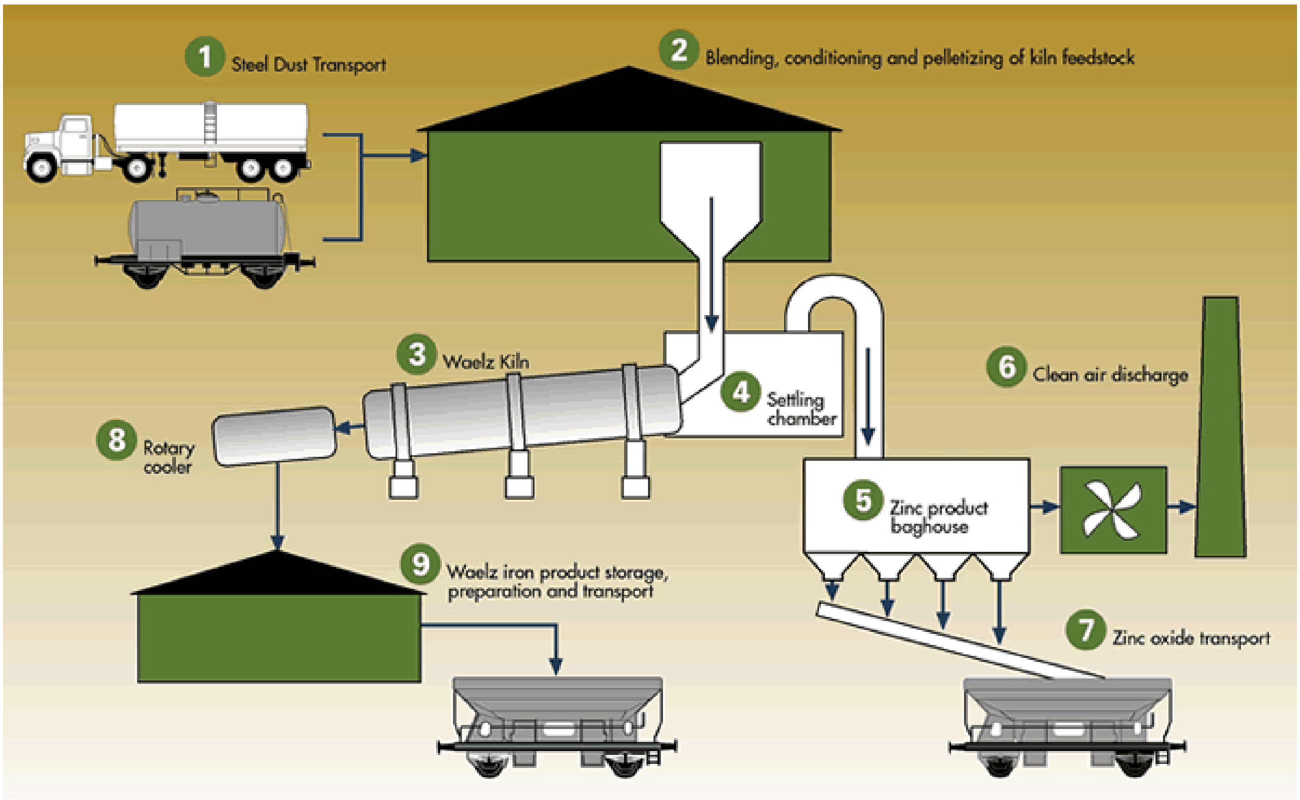


Figure 7: Schematic of Waelz Kiln Process

3.5 Summary recycling and treatment options

Dusts containing less than 0.5 % zinc can be agglomerated and recycled into the blast furnace. Those zinc levels can be achieved by separating the coarse zinc free fraction of the BOS dust using a degritter or a hydrocyclone. But the majority of the dust (the fine zinc rich fraction) has still to be landfilled. Other physical separation methods have played no or little role due to fine particle size and how the zinc is present in the dust.

Hydrometallurgical processes have yet to prove that they are commercial successful.

High temperature reduction, led by waelz kiln, is capable to produce environmental acceptable slags ready for disposal. The cost is directly off-set by recovered zinc from the feed material. Therefore feed needs at least 15-20% Zinc content. With zinc levels being much lower in BOS dust, it cannot be used solely in high temperature processes since it is not economical feasible. Pilot plants have been set up for this purpose, (Rhee, 1974) but the value of the generated products is too low offset the energy costs of the process. This process is therefore no option for BOS dust.

This shows that currently there is no solution to recycle and recover BOS dust. Because of this the following study was undertaken in order to examine if the zinc can be separately captured in the off gas before the typical BOS dust is generated.

4 Sampling and analysis

As seen in the last chapter, there is currently no option for recycling or treatment of BOS dust. Therefore a series of trials have been undertaken in order to reduce zinc contamination. In order to evaluate the different process conditions of the trials a robust sampling method had to be developed.

4.1 Primary dust

4.1.1 Sampling location

The dust material is transported away from the BOS converter via an off gas system and later oxidises and condenses when the temperature starts cooling down in the pipe work. After the venturi scrubbers separate the dust from the off gases in the primary dust extraction system, the generated slurry is pumped into seal tanks before transfer to clarifiers for settlement and dewatering, prior to filter pressing. Prior to this study, the BOS dust was primarily sampled from the discharge of a clarifier. However, due to the long residence time and the mixing process within the clarifier, the impact process changes had on dust levels and composition could not be accurately measured. Therefore, a new sampling location prior to the clarifiers had to be chosen (Figure 8).

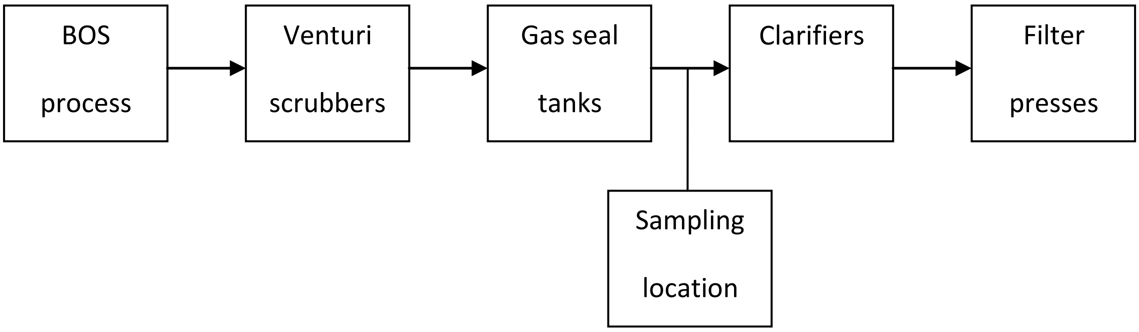


Figure 8: Sampling location of the primary dust extraction system

The BOS plant runs on a two converter operation. Both converters have an individual dust extraction system, and therefore individual slurry pipes. The new sampling location was external to the BOS plant, where the pipes run towards the clarifiers (Figure 9). Sampling at this location was aggravated by restricted access to the pipe sampling point via a narrow gangway 15 meters above ground level with an associated carbon monoxide gas hazard. Apart from these drawbacks, the location was very suitable for the sampling purposes as it was remote from the process and importantly contained all dust and waste water from the extraction systems. Also, the short residence time of approximately five minutes until the slurry reached the sampling location was very advantageous to achieve the sampling objectives.

Figure 9: Picture of BOS slurry pipe and sampling point

4.1.2 Sampling requirements

The low solids concentration slurry required ten litre samples, to ensure the collection of enough particles for later analysis. Also, as the samples had to be taken every minute during the 40 minute heat period to generate a representative profile of the dust generation and composition, the sampling technique had to be fast and easy to use.

A handheld operated sampler was not an option for this sampling task, as only a limited amount of time could be spent in close proximity to the slurry pipe due to the carbon monoxide gas hazard. Also the available space on the narrow gangway access to the slurry pipe was not sufficient for the safe handling and storage of the collected samples. To overcome the safety and logistic problems, a representative amount of the slurry had to be extracted from the pipe and diverted down to ground level. Apart from generating a representative sample, the installation of the extraction probe had to be carried out expediently because of the carbon monoxide gas hazard. Also, as the BOS plant operates with two converters, there was a requirement to expediently changeover the sampling probe from converter one slurry pipe to converter two slurry pipe, which ran parallel and in close proximity to it, whenever the occasion arose.

4.1.3 Theoretical considerations

In order to design a sampling system which was capable of generating a representative sample, critical parameters such as sampling location, flow and particle characteristics of the slurry had to be taken into account. To assure that the right amount of particles was collected, the sample should be taken under isokinetic conditions. Isokinetic sampling is a “technique in which the sample from a water stream passes into the orifice of a sampling probe with a velocity equal to that of the stream in the immediate vicinity of the probe” (British Standard, 2006). This generates the least amount of disruption of the flow lines in front of the intake nozzle. If the velocity in the sampling probe is greater than the stream velocity, the larger particles will be under sampled. If the velocity is too slow, they will be over sampled. This is caused by larger particles having a greater mass and therefore a higher inertial force, thus larger particles are not as likely to follow the curved flow lines created by a non isokinetic sampling nozzle. This effect is especially noticeable on particle sizes greater than 60 microns (Federal Interagency Sedimentation Project, 1941). Figure 10 and**Figure 10**Figure 11 (Gulliver, 2010) demonstrate the effect of the curved flow lines on the particles.

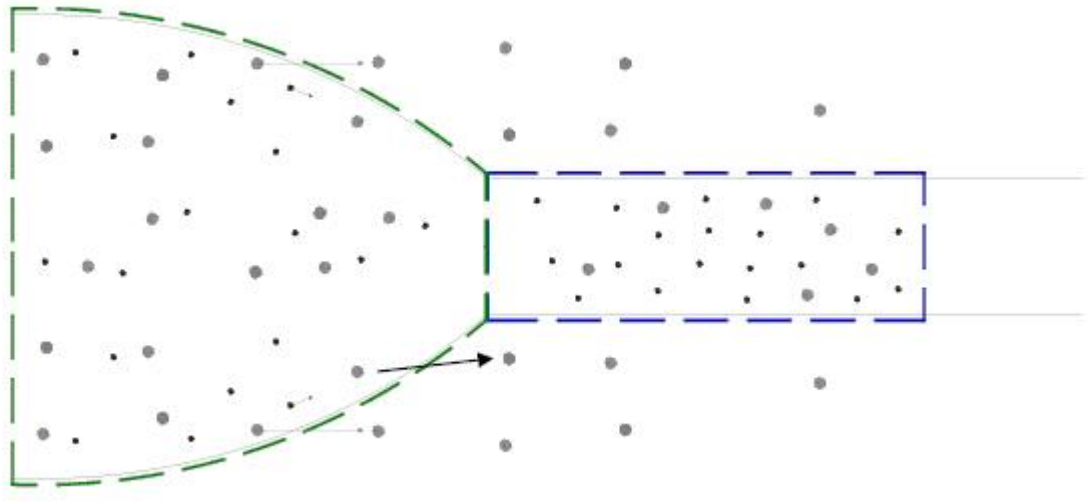


Figure 10: Intake velocity > flow velocity

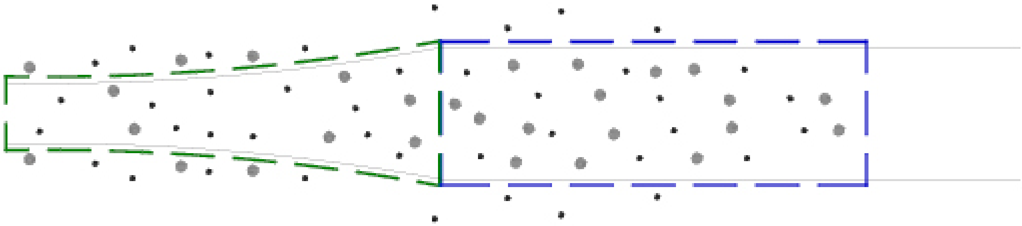


Figure 11: Intake velocity < flow velocity

Another aspect to consider was the vertical distribution of the particles in the slurry. Particles can be transported either as bedload along the bottom of the pipe, as a suspended load where they are carried along with the slurry either without touching or just periodically touching the bed, or as washload where they are fully swept along with the slurry.

Depending on particle size, density and the flow conditions in the pipe, the particle concentration will differ over the depth of the stream.

The Rouse number indicates how a particle is transported in a stream and therefore the vertical particle distribution in the slurry can be predicted. The Rouse number is the ratio between downwards and upwards velocity of the particle. Values smaller than 0.8 indicate washload, values between 0.8 and 2.5 indicate suspended load and values greater than 2.5 indicate bedload.

The Rouse number is defined as

$$P = \frac{\omega_s}{\kappa u_*} \qquad (1)$$

with shear velocity

$$u_* = \sqrt{\frac{\tau_b}{\rho_f}} \qquad (2)$$

and bed shear stress

$$\tau_b = \frac{f}{8}\,\rho_f(u)^2 \qquad (3)$$

The fall velocity of the dust particles in this study was calculated with the formula presented by (Ferguson & Church, 2004).

$$\omega_s = \frac{\mathrm{RgD}^2}{\mathrm{C}_1\nu + (0.75\mathrm{C}_2\mathrm{RgD}^3)^{0.5}} \tag{4}$$

With submerged specific gravity

$$\mathrm{R} = \frac{\rho_0 - \rho_\mathrm{f}}{\rho_\mathrm{f}} \tag{5}$$

where:

If not other stated the values are dimensionless

P = Rouse number
ω_s = fall velocity (m/s)
K = van Karman constant (0.41)
u_* = shear velocity (m/s)
τ_b = bed shear stress (kg/ms^2)
ρ_f = density of fluid (kg/m^3)
F = Darcy Weisbach friction factor
U = mean flow velocity (m/s)

R = submerged specific gravity
g = acceleration due to gravity (m/s^2)
D = diameter of particle (m)
C_1 = constant (18)
C_2 = constant (1)
ν = kinematic viscosity of fluid (m^2/s)
ρ_0 = density of particle (kg/m^3)

As shown in Figure 12, the Rouse number was calculated for particle sizes ranging from 100 to 1000 microns. It can be seen that particles smaller than 200 micron are transported as washload, particles up to 600 micron are in the suspended solids fraction, and particles larger than 600 micron are transported as bedload. With the majority of the slurry particles being smaller than 100 micron, nearly all of the dust particles are transported as washload.

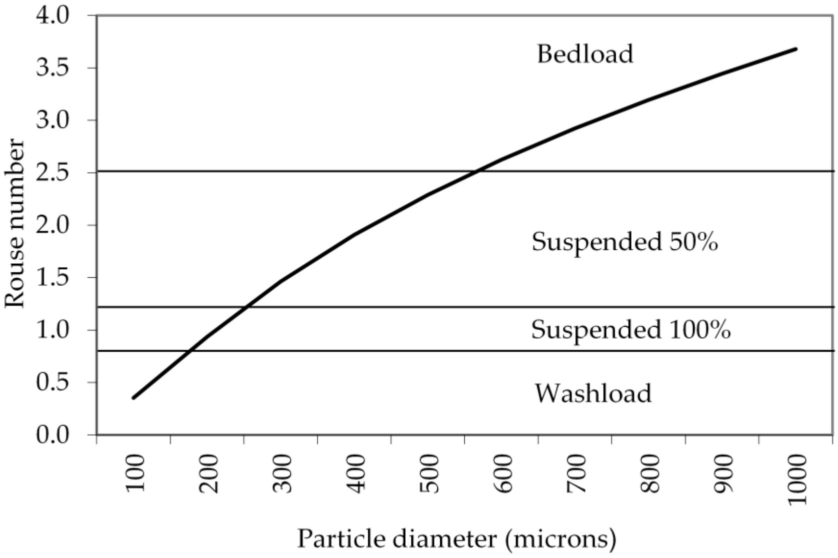


Figure 12: Relation particle diameter and Rouse number

4.1.4 Sampling design

As the high velocities and turbulences in the slurry pipe cause the majority of particles to be transported as washload, a constant particle distribution over the depths of the stream can be assumed. The Rouse number calculations further indicated that no particles are transported as bedload, therefore no additional bed sampler was required. However, as some particles were being transported as suspended load and therefore more likely to be situated in the lower regions of the slurry pipe, the aim was to sample over a wider cross section. For this purpose a sampling device was fabricated which consisted of three steel pipes as intake nozzles. The three steel pipes were connected via ball valves to three copper pipes, and the copper pipes were soldered to a brass connector (Figure 13). The connector combined the slurry streams from the three steel pipes, and generated a single slurry stream. This setup enabled it to extract the slurry at three different heights within the pipe. The inner diameter of the steel sampling pipes was 20 mm and this is in line with the guideline (Garcia, 2008) which states that the inner intake diameter of an automated sampler should be at least three times the diameter of the largest particles sampled. The sampling device was then inserted through an inspection chamber into the BOS slurry pipe (Figure 14) and secured with four g-clamps.

A 38 mm inner diameter hose was attached to the sampling device to transport the extracted slurry down to ground level where it was exhausted to a slurry return tank (Figure 15). The slurry passed through a three way valve assembly prior to exhaust at the slurry return tank as this assembly allowed for the slurry to be diverted into the ten litre sample containers at the required sampling intervals (Figure 16).

To further ensure that a representative sample of the slurry was extracted, the flow velocity within the slurry pipe had to be as close as possible to the flow velocity in the sampling probe. Initial calculations indicated that the velocity in the intake nozzle would be close to three metres per second by just making use of the siphoning effect caused by the height difference of the slurry pipe and the slurry return tank. In order to get the slurry running through the sampling system, it was initially primed using a vacuum cleaner for suction. Once the sample system was operating, BOS slurry flowed constantly through the hose to the slurry return tank. The flow rate in the sampling hose was measured and the nozzle intake velocity then back calculated. With a value of 2.8 metres per second and the velocity of the slurry varying between 2.7 and 3.0 metres per second, close to isokinetic conditions were achieved.

In addition to the sampling, the slurry flow velocity and depth had to be constantly measured. This enabled the mass flow rates of the particles to be calculated. The measuring was done via the Marsh McBirney Flo-dar™ open channel non contact measurement device, supplied by (Flowline Manufacturing Ltd, 2011). This device combines a radar sensor for velocity measurements and an ultrasonic-based pulse echo to measure the depth. The radar sensor can measure velocities of 0.23 to 6.1 m/s with an accuracy of 0.5%. The ultrasonic depth measure has an accuracy of 1%. The device was installed and secured in the slurry pipe above an inspection chamber immediately prior to the sampling probe and produced 200 sample data points per minute (Figure 17). These were then averaged and a slurry flow rate was produced per minute.

Figure 13: Sampler shown in laboratory prior to installation

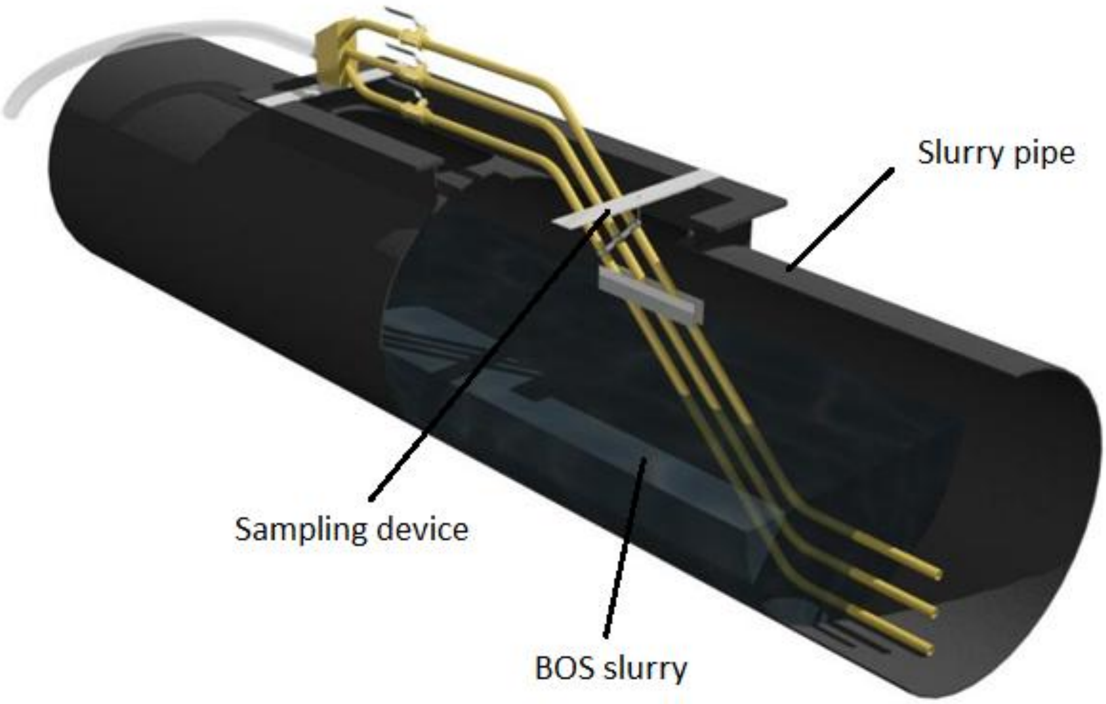


Figure 14: Sampling device installed in BOS slurry pipe

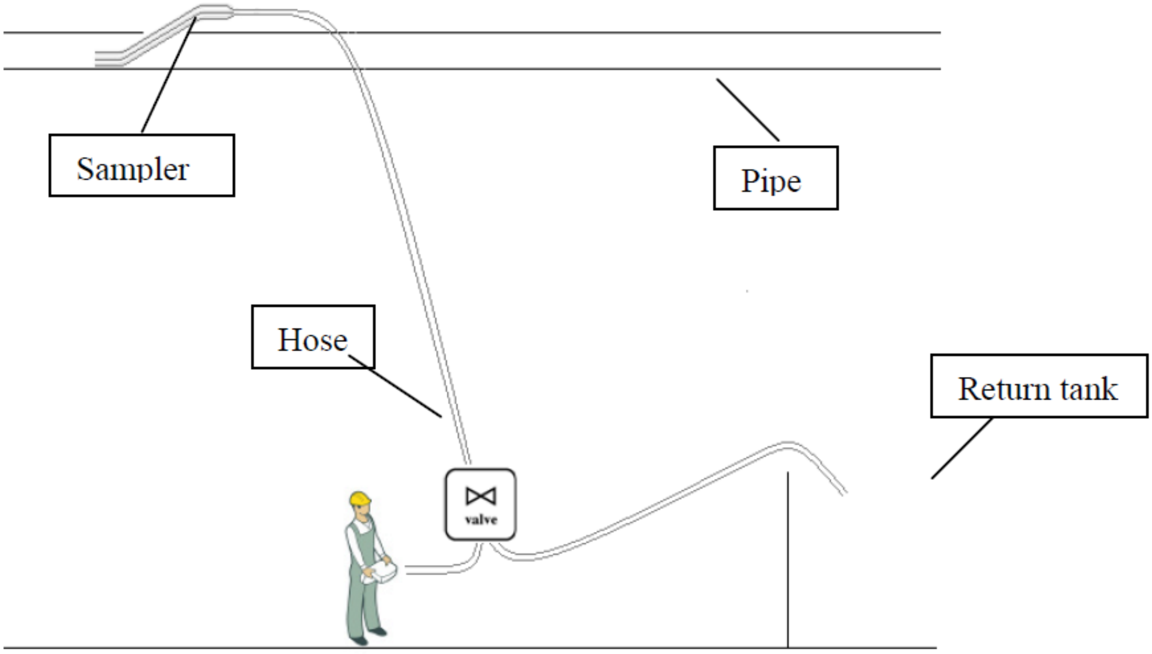


Figure 15: Schematic diagram of sampler, sample point and return pipe

Figure 16: Three way valve at sample point

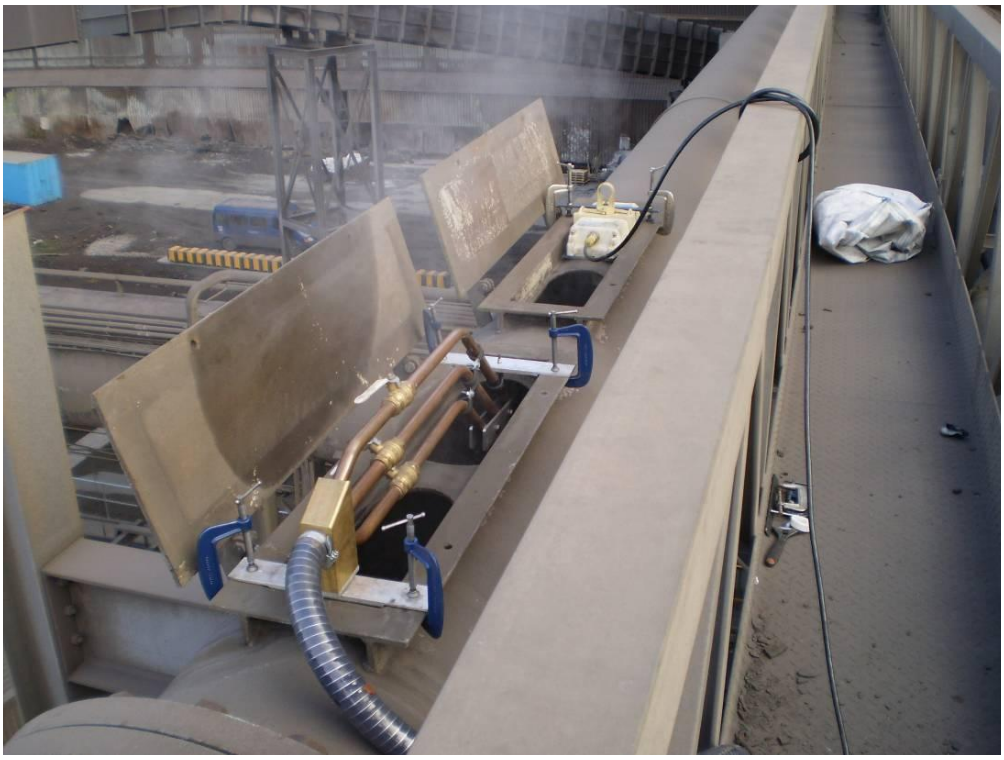


Figure 17: Sampler and flow meter installed in BOS slurry pipe

4.2 Secondary dust

The secondary BOS dust extraction is a ‘dry’ system, which removes dust from the BOS building and both converters, using filter bags. Three induced draft fans are used to suck air through a series of ducts in the BOS building. There are four ducts for the roof space and an extraction shroud which surrounds the outside of each of the two converters.

Zinc captured from the trial should enters the extraction shrouds and is sucked through the main duct. This duct splits into 3 ducts for each bank of 5 dust removal chambers containing a total of 7200 filter bags. Underneath each bank of chambers the dust is collected by a chain conveyor which removes it to a waste silo where the secondary sampling took place, as shown in Figure 18 and Figure 19 respectively.

Figure 18: Secondary dust waste silo

Figure 19: Secondary dust sampling point

4.3 Sample analysis

Up to three heats were sampled during a routine sampling day. This resulted in the generation of more than 100 samples and because of their size and weight, these samples were weighed on site, and then left over night allowing the particles to settle to the bottom of the containers. A wet vacuum cleaner was then used to reduce a large proportion of the waste water by suction. These lighter samples could then be easily transported to the laboratories, where they were subsequently dried, weighed and if necessary ground with a ring mill prior to their chemical composition being analysed.

The samples were analysed for solids concentration; a particle size analyser (Malvern Mastersizer) and sieves were used to determine the particle size distribution. Selected samples were analysed with a scanning electron microscope (SEM) and to determine its chemical composition, an Inductively Coupled Plasma (ICP) spectrophotometer (Perkin Elmer Optima 2100DV).

With the obtained data, detailed mass flow and composition profiles were generated, giving a valuable insight into how the dust varies during each heat, allowing direct correlations between process changes and dust generation to be identified. This data also informed research into treatment and recycling possibilities.

5 BOS trials

During the course of this project, four extended BOS trials have been undertaken: two trials to investigate methods to reduce zinc contamination of BOS dust by making process changes, a third trial to investigate high dust masses observed during a manufacturing period in December 2010 and a fourth trial to investigate the effect of WOBs.

The four separate trials consisted of 29 individual heats to investigate the effects of different process conditions on the quantity of dust and zinc collected. A total of 640 samples have been analysed to determine the dust mass flows and dust composition from the primary and secondary dust collection systems. To obtain accurate and reliable results a BOS slurry sampling device and system was designed and fabricated specifically for this purpose and a total of 485 x10 litre samples were taken over the 29 heats.

The sampling technique allowed detailed dust mass and metal composition profiles to be obtained giving accurate and unique heat to heat comparisons which could be related to specific heats and process conditions. It follows an overview of the aims of the three BOS trials:

1. Scrap hold trials

Aim: To investigate if zinc could be volatilised and captured in the secondary dust system by holding galvanised scrap in the vessel prior to the blow start. In this way zinc contamination in the BOS dust is reduced which could potentially make the dust recyclable.

Extend: The trial consisted of a total of 13 control heats with no additional scrap hold time, and 6 hold heats with a scrap hold time to volatilise the zinc into the dust.

2. Zero Waste Oxide Briquette (WOB) trials

Aim: To determine the minimum level of zinc achievable in BOS dust by using zinc free (non galvanised) scrap without WOBs.

Extend: This trial consisted of 3 heats with a zinc free scap charge and no WOB charge.

3. Dust mass verification trial

Aim: To determine the quantities of dust collected per heat. During the Zero WOB trial high dust masses had been observed which needed to be clarified.

Extend: This trial consisted of 4 heats during normal BOS processing with no changes.

4. Maximum WOB trial

Aim: To investigate the effect of high levels of WOBs on the zinc levels and the amount of dust generated during each heat.

Extend: This trial consisted of 3 heats with a maximum amount of WOBs added.

5.1 Scrap Hold trials

5.1.1 Idea behind BOS hold trials

Zinc has a boiling point of 907°C and preliminary studies, where galvanised metal was heated in a laboratory furnace at 900˚C for fifteen minutes in a nitrogen atmosphere, showed that the zinc was successfully volatilised from the surface of the metal with no presence of zinc oxide (Figure 20). Other research indicated complete zinc removal after five minutes at 600˚C and 70% zinc removal after three minutes at 850˚C, in a nitrogen atmosphere (Franzen & Pluschkell, 2000), (Ozturk & Fruehan, 1996). By purging the BOS converter with nitrogen, using the tuyres from the bath agitation system, and implementing a suitable holding time, to heat up the galvanised scrap using the residual heat of the converter, zinc could potentially be volatilised from the scrap before the bulk of the dust is produced during the blow.

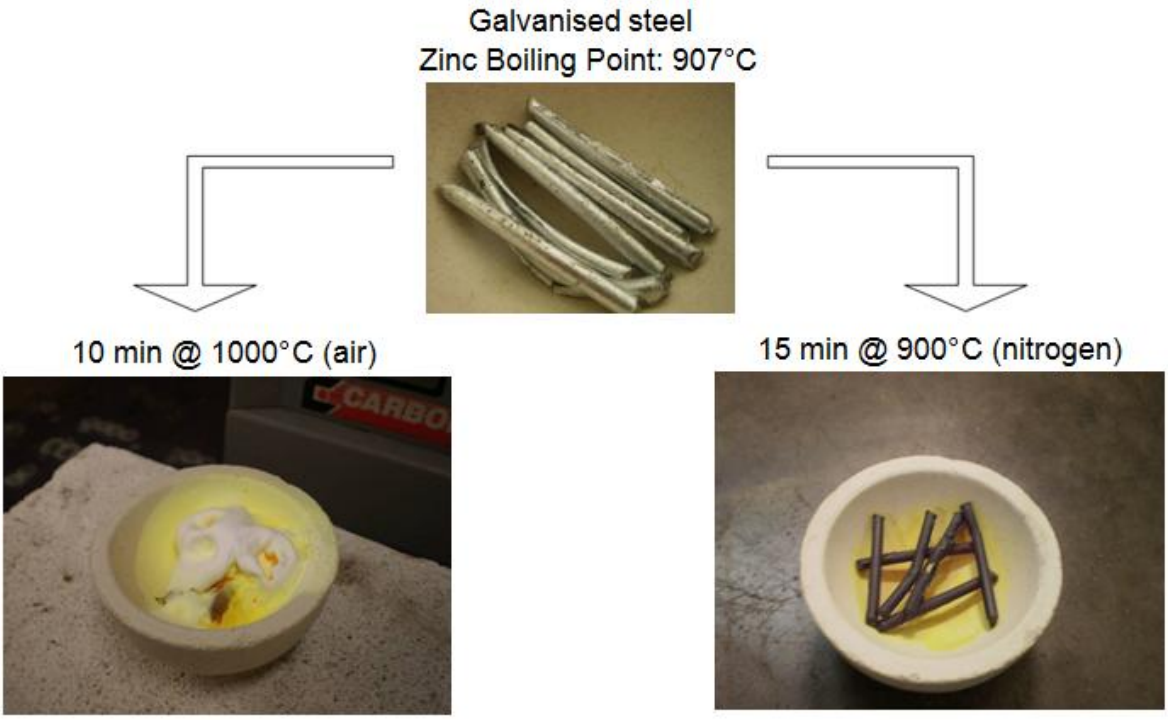


Figure 20: Furnace tests with galvanized steel

At Tata steelworks Port Talbot (UK), there are two dust extraction systems within the steelmaking process, a primary system (wet) which collects the dust from the BOS off gas by venturi water scrubbers, and a secondary system (dry) using filter bags, which collects dust from the area around the converters and the roof space in the BOS building. By tilting the converter during the scrap holding time towards the secondary dust extraction system, the aim was to divert volatilised zinc away from the primary dust collection system, resulting in a reduced zinc contamination of the vast majority of the dust. This project was initiated during a period of reduced production, when there was sufficient time in the production schedule to accommodate a scrap holding period.

5.1.2 Experimental setup

To achieve zinc volatilisation during the hold trials, the following set of production conditions were required:

- The holding time in the converter to sufficiently heat up the galvanised scrap bales, to achieve zinc volatilisation, was estimated to be 20 minutes, assuming that the inner surface temperature of the converter was 1500°C. However, this target was not achieved due to production constraints and the scrap hold time was reduced to 11 and 15 minutes for the two trial heats.
- The bath agitation system of the converter was used to create an inert atmosphere in the converter. The converter was purged with at least two volume changes of nitrogen prior to addition of the scrap ensuring oxygen is displaced. During the hold period purging continued to prevent the formation of zinc oxide in the converter.

- The converter was tilted towards the secondary dust extraction system during the hold period to increase its potential of capturing volatilised zinc.
- The converter was occasionally rocked during the hold time to increase its potential to heat up the galvanised scrap.
- The secondary dust extraction fans were ramped up to collect a maximum amount of the volatilised zinc.
- The primary dust extraction system was kept to the minimum before hot metal addition, to minimise the capture of zinc.

The scrap hold trials used a series of changes to the steelmaking process to decrease the level of zinc in the primary dust extraction system and increase the level of zinc in the secondary dust extraction system. By sampling the process dusts and recording flow measurements the aim was to determine if this had been achieved from the dust mass flow rates and zinc contents.

The objective of the sampling exercise was to collect the following samples and measurements from the separate dust collection systems at regular time intervals during the trial.

Primary system

- 10 litre slurry samples taken from the BOS slurry pipe prior to the launder system.
- Measurements of the flow velocity and slurry depth in the BOS slurry pipe.
- Composite sample and total mass of BOS grit collected.

Secondary system

- 50 gram samples taken from the waste silo inlet conveyor chain.
- Total mass of secondary dust collected over trial period.

However, not all the objectives could be met. The BOS grit sample and mass could not be collected because the area was waterlogged and access was restricted. Also, very limited data of the secondary dust mass could be collected because of the availability of an approved contractor required to empty the waste silo.

5.1.3 Trial summary

A total of 4 control trials and 3 hold trials were conducted between 23rd July 2009 and 4th December 2009, each trial consisted of a number of heats and in total 321 samples were analysed. It took multiple trial attempts to achieve the process and sampling conditions necessary for reasons shown in Table 2.

The control trial IV (sampled 13/10/09) and hold trial III (sampled 04/12/09) met the process conditions required for zinc volatilisation most closely when both the primary and secondary dust extraction systems were sampled simultaneously.

Table 2: Summary of previous trials

Trial	Dust system sampled	Process and sampling comments
Control I	Secondary only	• Trial run by Tata personnel only to evaluate the sampling protocol
Control II	Secondary only	• Galvanised scrap requested but not charged • No access authorisation for primary system
Control III	Secondary only	• Most process conditions met • No access authorisation for primary system
Control IV	Secondary/primary	• Process conditions met • 2 heats only
Hold I	Secondary only	• No access authorisation for primary system • Insufficient nitrogen purge rate • 1 heat only
Hold II	Secondary only	• No access authorisation for primary system • 2 heats only
Hold III	Secondary/primary	• Process conditions met

The control trial IV consisted of two trial heats 18793 and 18795. Table 3 shows the process timings for these heats according to the Tata process information system (PI).

Table 3: Tata process information for control trial IV 13/10/09

HEAT NUMBER	VESSEL	START SCRAP CHARGE TIME	START HOT METAL CHARGE TIME	START FIRST BLOW TIME	END LAST BLOW TIME	START TAP TIME	END TAP TIME
18790	2	08:34	09:08	09:12	09:30	09:32	09:37
18791	2	09:43	09:47	09:50	10:08	10:13	10:17
18792	2	10:23	10:25	10:29	10:46	10:51	10:54
18793	2	11:18	11:20	11:23	11:40	11:44	11:47
18794	2	11:54	11:56	12:01	12:19	12:23	12:28
18795	2	12:44	12:47	12:52	13:10	13:17	13:21
18796	2	13:32	13:44	13:48	14:06	14:10	14:15
18797	2	15:05	15:08	15:12	15:29	15:34	15:38
18798	2	15:58	16:18	16:22	16:40	16:43	16:48
18799	2	17:08	17:11	17:35	17:52	17:56	18:00

The hold trial III consisted of two trial heats 20641 and 20643 and Table 4 shows the process timings for these and other heats, taken from the Tata process information system. It should be noted that during the hold trials production was on double converter operation compared to the control trials when production was on single converter operation.

Table 4: Tata process information for hold trial III 04/12/09

HEAT NUMBER	VESSEL	START SCRAP CHARGE TIME	START HOT METAL CHARGE TIME	START FIRST BLOW TIME	END LAST BLOW TIME	START TAP TIME	END TAP TIME
20635	2	06:50	06:53	06:59	07:18	07:26	07:33
20636	1	07:26	07:39	07:45	08:02	08:07	08:13
20637	2	08:05	08:11	08:21	08:40	08:45	08:52
20638	1	08:42	08:46	08:58	09:15	09:17	09:24
20639	2	09:13	09:20	09:33	10:13	10:16	10:21
20640	1	09:28	10:08	10:11	10:29	10:43	10:50
20641	2	10:29	10:50	10:53	11:11	11:16	11:23
20642	1	11:08	11:19	11:23	11:41	11:48	11:54
20643	2	n/a	11:59	12:04	12:22	12:28	12:34
20644	1	12:14	12:24	12:26	12:42	12:46	12:53
20645	2	12:54	13:03	13:05	13:23	13:30	13:35
20660	2	23:50	23:53	23:56	00:13	00:19	00:25

During the trials an observer from Cardiff University was present in the pulpit to make a record of the timings for the main process stages as shown in Table 5 and Table 6. It was noted after the trials that the timings on the Tata PI system differed from the observed timings due to the triggers used by the PI system for each stage. For example, some of the addition times are triggered by the crane movement, if the crane is delayed at the last moment the addition is registered on the PI system even though it has not been added.

For the control trial heats 18793 and 18795, the scrap hold time prior to the hot metal addition was 4 minutes for both. In comparison, for the hold trial heats 20641 and 20643 the scrap hold time was 11 minutes and 15 minutes accordingly. Also, the hold trial heats included a purge time of 8 and 10 minutes respectively when the BAP flow of nitrogen was increased to ensure the converter was free of oxygen.

To collect zinc preferentially in the secondary dust extraction system the secondary fan current loading should have been as high as possible during the scrap hold period but this was difficult to achieve. For the hold heats 20641 and 20643 the respective fan current loadings were <50% and <40% of the maximum fan current obtainable.

Table 5: Cardiff University process timings summary for control trials

Heat number	**Time**	**Process note**	**BAP total flow Nm3/hr**	**Secondary fan current loading %**			
					Fan 6	**Fan 5**	**Fan 4**
Control 18793	11:08	BAP increased	1045		53	39	38
	11:11	BAP decreased	523		51	39	39
	11:15	Scrap addition	513		28	20	18
	11:19	HM addition	514		44	32	30
	11:21	Blow start	514		85	64	62
	11:39	Blow finished	729		73	56	53
	11:42	Tapping started	752		61	45	44
	11:52	Tapping finished	519		57	43	42
Control 18795	12:39	BAP increased	1049		53	40	38
	12:42	BAP decreased	860		53	39	39
	12:43	Scrap addition	517		45	32	33
	12:47	HM addition	516		26	19	18
	12:51	Blow start	516		61	46	44
	13:10	Blow finish	829		73	57	54
	13:16	Tapping started	1034		54	39	38
	13:24	Tapping completed	518		63	48	46

Table 6: Cardiff University process timings summary for the hold trials

Heat number	**Time**	**Process note**	**BAP total flow Nm3/hr**	**Secondary fan current loading %**			
Hold 20641	10:26	BAP increased	923		58	45	43
	10:28	BAP measured	1480		54	42	40
	10:36	Scrap addition	1620		48	37	36
	10:46	BAP reduced	712		73	56	54
	10:47	HM addition	431		78	60	58
	10:52	Blow start	431		68	54	51
	11:12	Blow finished	720		49	38	37
	11:16	Tapping started	518		58	45	53
	11:24	Tapping completed	428		83	65	62
Hold 20643	11:36	BAP increased	1293		52	40	39
	11:44	Scrap addition	1583		39	35	30
	11:58	BAP reduced	532		54	44	40
	11:59	HM addition	431		81	62	60
	12:03	Blow start	431		69	54	51
	12:21	Blow finish	578		47	36	36
	12:27	Tapping started	737		65	51	45
	12:34	Tapping completed	431		66	50	48

Each trial heat was charged with hot metal, scrap metal and other materials for the steel making process. For each trial heat, 20 tonnes of merchant bales (galvanised scrap) was required, with no waste oxide briquettes (WOB's), to provide comparable conditions for the trial heats.

In Table 7 the scrap charge and additions are compared between the heats. For the control heats 18793 and 18795 less than 20 tonnes of merchant bales were recorded on the PI system. However, the scrap charge weigher noted that the balance of merchant bales required to make the 20 tonnes required for each trial was substituted from the milled products charge because the charge request could not be altered on the system.

Table 7: Material additions for each trial

	Control trials		**Hold trials**	
	18793	**18795**	**20641**	**20643**
Hot metal	296.1	282.9	295.4	307.0
Dolomet	5.5	5.1	3.5	2.6
Doloflux	0.0	0.0	4.0	4.0
Lime	10.0	9.0	13.9	13.9
Ore	4.1	1.3	7.2	0.0
WOB’s	0.0	5.9	0.0	0.0
Subtotal (tonnes)	**315.7**	**304.2**	**324.0**	**327.5**
4C Merchant bales	7.0*	11.5*	21.0	20.5
A Steel skull	4.0	8.0	13.5	8.0
C Steel skull	2.0	4.0	11.0	8.5
Tin & steel cans	1.0	3.0	1.0	1.0
Incinerated bales	0.0	0.0	1.5	1.0
A Desulp’ skull	0.0	5.0	0.0	0.0
Cold Iron	0.0	0.0	0.0	0.0
Mill products	51.5	43.0	20.0	20.0
Subtotal (tonnes)	65.5	74.5	68.0	59.0
Total mass (tonnes)	**381.2**	**378.7**	**392.0**	**386.5**
Mass of steel tapped (tonnes)	**333**	**324**	**327**	**n/a**

* The balance of merchant bales required to make the 20t required for each heat was substituted from the milled products charge by the scrap charge weigher.

5.1.4 Primary dust extraction system

5.1.4.1 BOS Slurry flow rate

The BOS slurry flow rate in the pipe from the BOS plant to the launder and clarifiers was measured using a Flo-dar combined ultrasonic and laser doppler instrument every minute. Each figure recorded by the Flo-dar apparatus was obtained from up to 200 counts averaged by the instrument over a 1 minute period (see Appendix Tables A1-A5).

Figure 21 and Figure 22 show the flow rate profile for the entire sample period for the two control trial heats 18793 and 18795.

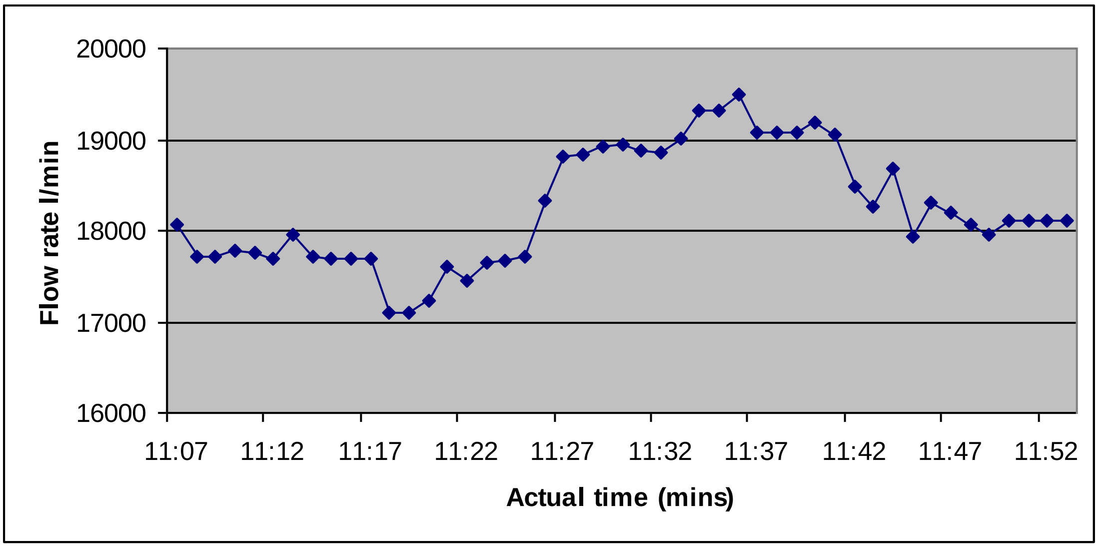


Figure 21: Slurry flow rates during the sampling trial for control heat 18793

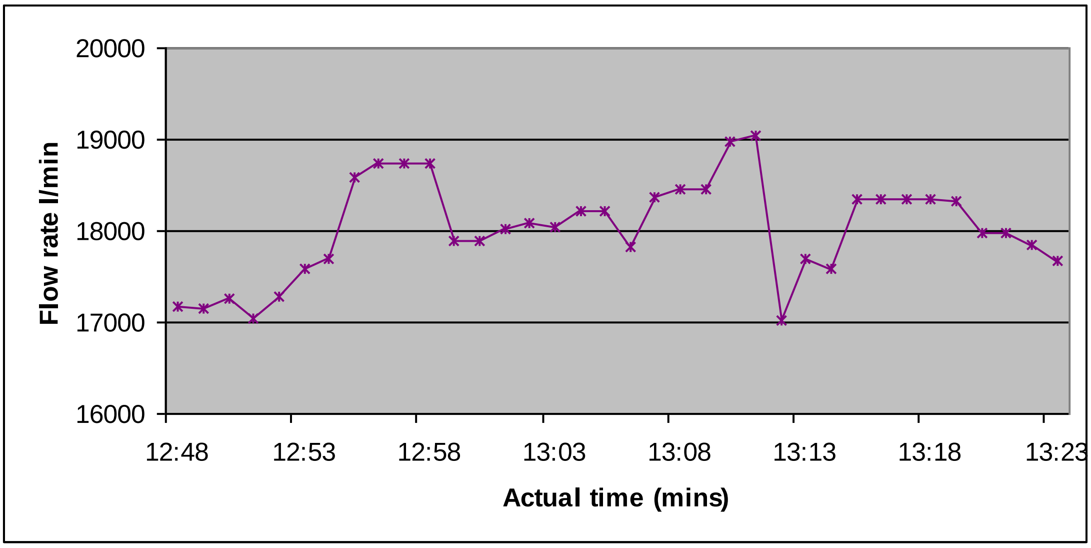


Figure 22: Slurry flow rates during the sampling trial for control heat 18795

For the control trial heats a total of 46 and 61 flow measurements were recorded during the sampling period respectively. In contrast, for the hold trial heats 33 and 30 sample points were recorded respectively. This is likely to be due to turbulent flow in the BOS slurry pipe when the Flo-dar instrument could not acquire sufficient counts per sample to record an averaged result for that time period.

A comparison of the BOS slurry flow rates measured during the trial heats is shown in Table 8, which shows close agreement in the average flow rates for the control trials of 18247 l/min and 18040 l/min respectively. The two hold trial heats also show close agreement of 17277 l/min and 17315 l/min, but in comparison with the control heats the flow rates were slightly lower.

Table 8: BOS slurry flow rate summary table

	Minimum flow rate (l/min)	Maximum flow rate (l/min)	Average flow rate (l/min)	Sample period (min's)
Control trials				
18793	17107	19501	18247	46
18795	17029	19053	18040	34
Hold trials				
20641	16681	18512	17277	53
20643	16790	18487	17315	46

5.1.4.2 Dust mass flows

During each trial heat 10 litre samples were taken at varying time intervals. For the control trials these approximated to every 2 minutes outside the blow and every 1 minute during the blow. In comparison, for the hold trials the number of samples was increased to every 30 seconds during the initial stage of the blow to capture the rapidly changing composition more accurately.

For the two control trial heats a total of 64 samples were taken whereas for the 2 hold trial heats a total of 93 samples were taken. For each sample the dust content was measured (see Appendix Tables A6 – A9) and has been plotted against the sample time to give a profile of the dust liberated across each heat. The two control heats have been plotted as Figure 23 and Figure 24.

Control heat 18793 shows a flat profile with maximum solids content in the BOS slurry of 34g/l compared to heat 18795 which has a very sharp spike at 75g/l. Both profiles show an increase in the solid content corresponding to the start of the blow when the largest quantity of dust is given off. A gradual decline in the solids content was observed through the rest of the heat.

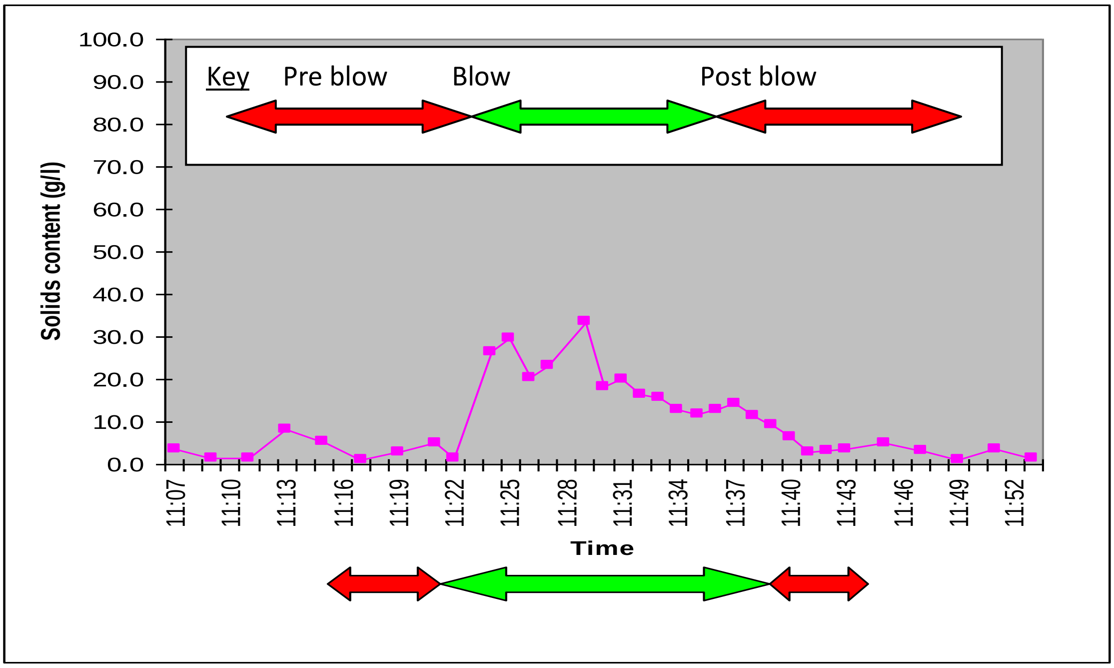


Figure 23: Profile of BOS slurry solids content through control heat 18793

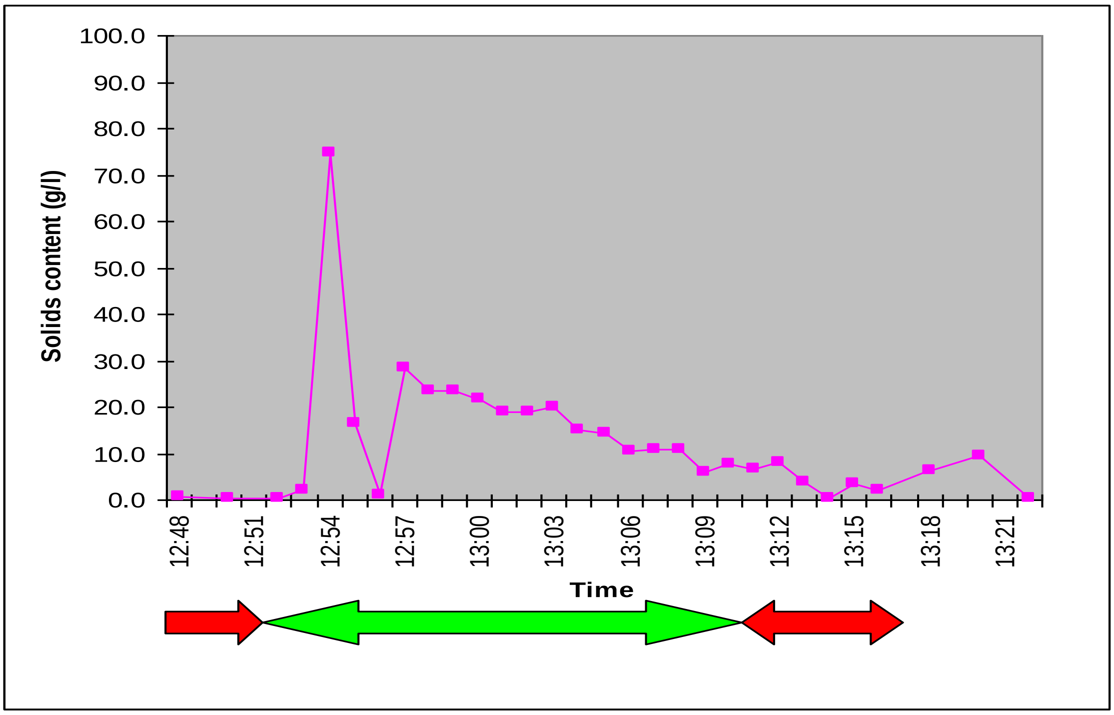


Figure 24: Profile of BOS slurry solids content through control heat 18795

The two profiles for the hold trial heats are comparable with the control trials. Heat 20641 shown in Figure 25 has a flat profile with a peak solid content of 39g/l compared to heat 20643 in Figure 26 which has a sharp peak at 88g/l.

However, there are some differences at the beginning of the heat prior to the addition of scrap in the process, as well as the end. In heat 20641 prior to the scrap addition the dust content peaked at 11g/l and at the end of tapping it peaked at 37g/l. Heat 20643 peaked at 15g/l prior to the scrap addition without a notable peak during the tapping stage.

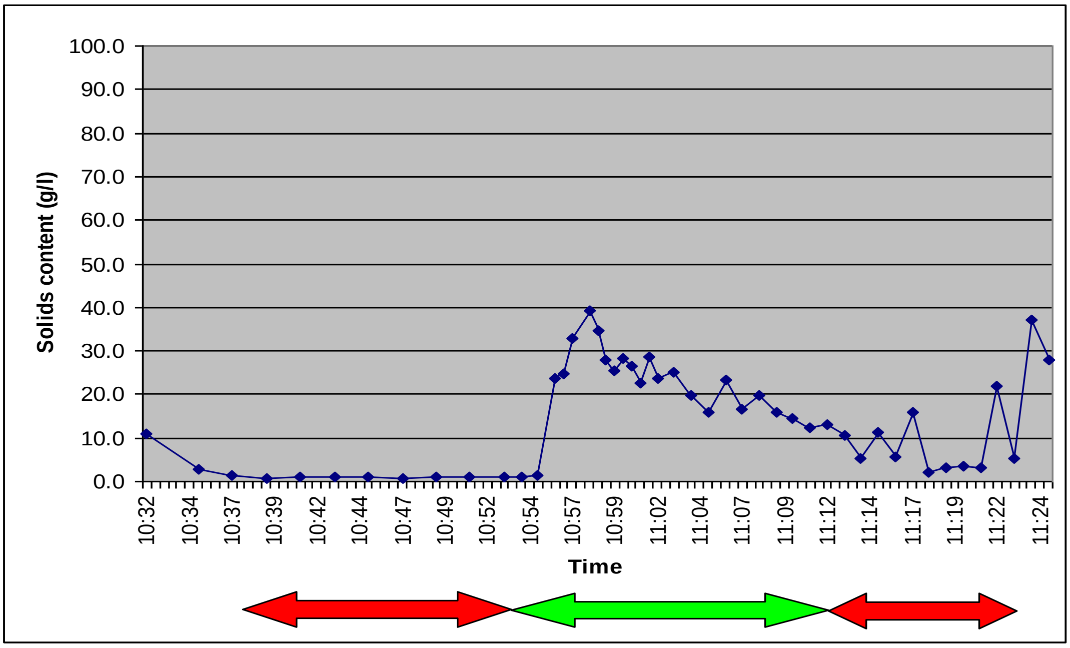


Figure 25: Profile of BOS slurry solids content through hold heat 20641

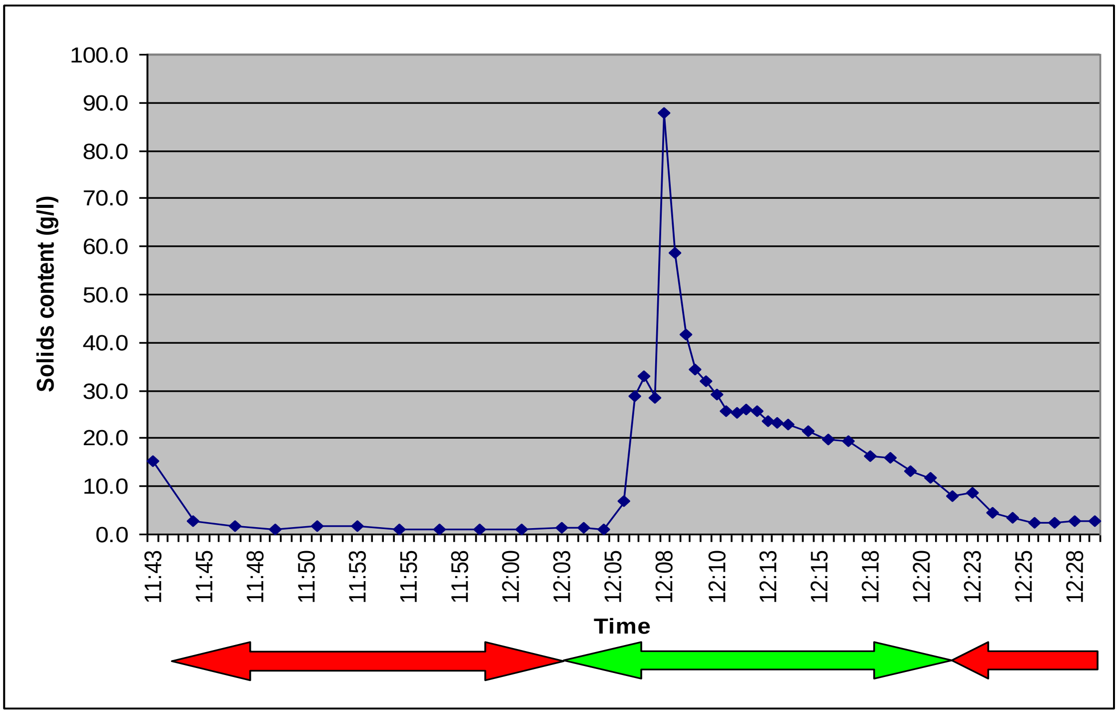


Figure 26: Profile of BOS slurry solids content through hold heat 20643

The solid dust mass flows (kg/min) were calculated (see Appendix Tables A10 – A13) from the BOS slurry flow rates (l/min) measured during the trial heats, and the solids contents (g/l). This gives the rate at which dust is being liberated from the converter during each heat.

The original objective was to sample the BOS dust liberated during the blow because large quantities of dust were not expected outside this period. However for the hold trials the sample period was extended before and after the blow start to give a wider picture of the dust liberated.

To compare the two control and two hold heats, Figure 27 highlights the rate of dust production (kg/min) against the time which has been normalised to the blow start at zero minutes. The time delay noticed after the blow start, to the dust levels increasing rapidly was between 3 and 4 minutes and corresponds to the residence time before the liberated dust captured in the off gas system (OG) is collected at the sample point.

During the blow periods (from 3 to 23minutes accounting for the residence time) the control heat 18793 and the hold heat 20641 showed similar profiles with peak dust mass flow rates of 635 and 680kg/min. Control heat 18795 and the hold heat 20643 also show similar profiles to each other but with much greater peak mass flow rates of 1321 and 1524kg/min respectively.

It has been observed that some significant dust mass flow rates were measured outside the blow period. Hold trial heat 20641 and 20642 gave dust mass flow rates of 187 and 262kg/min 20mins before the blow start. For the hold trial 20641 a peak of 640kg/min was also observed 30mins after the blow start.

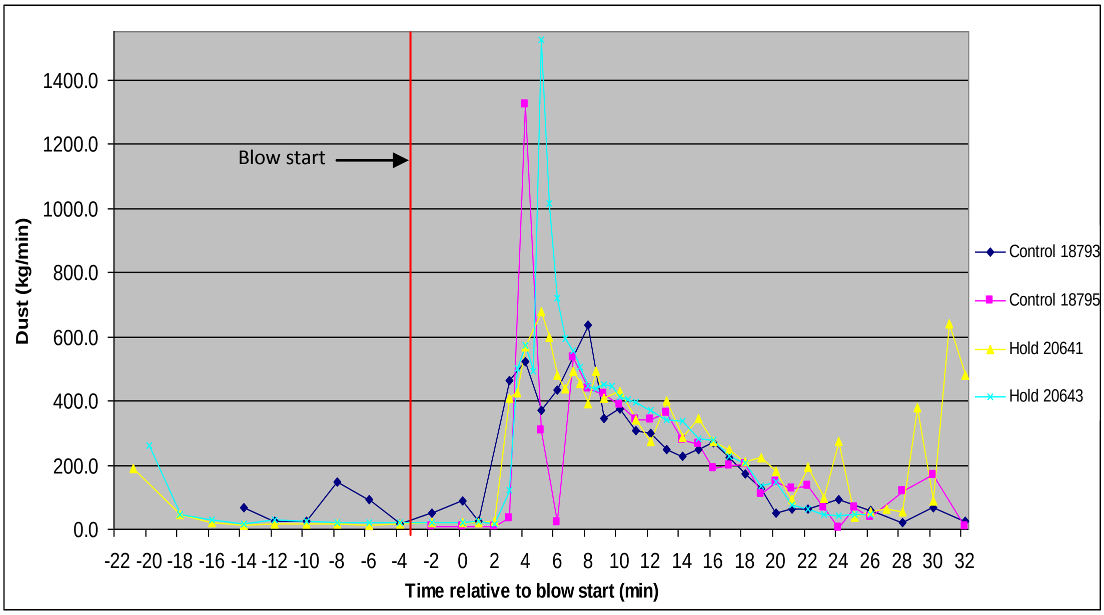


Figure 27: Dust mass flow profile comparison for control and hold trials

Each heat typically takes 40 minutes from tap to tap, the time when the steel gets poured out of the converter. This can vary according to production constraints, production plans, the steel manufacturing grade, and day to day breakdowns and maintenance. On the day of the control trial the BOS plant was on single converter operations and 9 of the heats ranged between 37 – 83 minutes (tap to tap). On the day of the hold trial the BOS plant was on double converter operation when 5 of the heats in vessel 2 ranged between 61 – 79 minutes (tap to tap).

The total dust masses measured during the control and hold trials are compared in Table 9 for two time periods, the blow period when the majority of the dust was liberated, and the entire sampling period which varied for each trial heat according to the sampling conditions on the day. Compared to the control trials the hold trials were sampled over a longer period of time, which included the additional scrap hold.

Table 9: Dust masses collected during trials

	Control trial		**Hold trial**	
Heat number	**18793**	**18795**	**20641**	**20643**
Tap to tap process time (minutes)	53	53	62	73
Dust mass collected over blow period				
Dust mass (kg)	5555	5763	6512	7106
Dust mass per tonne of steel tapped (kg/t)	16.7	17.7	19.9	n/a
Time (minutes)	18	19	19	19
Dust mass collected over complete sampling period				
Dust mass (kg)	7453	6991	10082	8692
Dust mass per tonne of steel tapped (kg/t)	22.4	21.6	30.8	n/a
Time (minutes)	47	35	53	46

A more detailed breakdown of the total dust mass liberated in the 5 main process periods is represented in Figure 28, which compares the dust masses for each trial period and is labelled with the length of time for that period. It should be noted when comparing the masses of dust liberated, that the total sample time for control trial 18795, and the hold trial 20643, did not cover all the 5 main process periods.

For the first period prior to the scrap addition, the control trial heats and the hold trial heats liberated similar peak quantities of dust, 531kg of dust for the control 18793 compared to 654kg for hold 20441.

For the second period, between the scrap addition and the blow, the quantities of dust for the control trials were also comparable with the hold trials. Control trial 18793 had a mass of 329kg compared to 454kg for the hold trial 20643. Despite a much longer hold time of 17 minutes compared to 6 minutes, the hold trials did not yield significantly more dust.

For the blow period, when the majority of the dust was liberated, bigger differences in the mass collected were observed even though the blow periods for all the trials were within 1 minute of each other. The two hold trials liberated 6512 and 7106kg compared to the two control trials at 5555kg and 5763kg.

Compared to the control trials, the hold trial 20641 liberated quantities of dust after the blow period that add significantly to the total dust collected for the entire sampling period. From the end of the blow to the end of tapping this measured 1517kg and for the post tapping period this totalled 1121kg. It is not clear why the hold trials yielded additional dust to the control trials during the blow periods.

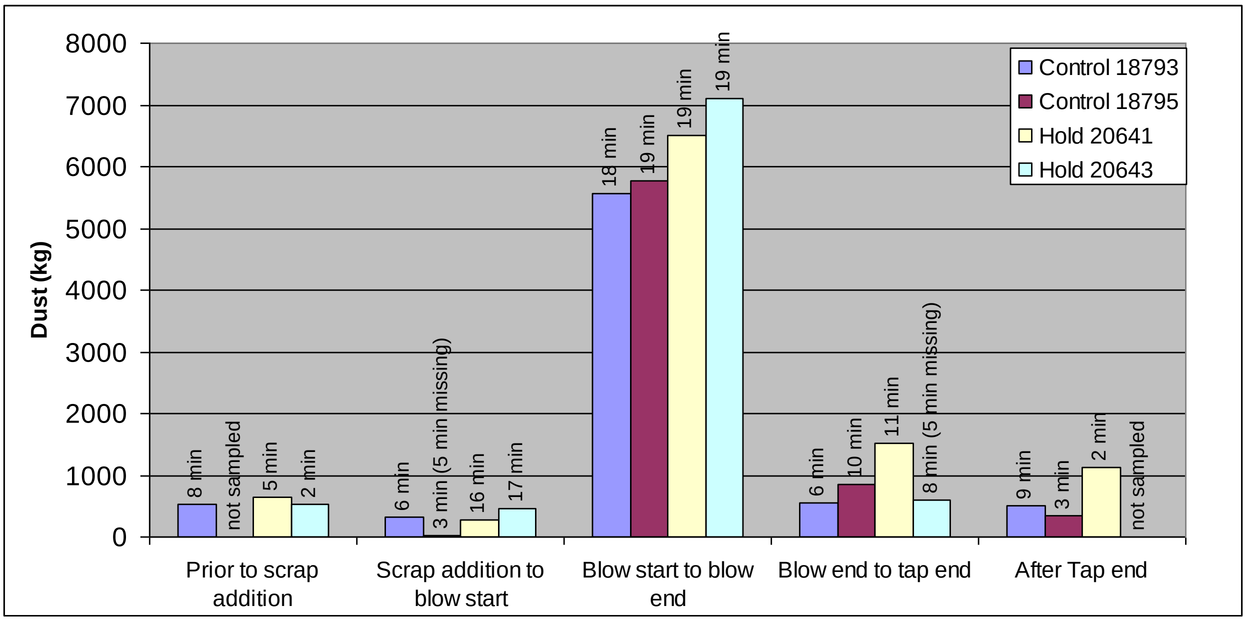


Figure 28: Dust mass generation during the main process periods

The rate of dust liberation for each period is compared for each trial heat in Figure 29. The dust was liberated most steadily during the blow period when the rate was higher for the hold heats compared to the control heats, typically 300kg/min for the controls compared to 350kg/min for the holds.

Outside of the blow period the dust was liberated more randomly. Prior to the scrap addition, and before any changes to the standard processing, the two hold trials liberated dust at a higher rate compared to the control trials. After the blow period the hold heat 20641 showed an increased rate of dust liberation for the blow end to the tap period and a very high rate for post tapping.

However, the PI data shows no obvious reason why this is the case as no slag splashing took place during the hold trials and the steel had been tapped out of the converter.

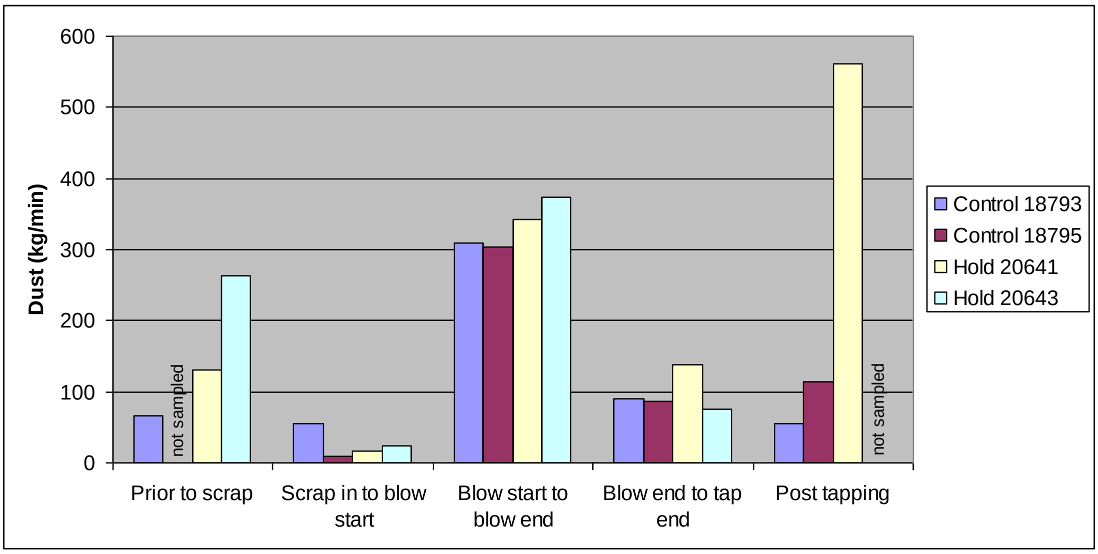


Figure 29: The rate of dust mass generation during the main process periods

5.1.4.3 Zinc concentrations and mass flows

Each sample from the trials was dried, milled and analysed by an Inductively Coupled Plasma (ICP) spectrophotometer to determine the concentration of zinc in the corresponding compounds. For comparison, the mass of zinc contained in the 20t of galvanised merchant bales charged to the converter has been calculated as 316kg (see Mass **of zinc in 20t of galvanised scrap** Table A14). This compares with a zinc content of 594kg quoted from a Tata internal report (Hill, Pickin, Butt, & Turner, 1991).

In Figure 30 the profile of the percentage zinc concentration is plotted during each of the trial heats. The control trials had higher peak zinc concentrations, 14.9% and 11.31% compared to the hold trials with 10.3% and 4.8%. Also, the profiles of the control trials are broader with a greater number of samples of high zinc concentration compared to the hold trials.

There was a residence time of 3-4 minutes from the dust liberation out of the converter to its capture at the sample point, where the zinc mass flow rate increases rapidly 3-4 minutes after the blow start when peak masses are produced.

However, the concentrations in Figure 30 show the zinc concentration for heats 20641 and 18793 increase rapidly before the big increase in the dust mass flow. This suggests that the increase in primary off-gas flow, prior to blow start, purges dust with higher zinc content that may have been lodged in the OG system.

If this is the case it also suggests that higher OG flow rates, with the converter in the vertical position during the hold, might capture the volatilised zinc dust in the primary system prior to the main dust mass liberation. If this were the case then potentially this could be redirected to separate the dust with high zinc content but lower mass, prior to the main dust mass liberation during the blow.

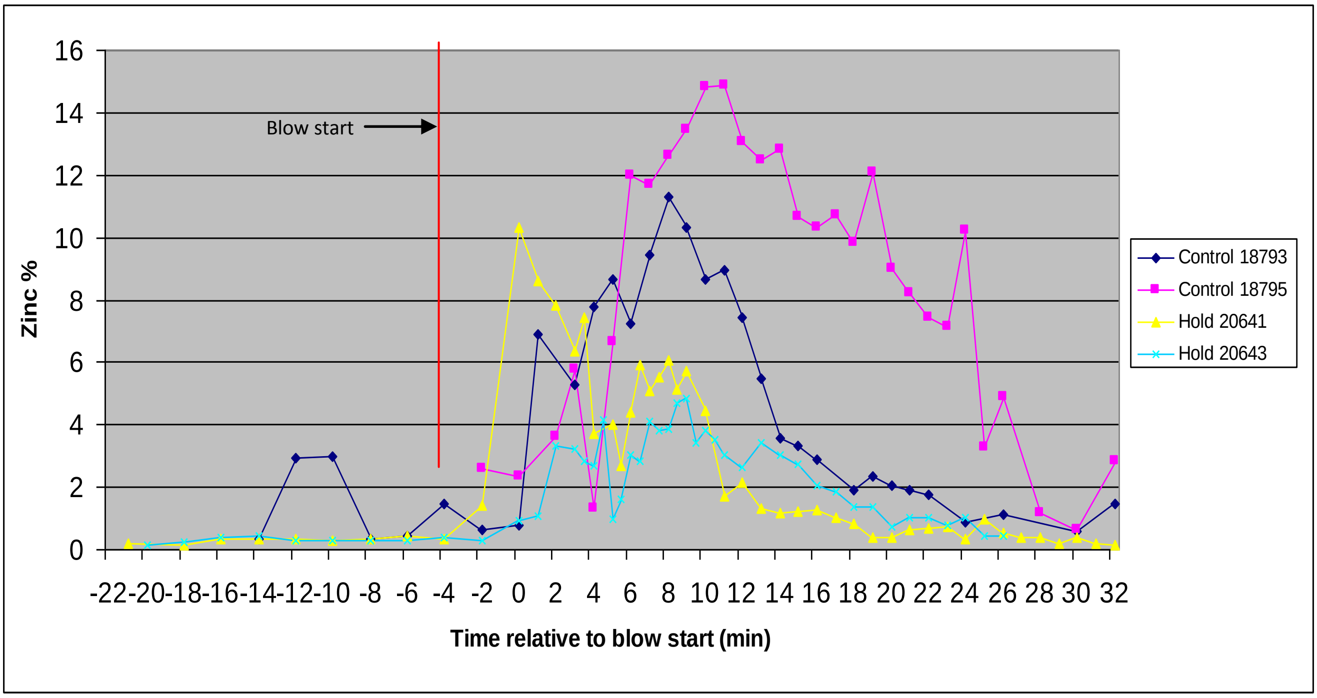


Figure 30: Zinc concentration in dust samples collected during trials

The rate of zinc liberated in the dust (kg/min) was calculated from the measured dust mass flow (kg/min) and zinc concentration (%) for each sample. Figure 31 illustrates the control profiles are higher and broader compared to the hold trials thus indicating a lower quantity of zinc in the primary dust of the hold trials compared to the controls.

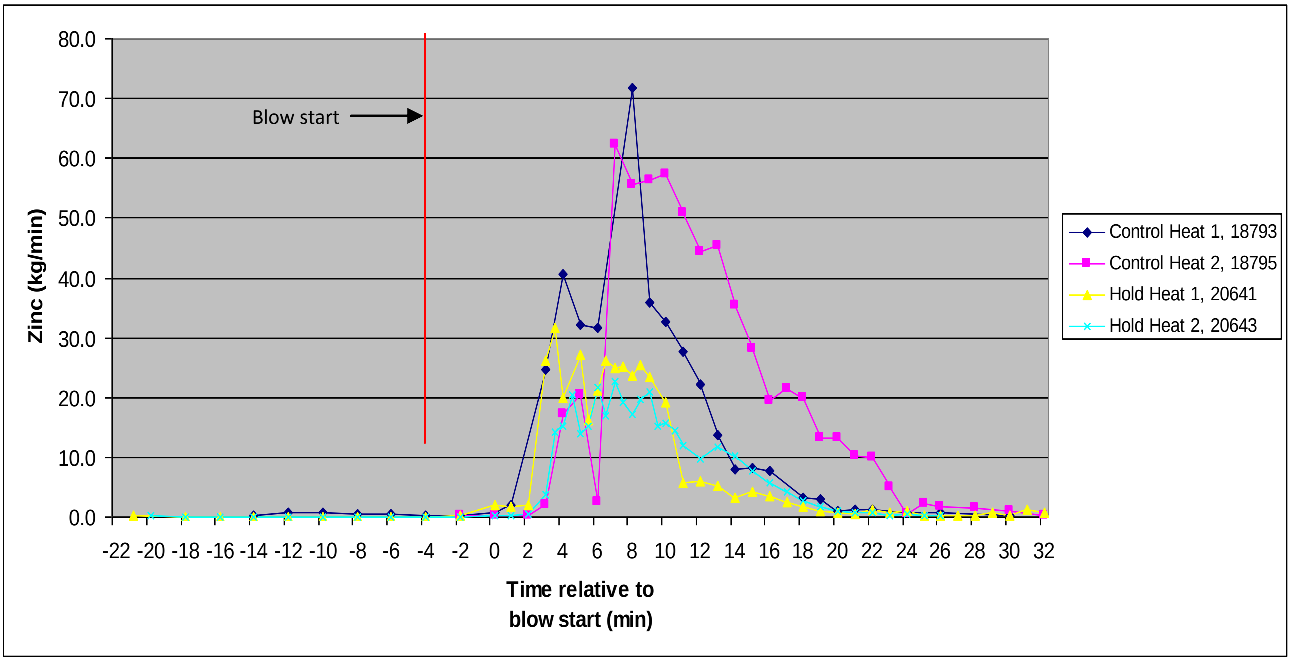


Figure 31: Zinc mass profile measured in dust collected during trials

A comparison of the total mass of zinc liberated during the trials is shown in Table 10. For the blow period, when the majority of the dust is liberated, a complete set of samples were collected for all the trial heats. The mass of zinc contained in the primary dust for the control trial heats was 409kg and 552kg respectively. In comparison the hold trials produced much less at 224kg and 199kg despite longer sampling period and larger dust mass for the hold trials.

Table 10: Zinc masses collected during trials

	Control trial		Hold trial	
Heat number	**18793**	**18795**	**20641**	**20643**
Dust and zinc mass collected over blow period				
Dust mass (kg)	5555	5793	6512	7106
Zinc (kg)	409	552	224	199
Average zinc content (%)	7.4	9.5	3.4	2.8
Dust and zinc mass collected over complete sampling period				
Dust mass (kg)	7453	6991	10082	8692
Zinc (kg)	431	603	236	206
Average zinc content (%)	5.8	8.6	2.3	2.4

Figure 32 shows a more detailed breakdown of the total zinc mass liberated during the five main process periods. The figure compares the zinc masses for each period during each trial and is also labeled with the length of time for that period. It is important to note, when comparing the masses of zinc liberated, that the total sample time for control trial 18795, and the hold trial 20643, did not cover all the 5 main process periods. The figure shows the majority of zinc is liberated during the blow period and for all the trial heats this was between 18-19minutes in length.

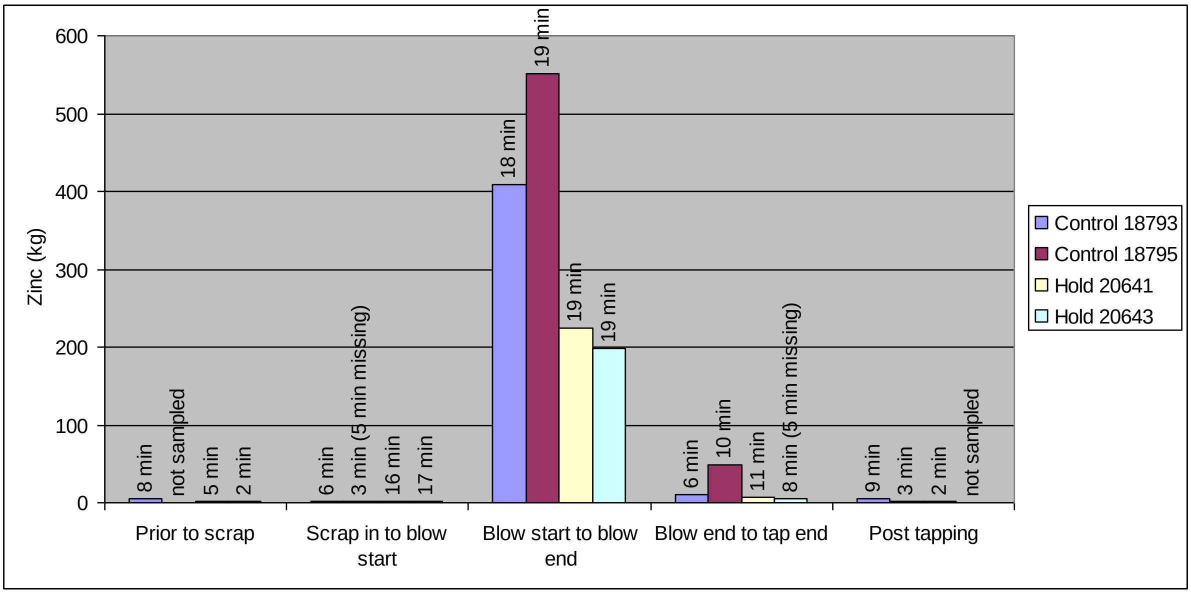


Figure 32: Zinc mass generation over the main process periods

5.1.4.4 Iron, calcium and magnesium concentrations and mass flows

The iron mass flow profile shown in Figure 33 is similar for all the heats during the blow period with peak iron content flow rates at 389kg/min in the early stages of the blow gradually decreasing to the end of the blow.

The two hold trial heats 20641 and 20643 show some spikes in the mass flow rate outside of the main blow period. Peak flow rates of 153 and 218 kg/min were noted before the scrap additions and scrap hold period. After the tapping stage was complete the hold trials also measured peaks for 20641 at 453kg/min and for 20643 at 149kg/min.

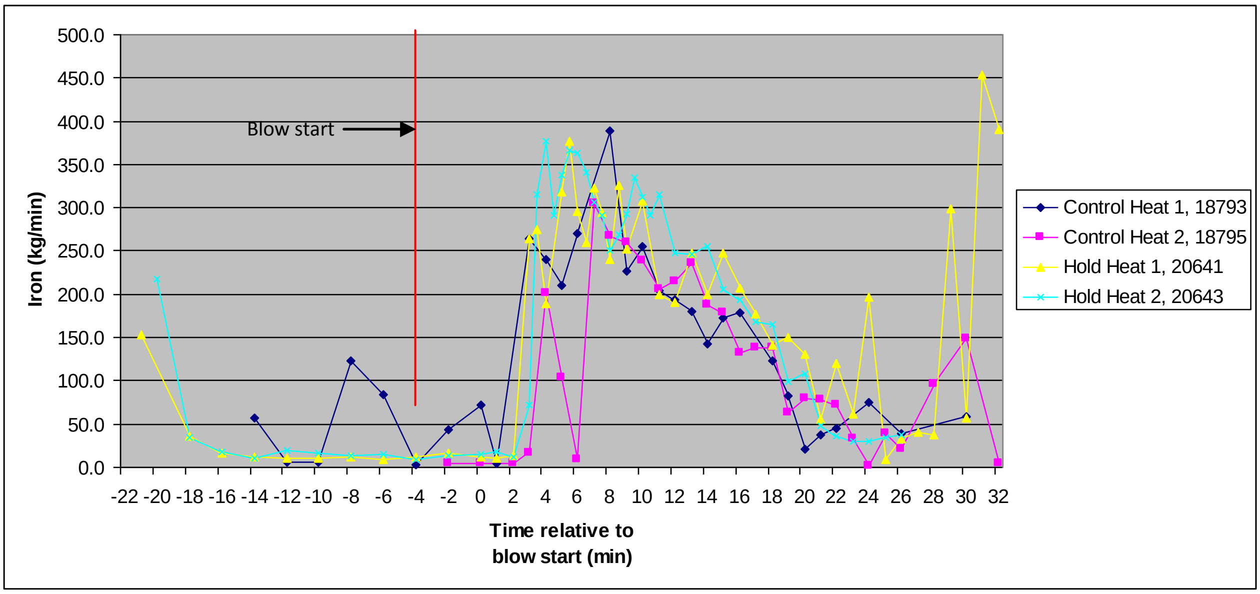


Figure 33: Dust iron content mass flow during trials

The calcium mass flow profile, shown in Figure 34, peaks at the blow start when the flux additions are made. The control heat 18795 and hold heat 20643 peaked at 446kg/min and 440kg/min respectively, whereas the control heat 18793 and hold heat 20641 peaked much lower at 54kg/min and 98kg/min. With only a limited number of heats as comparison it is not clear if this is within the normal process variance and the process notes showed no obvious reasons for such differences.

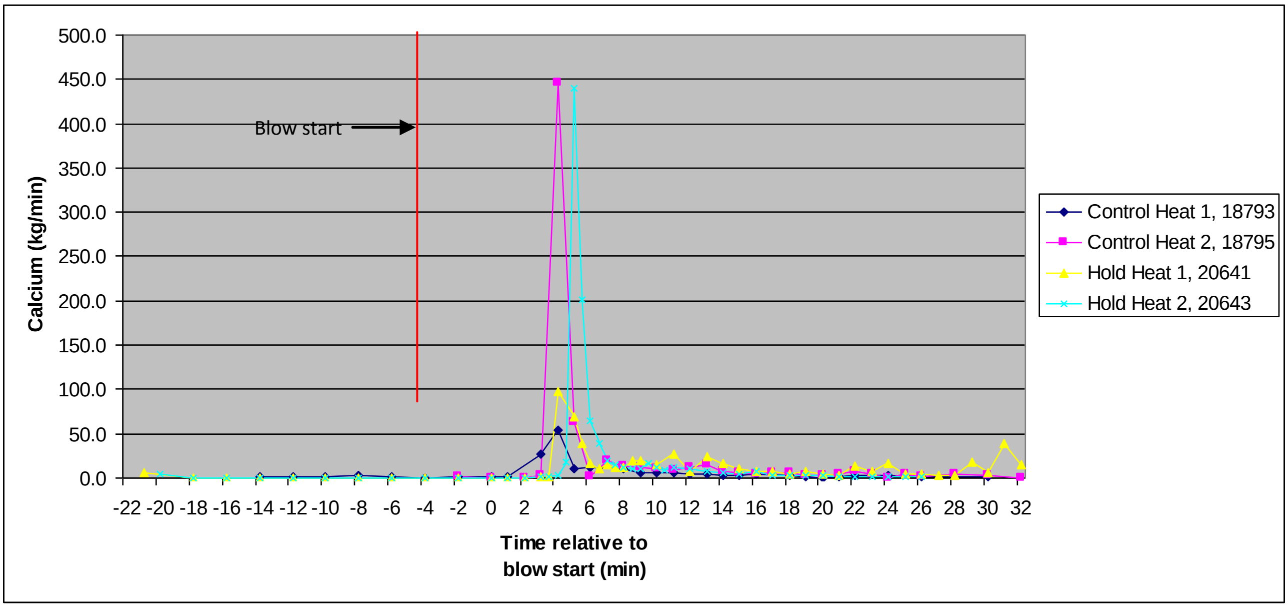


Figure 34: Dust calcium content mass flow during trials

The magnesium mass flow profile, shown in Figure 35, also shows peak flow rates at the blow start corresponding to the flux additions, as observed with the calcium. Two heats peaked very high and two peaked much lower, the control heat 18795 and hold heat 20643 peaked at 74kg/min and 33kg/min, whereas the control heat 18793 and hold heat 20641 peaked much lower at 6kg/min for both.

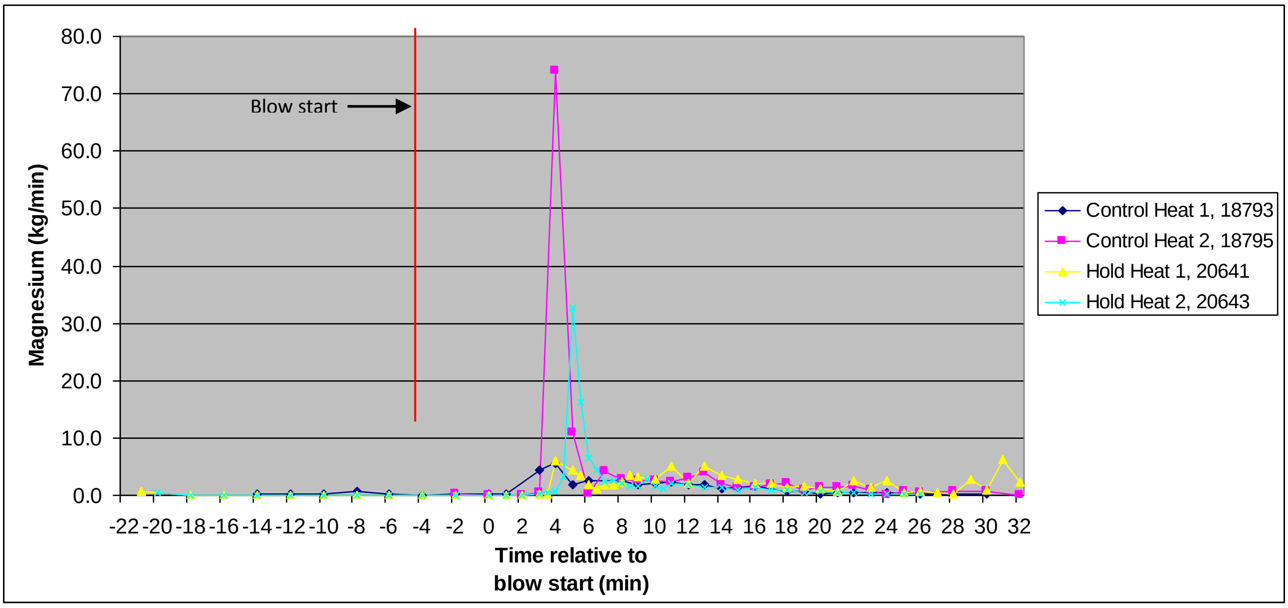


Figure 35: Dust magnesium content mass flow during trials

5.1.4.5 *Particle size distribution*

The particle size distribution of the dust particles during a heat was measured for the control 18793 by running each sample collected during the heat through a Malvern Mastersizer. The instrument measures the size of the particles by laser diffraction. A laser beam passes through the diffuse sample and the laser beam gets scattered. Then the intensity of the scattered light is measured and the particle size of the sample which created the scattering pattern is calculated. (http://www.malvern.com, 2015) This instrument measures the particle size distribution for a sample and a volume percentage of the particles below a mean particle size diameter. For example, a sample with a D(v,0.9) of 100 micron indicates that 90% of the volume of particles of that sample have a mean particle size diameter below 100 micron.

Figure 36 is a plot of the mean particle size diameters, D(v,0.1), D(v,0.5) and D(v,0.9), for each sample taken during the heat. These figures correspond to 10%, 50% and 90% of the sample volume that are below the mean particle size diameter quoted.

Accounting for the 3 minute residence time taken for the dust to be captured at the sampling point, dust samples from the blow started at 11:24 and finished at 11:42. For all the samples during the blow period, 90% of the dust particles had a mean particle size diameter less than 36 micron. Before and after the blow period the samples had a much higher mean particle size diameter, up to 567micon and 279 micron respectively.

In comparison to the particle size analyses, the zinc concentrations of the samples plotted in navy blue on Figure 36, were highest during the blow and lowest outside of the blow period.

To investigate if there was a link between particle size and zinc content, a composite BOS dust sample from control heat 1 was separated into different particle size ranges by wet sieving. The obtained particle size distribution was then assessed for mass percentages and zinc content. The results shown in Table 11 indicated higher zinc levels across the smaller particle size ranges. The sub 20 micron particle size range was especially high in Zinc with a value of 6.7 %. Similar results were obtained after sieving the other trial heats.

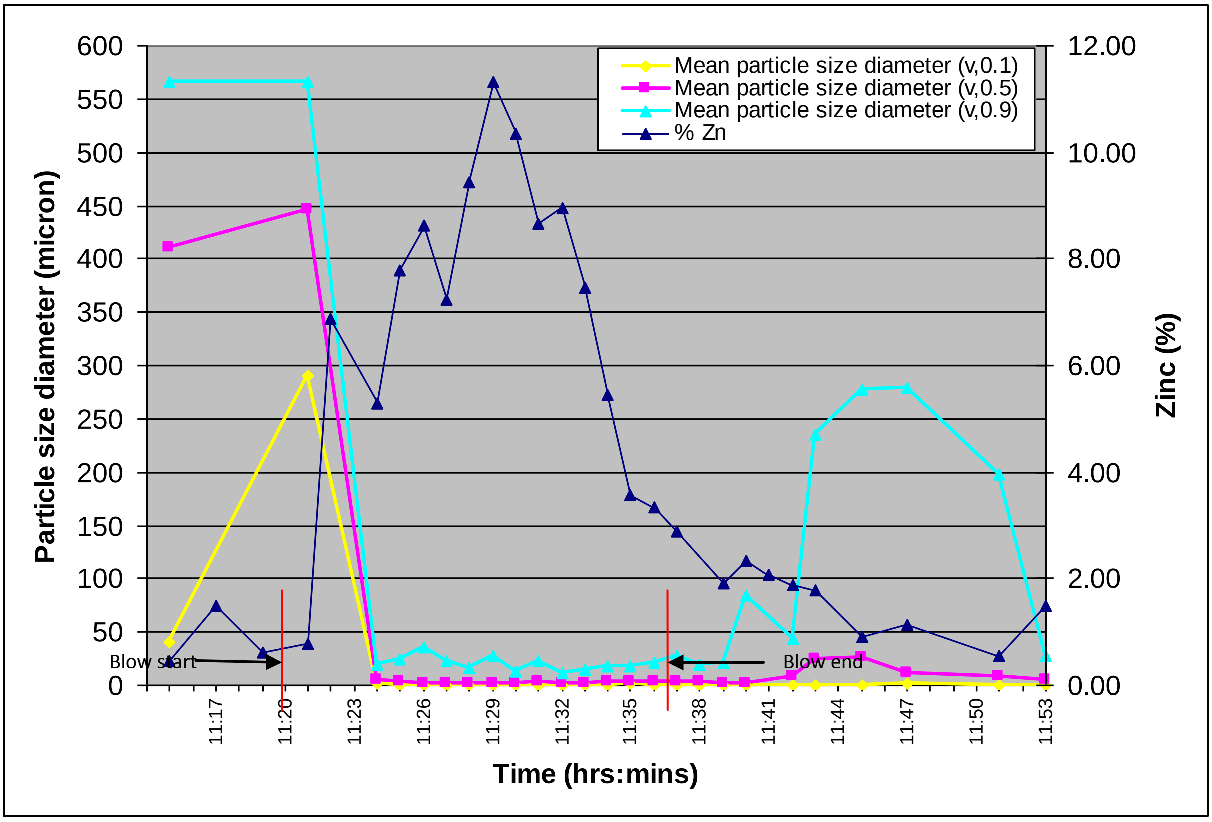


Figure 36: Particle size ranges compared to zinc content during control trial 18793

Table 11: BOS slurry sample separated by wet sieving

	Particle size (micron)				
	<20	**20 - 45**	**45 - 63**	**63 - 106**	**106 - 850**
Mass percent (%)	67.3	3.9	1.2	6.5	21.0
Zinc content (%)	6.7	2.0	0.6	0.9	0.7

5.1.4.6 Particle characterisation

A detailed SEM investigation of the samples was conducted.

Dust captured during the blowing period is characterised by its very fine particle size with 90% of the particles being smaller than 30 microns (Figure 37). Dust captured outside the blow period tends to be larger with some particles up to 1 mm. Particle size of the dust varies from heat to heat, but typically 90% of the particles from a composite sample will have a diameter less than 100 microns.

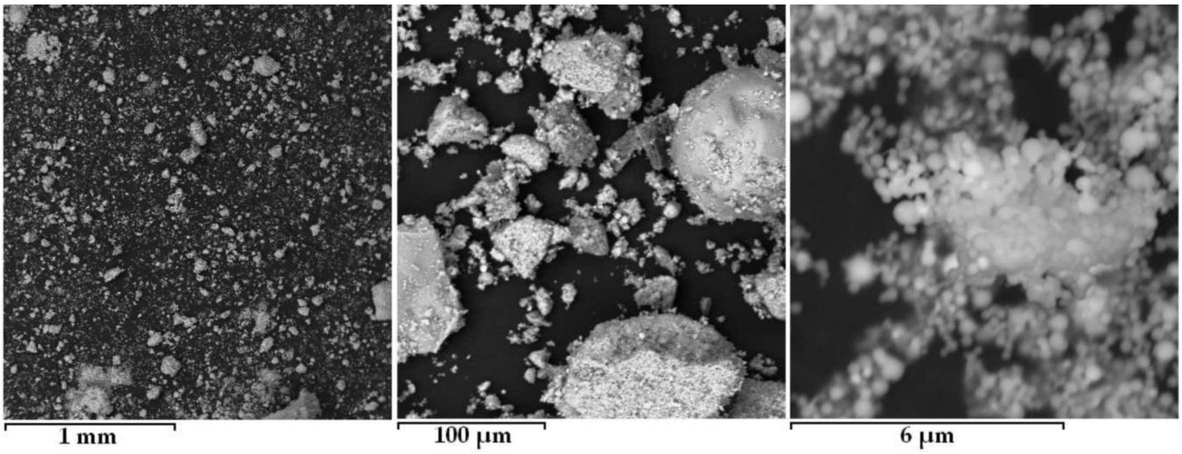


Figure 37: Scanning electron microscope pictures of BOS dust generated at the start of the blow

During the investigation three distinctive dust particles were identified.

- Fines (Figure 38a)

The vast majority of particles in the dust can be classified as fines. The sub micron particles form agglomerates, typically below 20 micron, but can occasionally grow up to 200 micron. The main constituent of the particles is iron. The particles are produced over the complete blowing period, but production rate decreases with time. Zinc seems to have a uniform distribution in the particles and is found inside and outside of the sub micron spheres. Zinc contamination of the particles varies with galvanised scrap input, but zinc levels can reach 15% in the first half of the blow, before the zinc levels decrease during the second half.

- Iron spheres (Figure 38b):

The iron spheres are produced after hot metal charging and during the blow. These particles are also found in the slurry water outside of the blow period as ‘carry over’ material. Being typically in the region of 60 – 500 microns, the iron spheres account for approximately 25% of the dust. Little zinc contamination is present with some zinc attached to the surface.

- Angular shaped particles (Figure 38c)

The angular shaped particles were predominantly found at the beginning of the blow, after top charging of the converter and outside the blow period as ‘carry over’ material. They account for a small share of the dust, typically consisting of top charged material like dolomite and lime (Ca) or remains of the desulphurisation slag (S, Na, K). They can be up to 500 microns in diameter, with some zinc attached to the surface.

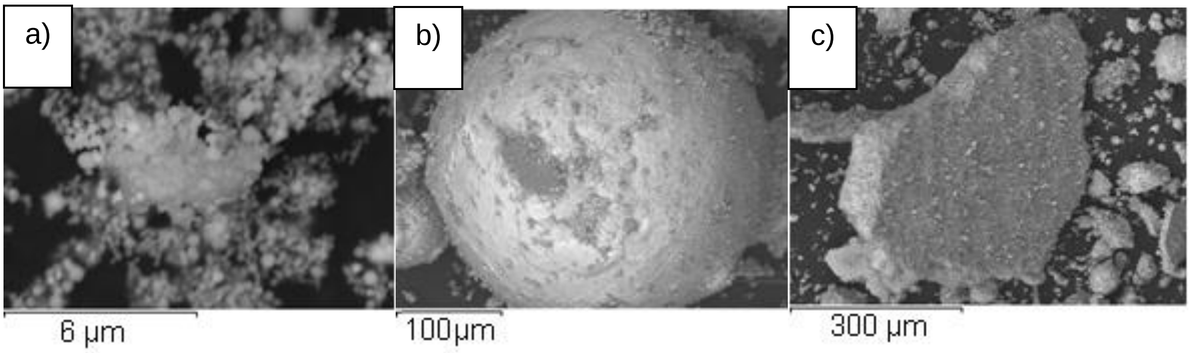


Figure 38: SEM pictures of most distinctive dust particles

5.1.4.7 Slurry liquor metal content

To investigate if the zinc was being collected in the slurry water a series of samples were tested during the hold trials and measured by ICP. The masses of the metal cations dissolved in the slurry water were calculated from the metal concentration measurements (weight/volume %) and the flow volumes (litres) to give the mass of metal (kg) for each sample. Figure 39 and Figure 40 shows the zinc and calcium profile during the hold trials 20641. The levels of zinc in the slurry water during the entire trial were negligible. The calcium content shows a sharp peak of 8.2kg at the beginning of the blow corresponding to the addition of lime in the flux additions. However, compared to the masses of calcium contained in the BOS slurry dust of 506kg and 243kg, and compared to the quantity of lime added to each heat (typically 10,000kg per heat), these levels do not represent significant losses.

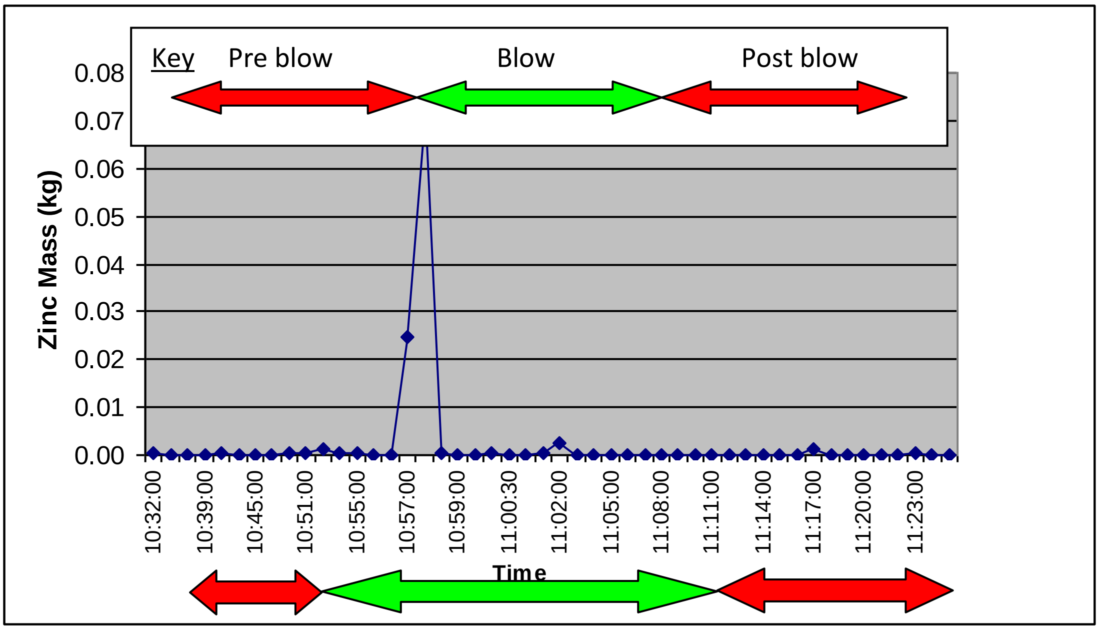


Figure 39: Zinc content in BOS dust slurry water hold trial 20641

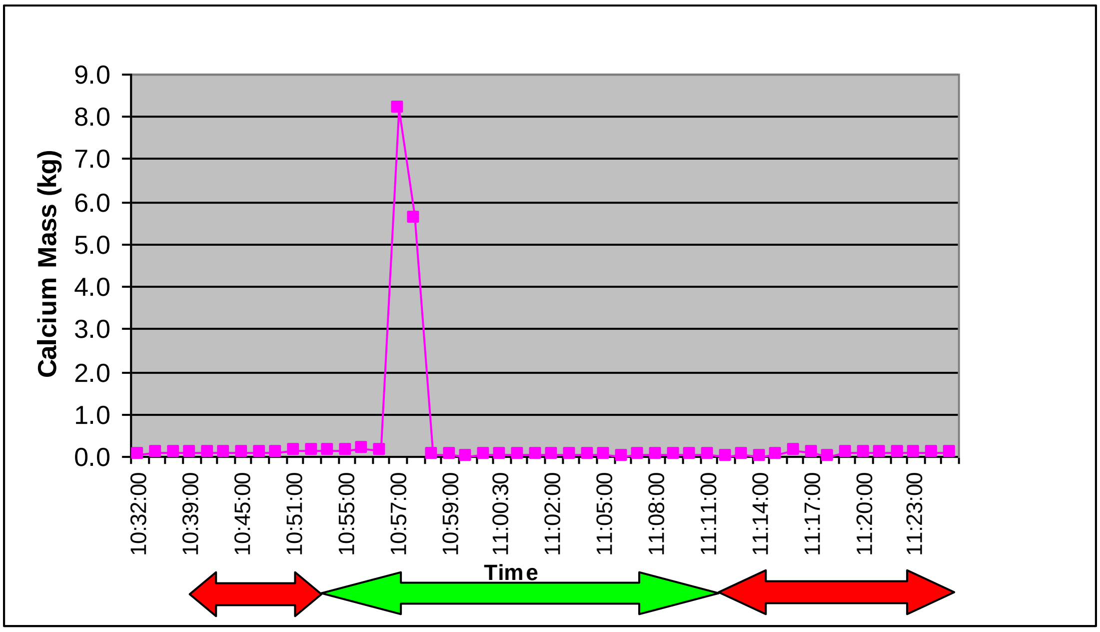


Figure 40: Calcium content in BOS dust slurry water hold trial 20641

5.1.4.8 Variation in pH

The BOS dust slurry water was analysed for changes in pH during all the trial heats (see Appendix Tables A15 – A18) and they all show similar profiles to the hold heat shown in Figure 41. The pH for each heat is alkaline throughout the process, varying around 9-10 with a peak of 12.6 at the beginning of the blow. This peak corresponds to the flux additions of lime and to the observed increase in calcium dissolved in BOS dust slurry water.

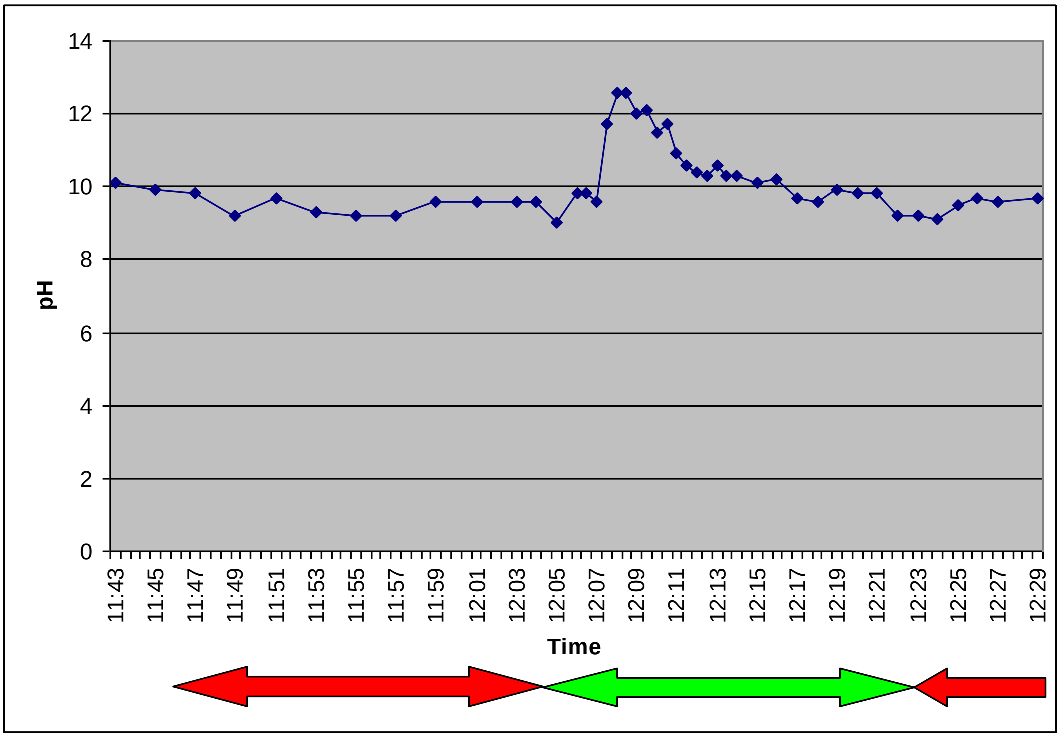


Figure 41: pH profile of BOS dust slurry during hold trial 20643

5.1.5 Secondary dust extraction system

The secondary dust extraction system was sampled every 15 minutes during the time period of the control trials and every 5 minutes during the hold trials. The hold trials were sampled more frequently because there was a constant flow of dust being collected, compared to the control trials when the flow was intermittent. This is because the control trials were on single converter operation but the hold trials were on double converter operation.

A comparison of the metal compositions for each heat in the primary dust is shown in Table 12, obtained by calculating the average concentrations from the measured mass of zinc and total dust mass collected during each heat for each trial. Table 13 compares the secondary dust collected over the two trial periods, but has been calculated as an average metal concentration for the samples collected.

Comparing the primary and secondary dust contents; the calcium levels tend to be higher, the iron levels lower and the zinc levels higher in the secondary dust. These results reflect where the dust is collected; the secondary system mainly collects dust resulting from additions to the converter whereas the primary system collects dust from the converter processes, in particular the blow period.

Table 12: Average primary dust metal concentrations for entire sampling period

	Calcium (%)	**Iron (%)**	**Zinc (%)**	**Number of samples**
Control trial 18793	2.8	64.4	5.8	35
Control trial 18795	9.8	53.7	8.6	30
Hold trial 20641	5.0	65.9	2.3	48
Hold trial 20643	6.1	62.2	2.4	45

Note: The entire sampling period varies between each heat.

Table 13: Average secondary dust metal concentrations for entire sampling period

	Calcium (%)	**Iron (%)**	**Zinc (%)**	**Number of samples**
Control trial 18793 & 18795	11.0	35.7	10.2	18
Hold trial 20641 & 20643	8.9	35.8	11.2	13

Note: The entire sampling period varies between each trial.

A comparison of the metal concentration in the secondary dust during the control and hold trials are shown in Table 14. The zinc results show little variation within the trials and little variation between the controls and hold trials.

Table 14: Secondary dust metal concentration

Control trial IV 13/10/09 Secondary dust			
10.35 - 14.20			
Sample ID	**Ca (%)**	**Fe (%)**	**Zn (%)**
C325	11.9	35.5	9.7
C326	11.1	35.0	10.0
C327	11.5	35.6	10.4
C328	11.9	35.7	9.6
C329	10.1	35.9	10.4
C330	10.8	36.0	11.2
C331	10.8	35.7	10.3
C332	10.8	35.3	10.4
C333	11.1	36.2	10.2
C334	10.7	36.6	10.1
C335	11.0	36.1	9.9
C336	10.9	35.5	9.2
C337	11.0	36.2	10.4
C338	11.5	35.3	10.1
C339	10.9	35.1	10.0
C340	10.6	35.6	10.4
C341	10.6	35.1	10.6
C342	11.1	35.6	10.3
Average	**11.0**	**35.7**	**10.2**

Hold trial IV 04/12/09 Secondary dust			
10:35 - 13:20			
Sample ID	**Ca (%)**	**Fe (%)**	**Zn (%)**
C436	9.3	35.0	10.9
C439	9.0	35.9	11.9
C442	9.0	36.7	10.5
C445	8.9	34.8	10.5
C448	8.5	36.1	10.9
C451	8.8	36.0	11.1
C454	8.5	36.6	11.5
C455	9.0	35.6	11.2
C457	9.1	35.7	11.0
C460	8.7	35.5	11.6
C463	9.0	37.0	11.3
C466	9.2	35.1	11.9
C469	8.9	35.5	11.3
Average	**8.9**	**35.8**	**11.2**

Steel production during the control trial was based on one converter, but for the hold trial both converters were running. Because of this, any increase or change in the zinc concentration of the dust could have been diluted by dust from the other converter making any conclusions difficult and uncertain.

The secondary dust extraction system consists of 3 banks of 5 chambers with a total of 7200 filter bags; the small variations within each trial heat suggest that the dust was being thoroughly mixed so that any increase in zinc concentration was being diluted.

5.1.6 Potential recoverable dust

To consider recovering iron bearing dust from the BOS plant through the sinter plant, Tata staff indicated the zinc concentration would generally need to be less than 0.5%

The dust mass and zinc levels of samples taken during the blow have been used to calculate the mass of potentially recoverable dust. Dust mass ‘cut-off’ levels of ≤0.5% and ≤1.0% zinc have been calculated and compared in two different ways.

1. **Zinc averaging** – by totalling the dust mass, before and after the blow period, when the average zinc concentration contained in that mass is ≤0.5% and ≤1.0%
2. **Concentration** – by selecting sample periods during the blow when the measured zinc concentration was 0.5 % and ≤1.0% then totalling the mass of dust measured for those periods.

5.1.6.1 Zinc average cut-off

The zinc average cut-offs have been obtained by totalling the dust mass and zinc mass produced through the heat and calculating the rolling average percentage zinc concentration until a zinc concentration cut-off level is reached (see Appendix Tables A19 – A20). This has been carried out from the start of the sampling period to the start of the blow and in reverse from the end of the sampling period to the end of the blow.

Table 15 and Table 16 show the potential masses that could be collected from the trial heats depending if a ≤0.5% or ≤1.0% cut-off is chosen (see Appendix Tables A21 – A22). Apart from a short period in control 18793, both control trials have zinc levels above 0.5% which would be difficult to recover through the sinter plant. However, the hold trials show that between 14% and 45% of dust, with an average zinc concentration less than 0.5%, can potentially be recovered.

It is interesting to note the wide difference in recoverable dust for the two hold trials. Particularly because the second hold trial 20643 has lower peak zinc concentrations compared to 20641. However, it has the higher proportion of non recoverable dust above 0.5% concentration because the profile of zinc liberation during the blow is broader and covers a longer period of time as shown in Figure 45 .

Table 15: Mass of dust with rolling average zinc concentration ≤0.5%

	Dust mass before blow (kg)	**Dust mass after blow (kg)**	**Total potentially recoverable dust mass (kg)**	**Potentially recoverable portion of total dust mass (%)**
Control heat 18793	130	0	130	2
Control heat 18795	0	0	0	0
Hold heat 20641	951	3600	4551	45
Hold heat 20643	1104	95	1199	14

Table 16: Mass of dust with rolling average zinc concentration ≤1.0%

	Dust mass before blow (kg)	**Dust mass after blow (kg)**	**Total potentially recoverable dust mass (kg)**	**Potentially recoverable portion of total dust mass (%)**
Control heat 18793	973	562	1535	21
Control heat 18795	0	579	579	8
Hold heat 20641	994	5245	6239	62
Hold heat 20643	1354	607	1961	23

Figure 42 shows a plot of the zinc concentration and the dust mass flow against the time relative to the blow start. The green line indicates the cut-off point during the blow when the average zinc content of the cumulative dust mass is ≤0.5%. For the control trial 18793 there is a small dust mass cut-off but the control trial 18794 in Figure 43 has no mass cut-off with ≤0.5% average concentration.

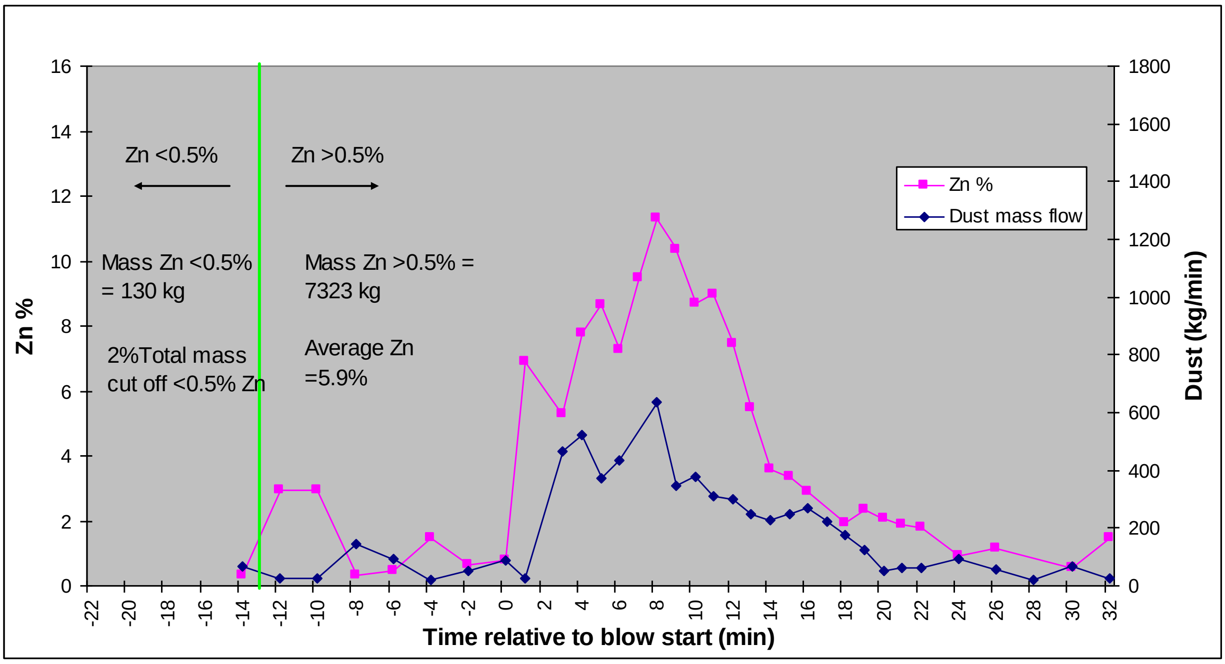


Figure 42: Control trial 18793 dust mass cut off with average zinc content <0.5%

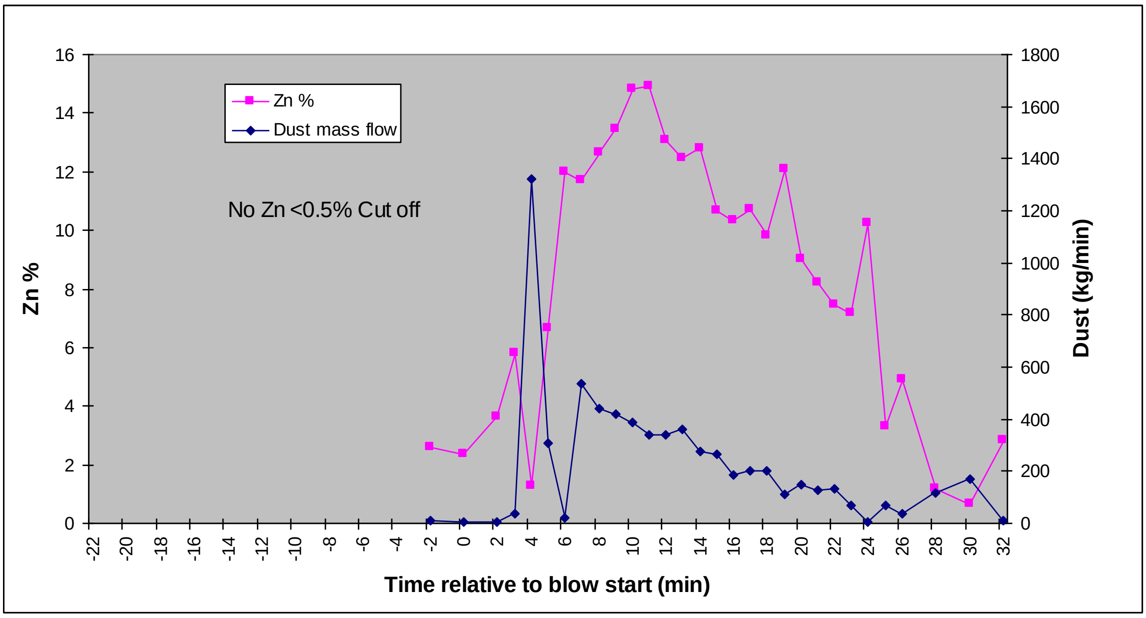


Figure 43: Control trial 18795 dust mass cut off with average zinc content <0.5%

The non recoverable dust portion for hold trial 20641, shown in Figure 44, is liberated over 16 minutes during the blow period. However, for the hold heat 20643, shown in Figure 45, the period when non recoverable dust is liberated is wider at 22 minutes. It should also be noted that 20643 was not sampled over such a long timescale after the blow, whereas 20641 liberated high recoverable dust levels, with high iron content, after tapping.

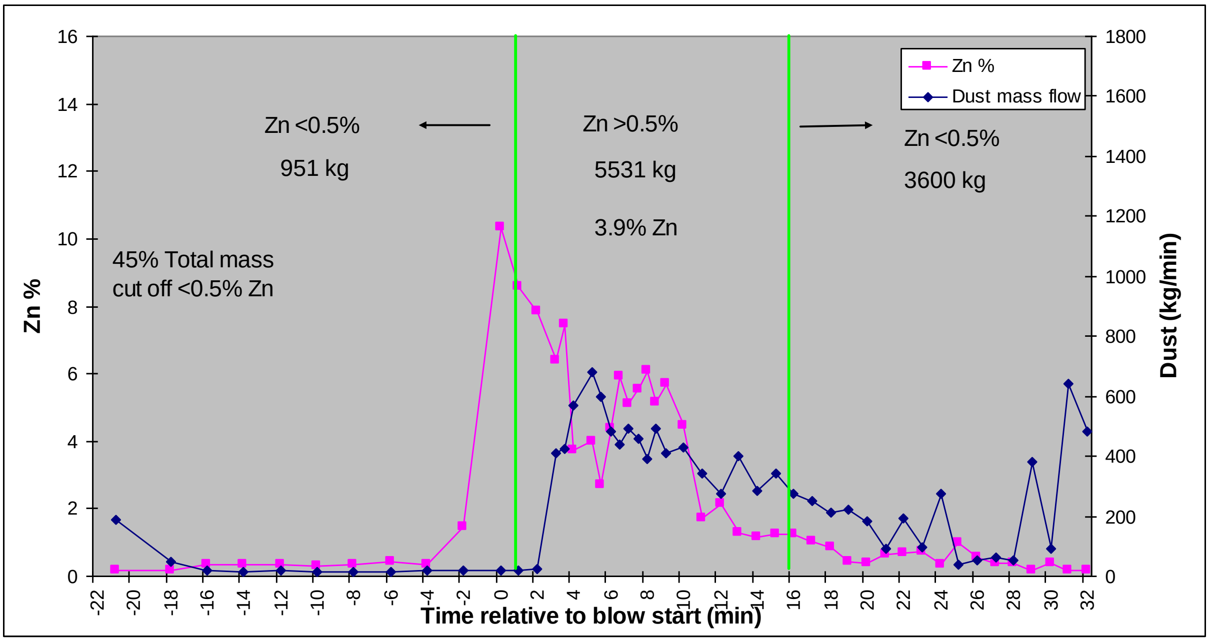


Figure 44: Hold trial 20641 dust mass cut off with average zinc content <0.5%

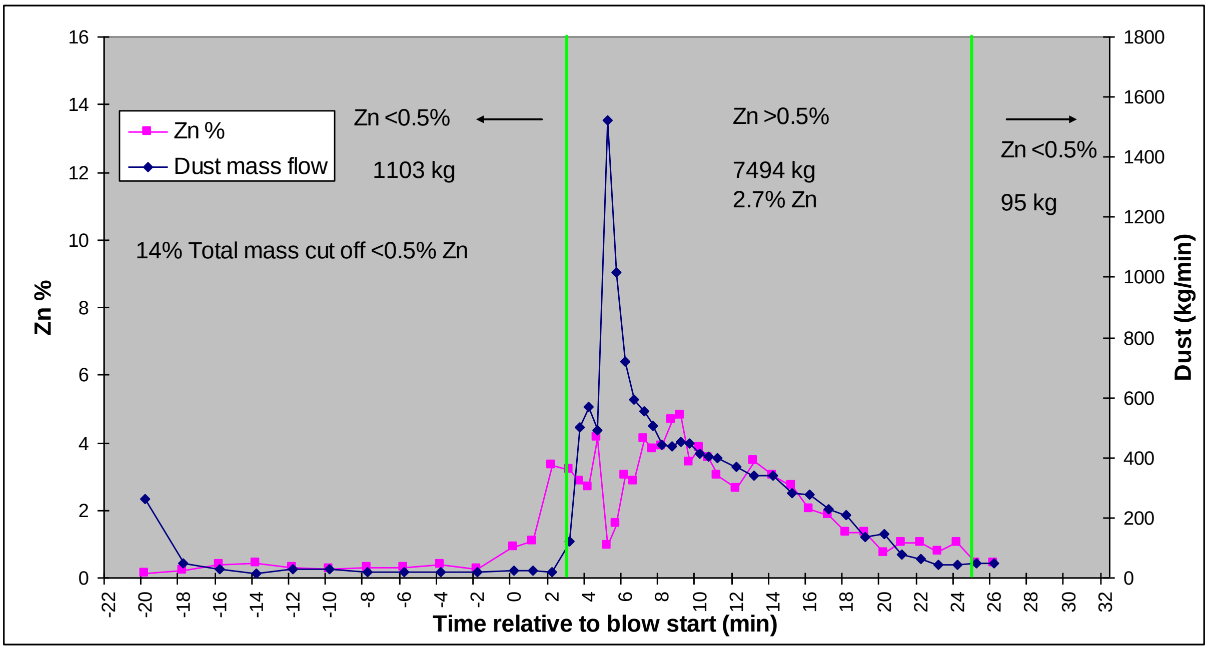


Figure 45: Hold trial 20643 dust mass cut off with average zinc content <0.5%

The potentially recoverable quantity of dust is compared for a variety of zinc concentrations in Figure 46. Hold heat 20641 stands out with the highest potential quantity of recoverable dust even though the peak zinc concentration was lower for hold heat 20643, because the zinc was liberated over a longer period of time. At ≤1.0% zinc level the control heats have a quantity of recoverable dust approaching the 20643 hold heat but falling far short of the hold heat 20641.

Figure 29 shows hold heat 20641 had a high rate of dust liberated in the post tapping period. If the mass of 1121kg for this period is subtracted from the total mass of 10082kg collected over the entire sampling period then the % recoverable dust is still much higher. At <0.5% and <1.0% dust zinc content, the % recoverable dust was 38% and 57% respectively compared to 45% and 62% respectively when the total mass includes dust collected during the post tapping period.

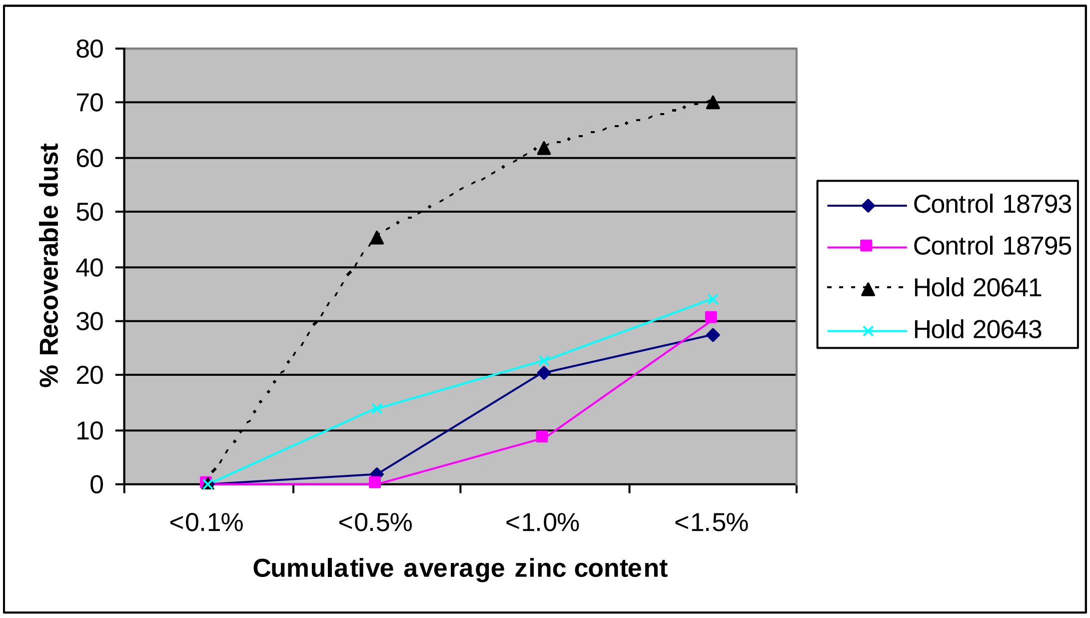


Figure 46: Potentially recoverable dust calculated from the rolling zinc average

5.1.6.2 Concentration cut-off

An alternative way to calculate and potentially separate recyclable dust is based on the measured zinc concentration for each sample and the dust mass for that sample period. The results shown in Table 17 indicate that at the ≤ 0.5% zinc level the control trial 18793 produced 8% dust which could be potentially recovered compared to 0% for the control trial 18795. In comparison more could potentially be recovered from the hold trials, 33% and 12% respectively.

Table 17: Potentially recoverable dust at ≤0.5% zinc concentration

	Potentially recoverable mass of dust (kg)	**Potentially recoverable portion of total dust mass (%)**
Control heat 18793	610	8
Control heat 18795	0	0
Hold heat 20641	3279	33
Hold heat 20643	1074	12

The results shown in Table 18 indicate that at the ≤ 1.0% zinc level the control trial 18793 produced 15% dust which could be potentially recovered compared to 5% for the control trial 18795. In comparison more could potentially be recovered from the hold trials, 39% and 17% respectively.

Table 18: Potentially recoverable dust at ≤1.0% zinc concentration

	Potentially recoverable mass of dust (kg)	**Potentially recoverable portion of total dust mass (%)**
Control heat 18793	1115	15
Control heat 18795	336	5
Hold heat 20641	3964	39
Hold heat 20643	1472	17

5.1.7 Dust Mass Flows

5.1.7.1 Introduction

The mass flow of dusts plus the zinc mass input and output, shown in Figure 47 to Figure 50, have been drawn to provide a visual picture of each trial heat. Each process stage is linked with blue or red arrows which represent the dust that has a zinc content <1% or >1% respectively. The arrow thicknesses represent the mass flow of dust for quantities <2t, 2-20t and >20t levels.

Because the zinc content of incoming scrap varies and is difficult to measure, an indicative zinc input range has been calculated. For 20t of the merchant bales scrap used in each trial heat, the bottom of the range of 316kg was calculated from an average zinc coating weight of 75g/m^2 per side for galvanised sheet metal. The top of the range of 594kg was taken from a previous BOS dust trial at Port Talbot.

The zinc mass output as BOS dust from the primary dust extraction system was measured for each trial and has been separated into two outputs, slurry and grit. The slurry and grit proportions have been calculated using the ratio 85:15 obtained from Tata annual dust figures of 55,000t of slurry and 10,000t grit.

The secondary dust zinc mass output was obtained using measured zinc concentrations for the trials, and the average dust mass per heat, from the DBI contractor tipping notes between December 2008 to March 2009. The average monthly mass tipped was 216.5 tonnes for this period and if a nominal 1000 heats were produced per month this would calculate to be 0.22 t/heat. It was not possible to get exact dust masses from DBI for the control and hold trials discussed in this report, but for comparison a previous trial mass (hold trial II 28/08/09) produced 0.2t for one heat.

The primary BOS slurry and secondary dusts are transferred to temporary storage where they are briquetted for recovery in the BOS process, or stockpiled depending on the zinc content and briquetting capacity. Typically the BOS grit has lower zinc contents and can be recovered through the Blast furnace route via the sinter plant.

5.1.8 Discussion Hold Trials

The zinc and dust mass flow for control heat 18793 shown in Figure 47 has an indicative zinc input between 316 and 594kg. The primary dust system collected 426kg and the secondary system collected 20kg during the heat. The total zinc mass output of 446kg falls into the zinc input range and indicates the dust collection system captured the expected zinc mass.

In comparison, Figure 48 shows control heat 18795 incorporated 177kg of additional zinc contained in waste oxide briquettes (WOBs). The primary dust system collected 603kg and the secondary system collected 20kg during the heat. The total zinc mass output of 623kg also falls into the zinc input range indicating the dust collection system captured the expected zinc mass. Observations by production suggest the use of WOBs increases the quantity of dust generated, however, no extra dust was collected, although the zinc contained in them appears to have been captured in the primary dust extraction system.

The mass flow shown in Figure 49 for hold heat 20641 had no WOBs and the same zinc input of 316-594kg as the first control trial. In comparison to the control, there was a marked decrease in the zinc contamination of the dusts. However, the zinc output of 234kg of primary dust and 22kg of secondary dust, falls short of the zinc input range suggesting zinc loss as fugitive emissions.

The mass flow shown Figure 50 for hold heat 20643 also showed a marked decrease in the zinc contamination in the dusts compared to the control trials. However, the zinc output of 206kg of primary dust and 22kg of secondary dust, also falls short of the zinc input range like the hold heat 20641 indicating zinc loss as fugitive emissions.

The scrap hold trials prior to the blow show a very significant reduction in the measured zinc contents compared to the control trial heats. However, the results suggest that the tilting of the converter after charging the scrap does not collect the zinc contaminated dust preferentially in the secondary system.

It should be noted that although it was straightforward to take samples from the secondary waste silo some limitations were encountered due to the trial conditions. The hold trial was carried out when both converters were running which would dilute the measured zinc contents because of additional dust mass from the second converter. The residence time was in the region of 45 minutes making it difficult to correlate changes in zinc contents with changes in the process. It was not possible to arrange an empty waste silo at the beginning and end of the trials to correlate accurately with the start and finish of the trial.

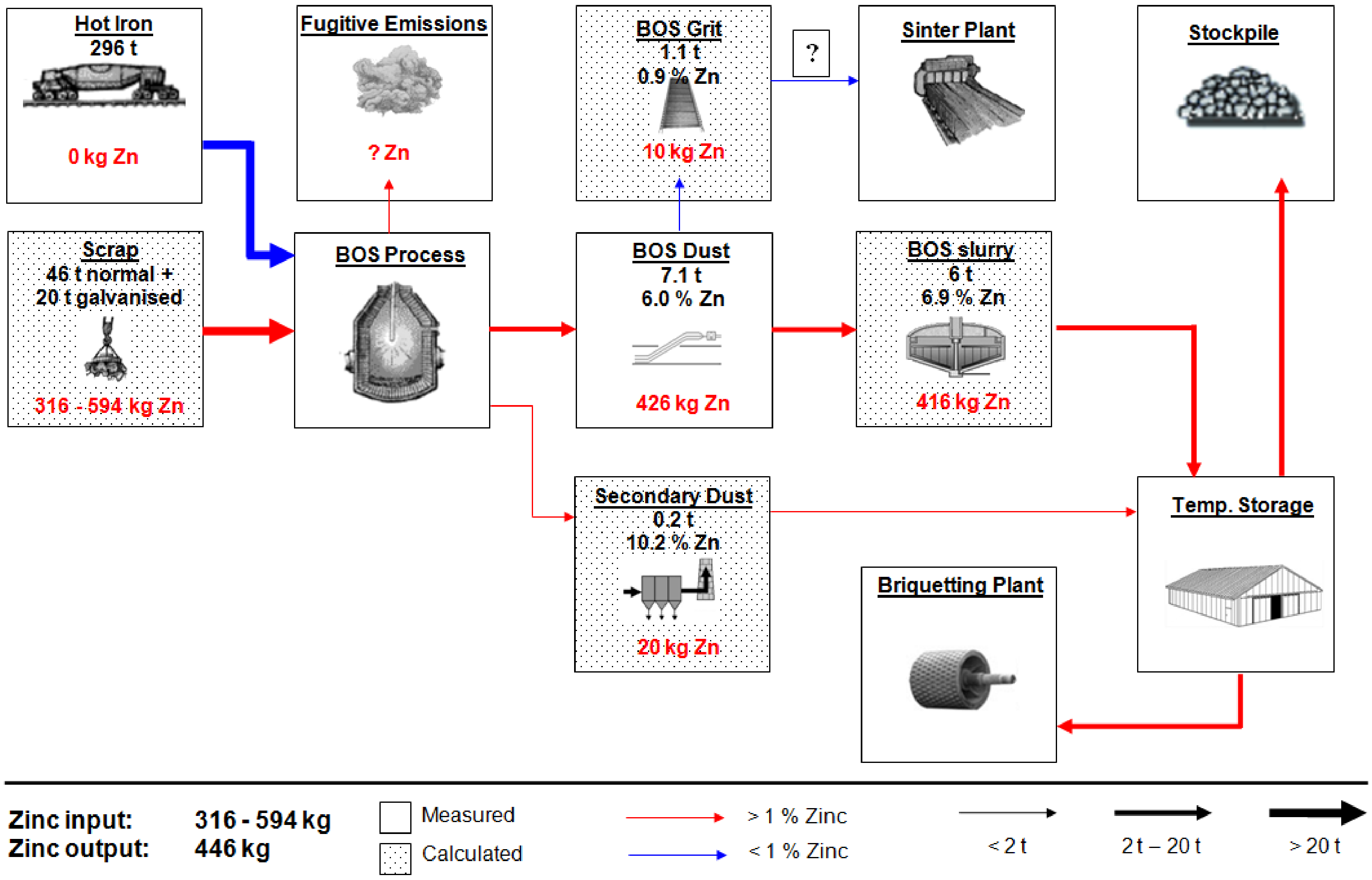


Figure 47: Zinc and dust mass flow – control heat 18793

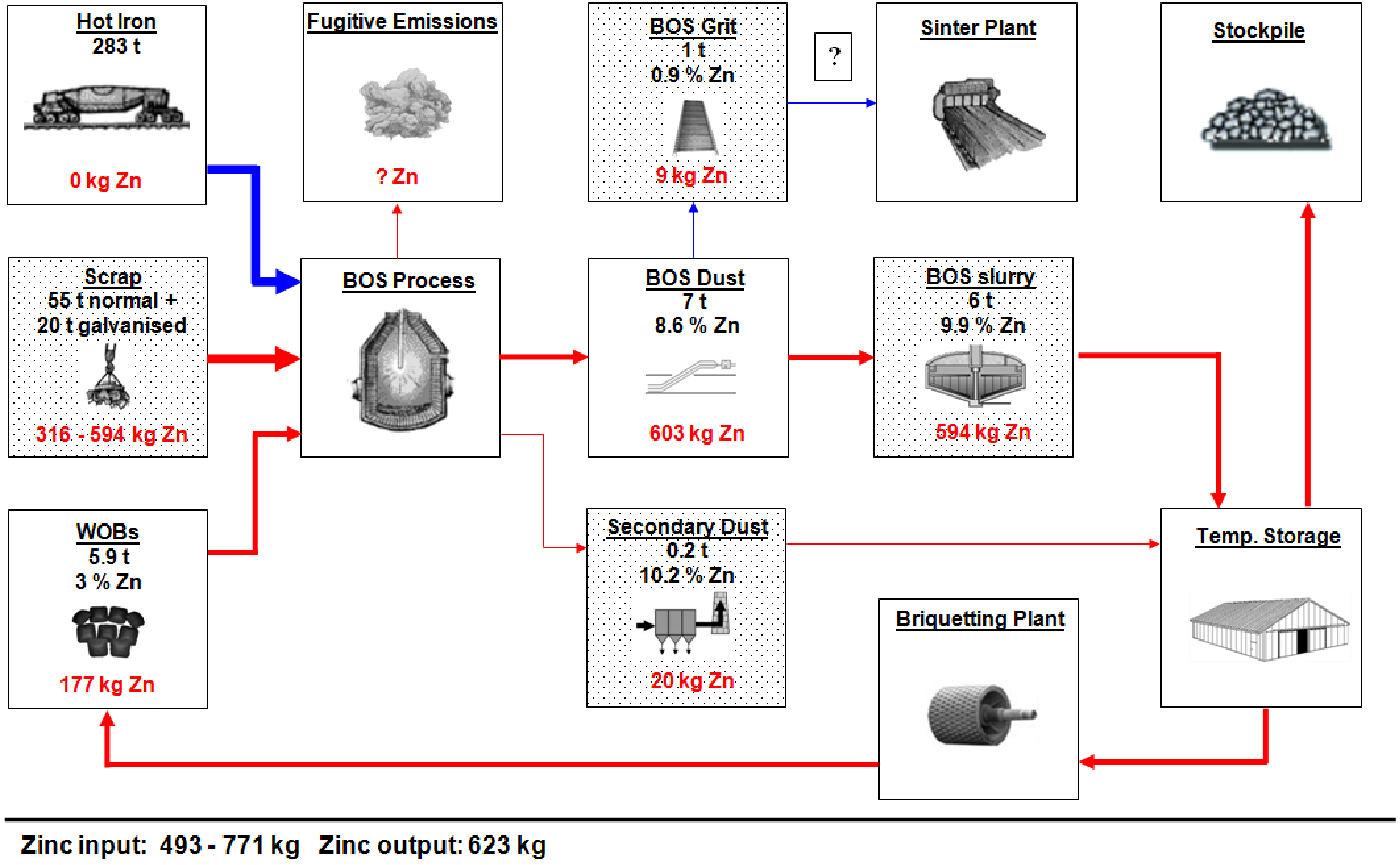


Figure 48: Zinc and dust mass flow – control heat 18795

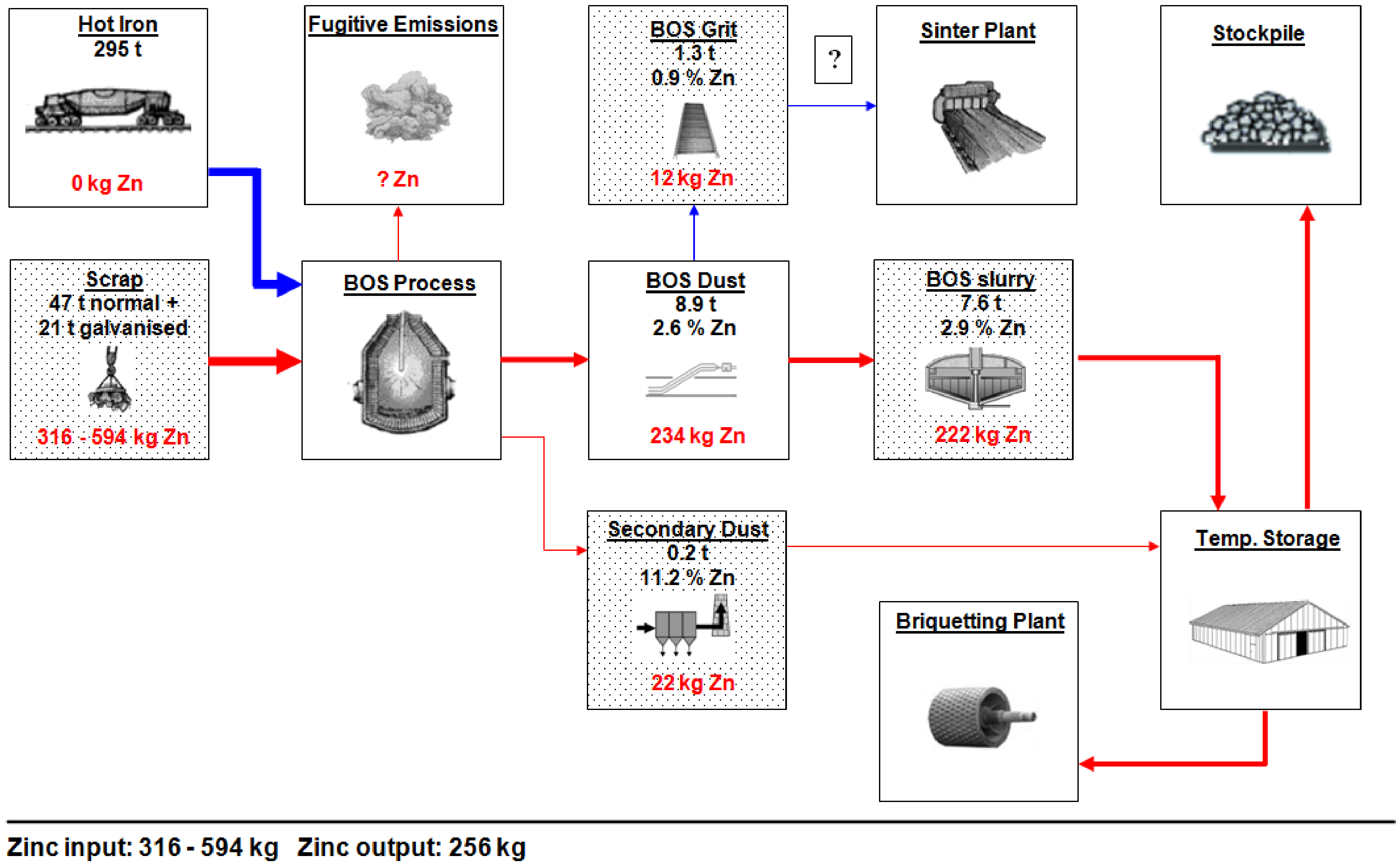


Figure 49: Zinc and dust mass flow – hold heat 20641

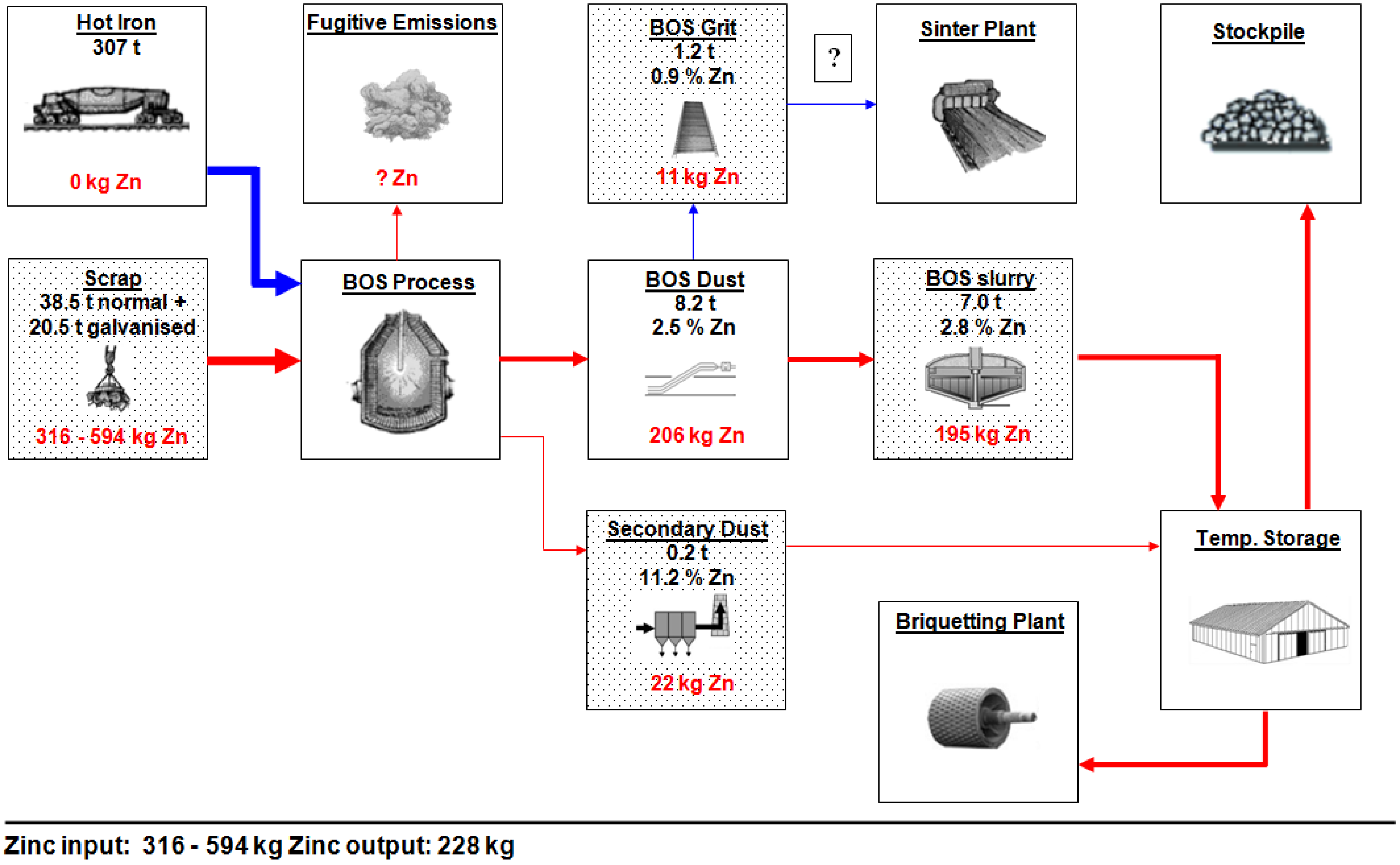


Figure 50: Zinc and dust mass flow – hold heat 20643

5.1.9 Conclusion Hold Trials

The average zinc concentrations for the entire sampling period for each heat were much lower during the hold trials compared to the control trials. The hold trial heats were 2.3% and 2.4% compared to the control trial heats which were 5.8% and 8.6%.

The average zinc concentrations for the blow period for each heat were much lower during the hold trials compared to the control trials. The hold trial heats were 3.4% and 2.8% compared to the control heats which were 7.4 and 9.5%.

The zinc concentrations in the secondary dust extraction system were not readily comparable because the control trial was run during single converter operation and the hold trial on double converter operation. There was little indication that additional zinc volatilised from the scrap hold was collected preferentially in the secondary system.

The two hold trials liberated 6512kg and 7106kg of primary BOS dust during the blow period, compared to the two control trials which produced 5555kg and 5763kg.

A significant quantity of dust mass was collected outside the blow period. For the hold trial heats 1586kg and 3570kg was measured compared to the control trial which produced 1228kg and 1898kg.

For the entire trial sampling periods for each heat, the percentage of dust potentially recoverable with an average zinc concentration of ≤0.5% was much higher at 14 and 45% for the hold trial compared to 0 and 2% for the control trial.

Using the measured quantity of primary BOS dust of the control and hold trials of 6991kg to 10082kg the annual primary dust generation would range from 82787 t to 119391 t (based on 12000heats per year).

The flow rate of the slurry that was measured in the pipes of the primary dust extraction system during the trials varied between 16681 l/min to 19501 l/min.

For each sample taken during the blow period of the control trial 18793, 90% of the particles in each sample had a measured mean particle size diameter less than 36 micron. This compares to samples from the pre blow period where 90% of the dust particles were less than 567 micron and samples from the post blow period where particles measured less than 279 micron.

The measured output of zinc during the sampling period of the hold trial heats was 256 and 228 kg. This compared to a zinc input range of 316 – 594kg which was calculated from typical coating thicknesses, however the zinc content of the scrap is likely to vary.

5.2 Zero WOB trials

5.2.1 Aims

The aim of this trial was to determine the minimum level of zinc achievable in BOS dust by using zinc free (non galvanised) scrap without WOBs for at least 5 consecutive heats in the same vessel. Potentially this could maximise dust that could be recycled through the Sinter Plant and potentially reduce the WOB briquetting cost.

5.2.2 Objectives

The objective of the trial was to take samples from the primary dust collection system at regular intervals. The mass and composition of dust produced during each trial heat was measured to verify the quantities and composition of dust compared to previous trials.

5.2.3 Methodology

5.2.3.1 Trial protocol and conditions

The trial was designed to cause a minimum of disruption to the operation of the BOS plant and essentially it consisted of normal BOS process operation conditions. To achieve the objectives the following set of additional requirements were requested for each trial heat.

- Using a zinc free scrap charge for each heat.
- No waste oxide briquettes (WOBs) to be added.
- The control trial to consist of not less than 5 heats to obtain representative samples of the trial conditions not previous heats, see trial sample in Table 19.

Table 19: BOS trial plan

Heat number	**Process action**
1	Vessel purge
2	Sampling
3	Sampling
4	Sampling
5	Contingency

5.2.3.2 Sampling plan

Two separate sample points were used for the trial to take physical samples from the primary dust collection system for analysis in the laboratory, and to take flow velocity and slurry depth measurements. The two sampling points were as follows:

1. BOS dust slurry launder pipe
2. BOS degritter

Three Centre of Excellence staff were required to take samples from the primary dust collection system at the different sample points, and one member of staff was required in the control room pulpit to note process observations.

1. BOS dust slurry pipe

The samples were taken in the same way described previously.

2. BOS degritter

A composite sample of the BOS grit was taken from underneath the BOS degritter. This area was cleared initially with an excavator which returned to collect the grit at the end of the trial. The excavator had a load cell on its shovel which recorded the mass of grit and samples were taken from the grit pile manually. The grit was collected over a period of 4.5 heats.

5.2.4 Results and discussion zero zinc trial

5.2.4.1 Introduction

Three out of five trial heats were sampled from converter number two after a reline maintenance period. The following samples were collected for analysis:

- 92 x 10litre samples from the BOS slurry pipe
- 1 composite sample of BOS grit collected over 4.5 of the trial heats

The BOS dust slurry flow velocity and depth was also measured in the pipe for each of the trial heats to determine the mass flow rate of the dust and its components.

5.2.4.2 Process additions

Each trial heat was made up of additions of hot metal, scrap and fluxes in varying proportions depending on the hot metal composition, temperature and grade of steel being made. As shown in Table 20, the trial heats did not contain any WOBs as requested in the workplan. Also the amount of galvanised was minimized in the scrap charge. Of particular note in all three trial heats was the addition of iron ore during the blow and post blow periods.

Although each heat has an addition and scrap charge specific to itself the trend for the previous scrap hold trials was for larger scrap charges, this was reflected in the scrap: hot metal ratio which ranged between 19 - 26% compared to the zero WOB trial which ranged between 11 - 18%.

Compared to the previous trials the ore additions were between 11.1 - 12.4t compared with 0 – 7.2t, also between 7.0 - 8.5t of cobble additions were made whereas previous trials had none.

Table 20: Material additions zero zinc trial

Additions	Heat number		
	32502 **(t)**	**32504** **(t)**	**32505** **(t)**
Hot Metal	307.2	301.0	290.3
Dolomet	5.5	3.0	6.0
Doloflux	6.0	3.5	0.0
Lime	10.0	9.9	12.0
Ore	12.4	11.1	11.3
WOBs	0.0	0.0	0.0
Total	**341.1**	**328.5**	**319.6**
4C merchant bales	0.0	0.0	0.0
A steel skull	12.5	13.0	13.0
C steel skull	3.0	2.0	2.0
A desulph skull	0.0	0.0	0.0
Tin & steel cans	0.0	0.0	0.0
O/size demo cobbles	8.0	7.0	8.5
Incinerator scrap	0.0	0.0	1.5
Hot briquetted iron	0.0	0.0	10.0
Non galvanised mill products/slab	5.5	9.5	12.0
Galvanised portion of mill products	5.0	6.0	5.0
Scrap total	**34.0**	**37.5**	**52.0**
Total mass	**375.1**	**366**	**371.6**
Scrap: hot metal (%)	11.1	11.4	17.9

5.2.5 Trial process notes

As seen with the scrap hold trial, two sets of process information have been used to correlate with the sample results. Firstly, observations were taken by a member of Cardiff University staff in the pulpit control room while secondly information was taken from the Tata computer generated shift log. The results shown in Table 21, Table 22 and Table 23, are the observations taken from the pulpit and are the timings used for reference for the results, figures and discussion.

Table 21: Comparison of process timings for heat 32502 (4/11/10)

Time	Cardiff pulpit observations	Tata shift log
11:52	Scrap addition	
12:07	Hot metal addition	
12:08	Hot metal addition complete	
12:09	Tilting vessel to vertical	
12:11		Blow start
12:12	Blow start	
12:13		Flux addition
12:15		Ore addition (4.5t)
12:17	Skirt lowered	
12:29		Ore addition (5.8t)
12:30	Blow finished	
12:32		Ore addition (2.1t)
12:35	Start tap	
12:36	Large fall of material from OG duct	
12:37		Start tap
12:43	No finish tap time recorded	Finish tap

Table 22: Comparison of process timings for heat 32504 (4/11/10)

Time	**Cardiff pulpit observations**	**Tata shift log**
12:50	Scrap addition	
13:02	Hot metal addition	
13:04	Hot metal addition complete	
13:07	Blow start	Blow start
13:10		Ore addition
13:23	Blow finish	
13:24		Ore addition
13:25		Blow finish
13:26		Ore addition
13:37	Start tap	
13:39		Start tap
13:46		Finish tap
13:45	Finish tap	

Table 23: Comparison of process timings for heat 32505 (4/11/10)

Time	**Cardiff pulpit observations**	**Tata shift log**
13:49	Scrap addition	
13:51	Hot metal addition	
13:54	Hot metal addition complete	
13:57	Blow started and stopped shortly afterwards due to oxygen sensor in BOS gas recovery system	
13:59		Flux addition
14:04	Blow restart	
14:06		Blow restart
14:08		
14:21	Blow finish	Ore addition (4.3t)
14:22		Blow finish
14:23		Ore addition (2.3t)
14:27	Start tap	
14:28		Start tap
14:39	Finish tap	
14:35		Finish tap

5.2.6 BOS dust slurry flow rates

The BOS dust slurry flow rate was again measured using a Flo-dar™ combined ultrasonic and laser doppler instrument every minute. Each figure recorded by the instrument was obtained from up to 200 counts averaged per minute and shown in Appendix Tables A27 – 29.. Figure 51, Figure 52 and Figure 53 all show the flow rate profiles for the entire sample period of each trial heat. All three show a variation in the flow rate during the heats but little can be correlated with the process operations at any time.

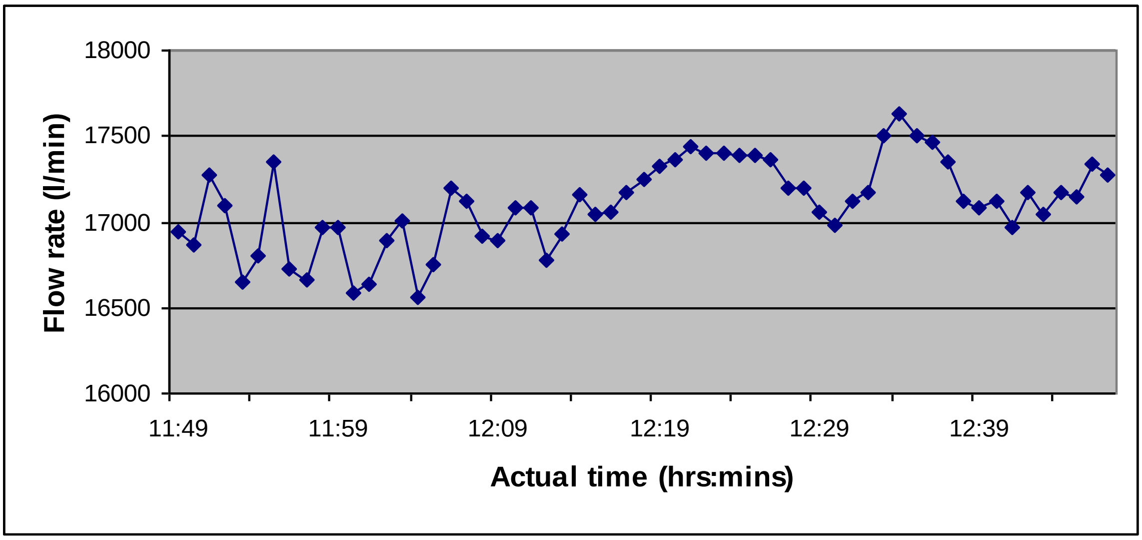


Figure 51: BOS dust slurry flow rates for heat 32502

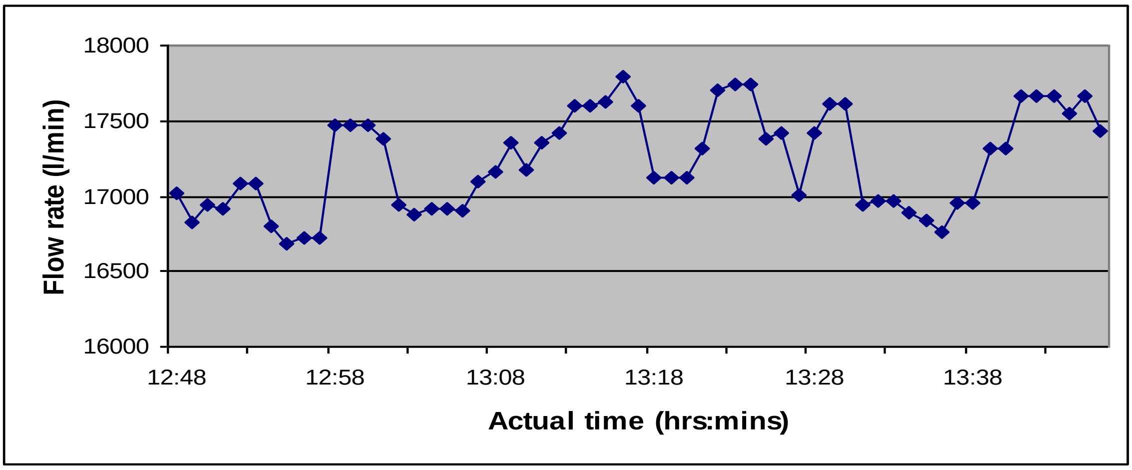


Figure 52: BOS dust slurry flow rates for heat 32504

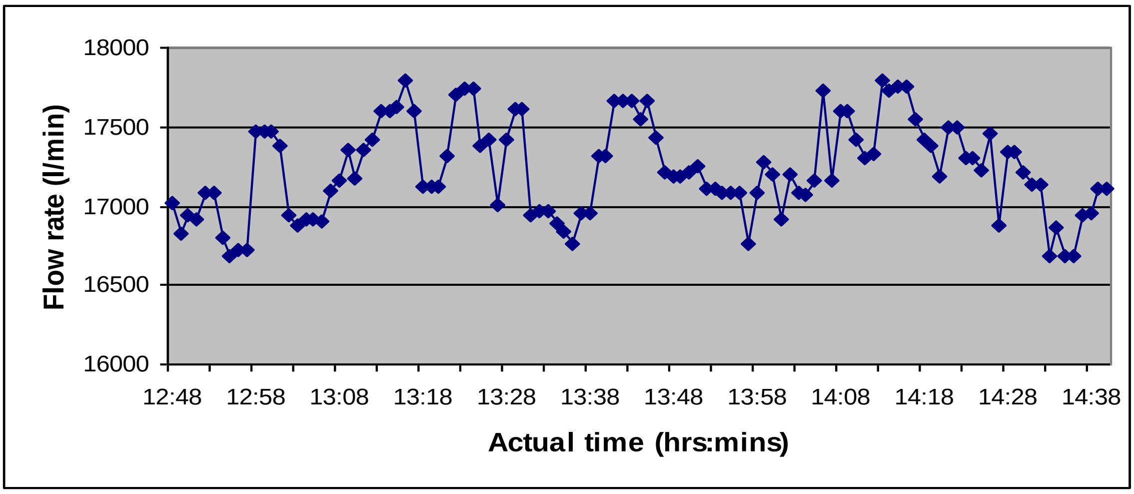


Figure 53: BOS dust slurry flow rates for heat 32505

During the previous trials the flow rate range measured between 1,697 to 2,394L/min, whereas the flow rate range for the zero WOB trials was between 1,064 to 1,104L/min which was more consistent and less varied. Also, the peak maximum flow rate of 17,975L/min for the zero WOB trial was lower than the 19,501L/min measured during the previous trials.

5.2.7 BOS dust mass flows

For each trial heat, 10 litre samples were taken every 2 min outside the blow periods and every 1 min for the first 10min of the blow period. Flow measurements were taken continuously.

For each sample the dust content was measured and has been plotted against the sample time to give a profile of the dust liberated across each heat. The raw sample data is shown in Appendix Tables A30 – A32.

The dust mass flow profiles for the three zero WOB trial heats are shown in Figure 54 and plotted relative to the blow start.

The profiles highlighted in Figure 54 are important to calculate how much dust was produced and to describe when the dust is produced during each heat. They show considerable variation for each heat and between each heat. Most dust was expected during the blow when oxygen is blasted into the converter at high velocities which increases the gas flow and molten metal surface agitation in the converter.

However, the measured profiles show that dust was also liberated outside of these periods, even when accounting for a residence time.

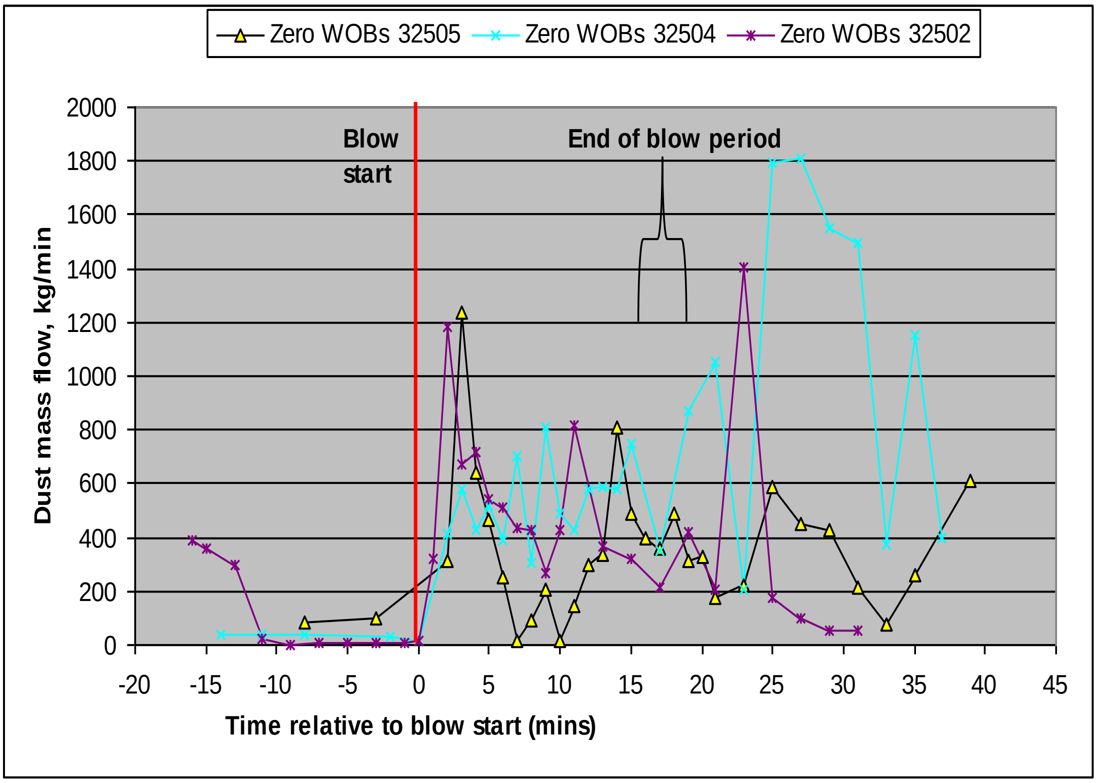


Figure 54: Dust mass flow profile comparison

The data in Table 24 shows very large dust masses collected over the entire sampling period ranging between 14,055kg to 30,613kg and masses during the blow periods ranging between 5,274 to 8,752kg. In previous trials the dust masses collected outside the blow period ranged between 1,228kg to 3,570kg, however, the masses of dust for the zero WOB trial were much greater ranging between 6,790kg to 23,032kg.

A number of additions of ore were made ranging between 10,000kg to 11,000kg to each of the three heats which could contribute to the dust mass produced. However, it seems unlikely that all of the additions could be collected as dust, and even if it had the levels collected were larger than the inputs. It has been suggested by Tata staff that the additional material might be due to filter press cleaning operations taking place in the area or due to dust settlement and carry over from the seal tanks caused by low agitation flow rates.

Table 24: Dust masses collected during trials

Heat number	**32502**	**32504**	**32505**
Scrap to tap process time (minutes)	56	63	49
Dust mass collected during blow period			
Dust mass (kg)	8,752	7,581	5,274
Time (minutes)	18	16	19
Dust mass collected outside blow period			
Dust mass (kg)	6,790	23,032	8,781
Time (minutes)	30	34	28
Dust mass collected over the entire sampling period			
Dust mass (kg)	15,542	30,613	14,055
Time (minutes)	48	51	47

5.2.8 BOS dust compositions

Each sample from the trial heats was dried, milled and analysed by an Inductively Coupled Plasma (ICP) emission spectrophotometer to determine the concentration of metal elements and the results of the analyses are shown in Appendix Tables A33 – A35. The concentrations of the different elements have been plotted against time to give a profile of the variation during the process. Also, by using the measured figures for the slurry flow rate and solids contents for each sample, the masses of zinc, iron and calcium have been calculated for each heat.

The three trial heats each had a low zinc charge of less than 6t of galvanised scrap and no WOBs during each heat and this is reflected in the zinc mass flows. The zinc profiles shown in Figure 55 have promisingly low values which peaked at only 1.1%. This compares to the previous control trial heats which had 20t of zinc containing merchant bales, and which peaked at 14.9%.

The two heats, 32504 and 32505, had peak values of 0.6 and 0.7% after 3 and 7minutes into the blow respectively. Interestingly, heat 32505 had a peak value of 1.1% at the start of the blow at 0mins, this heat also had the longest scrap to blow hold time of 20minutes, when zinc could potentially be volatilised from the converter.

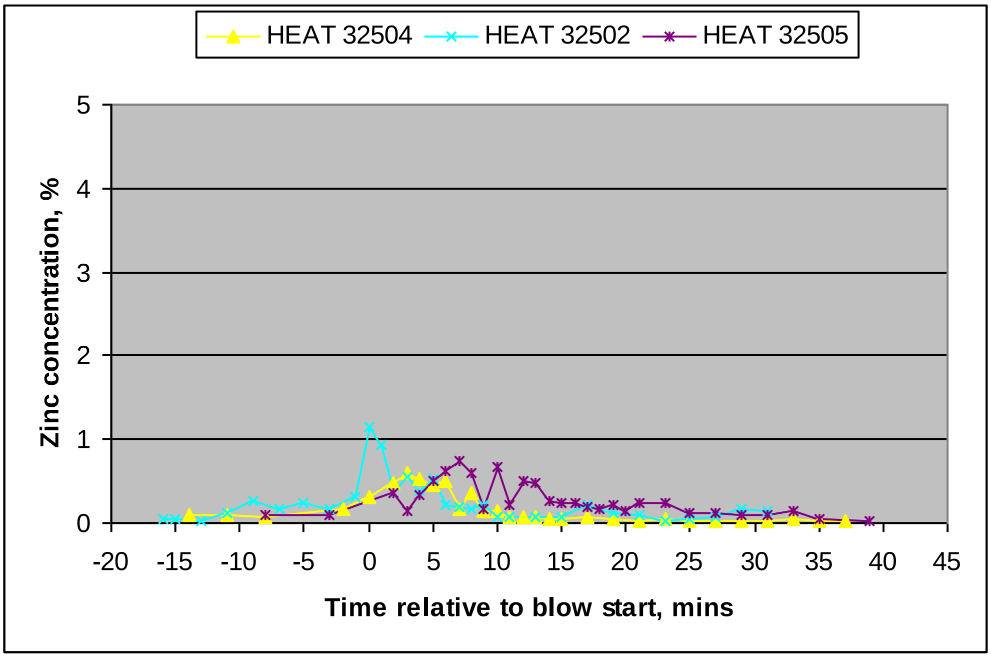


Figure 55: Zinc concentration profile for trial heats

Figure 56 shows the variation of iron concentrations measured during the heats which was above 60% for the majority of the heats, except for the sharp dip in the first 5 minutes after the blow start corresponding to the flux additions. Of particular interest are the particularly high levels of iron peaking at a massive high of 99% after the blow period. Iron levels this high are a valuable resource suitable for recovery. Heat 32505 shows a number of dips in the iron level during the blow and post blow which also correlate with increases in calcium concentration.

The calcium profiles shown in Figure 57 show peak values of 27% corresponding to the flux additions at the beginning of the blow after which the observed levels decrease.

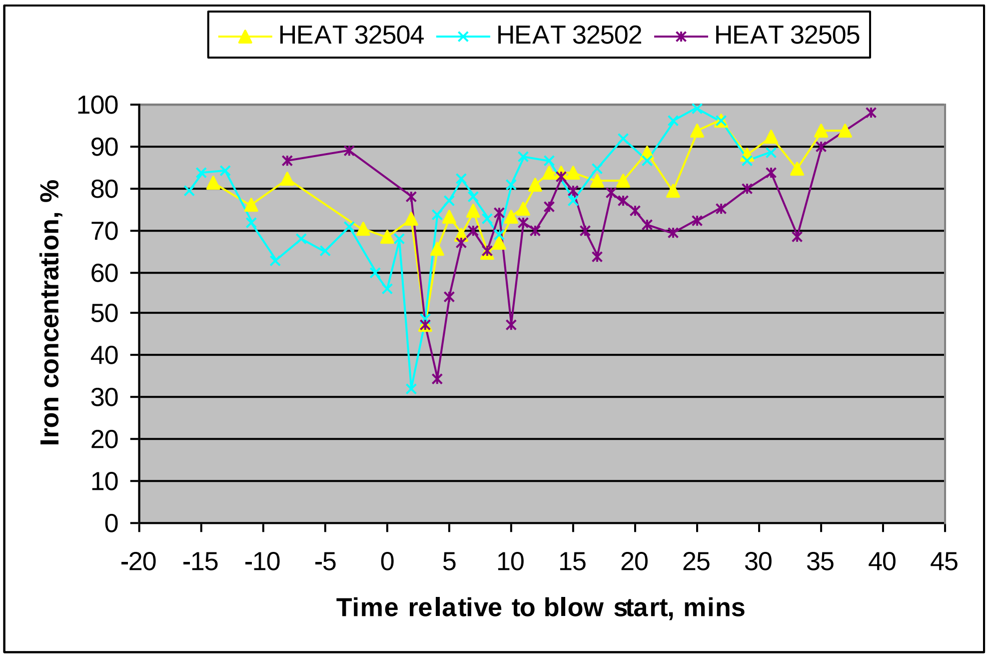


Figure 56: Iron concentration profile for trial heats

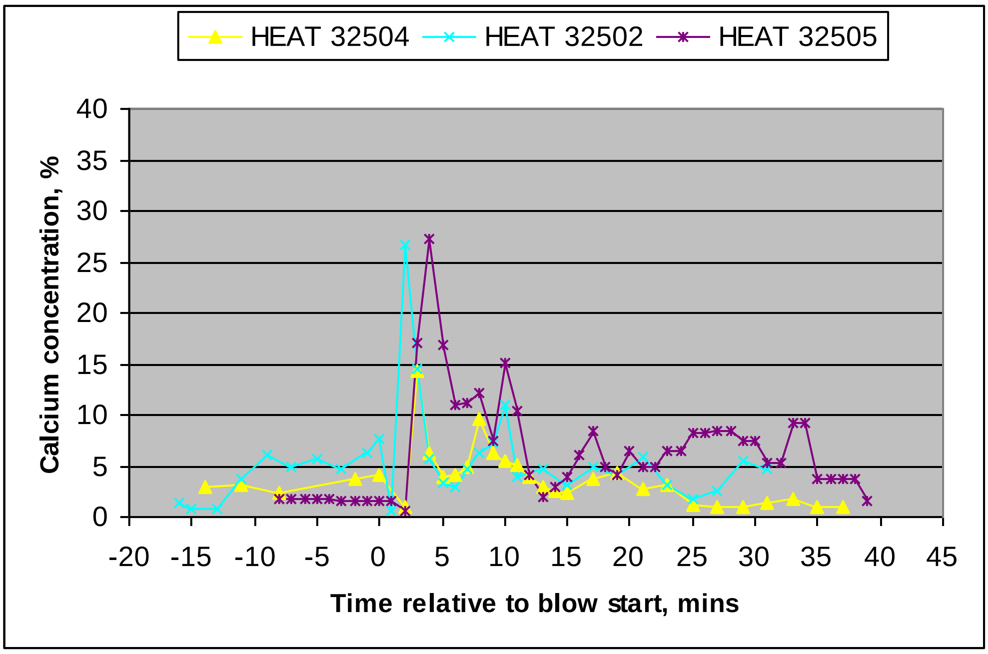


Figure 57: Calcium concentration profile for trial heats

Table 25 shows the dust mass figures for the zero WOB trials and the previous hold trial control and hold heats. The zinc masses collected for the zero WOB heats are promisingly small, especially when compared against the hold trial heat 20643 which itself had much reduced levels of zinc following a scrap holding period. However, in contrast to the zero WOB trials, the hold trials included 20t of galvanised merchant bales scrap. The results show that, under the right conditions, with a low galvanised scrap charge, it is possible to produce a low zinc content dust which can be recovered through the Sinter Plant and Blast Furnace.

In addition to the importance of the low zinc levels, the high iron levels are also very significant with some very large dust masses compared to the previous trials. In particular, the 32504 heat produced 26,312kg of iron which is almost five times the amount collected during hold trial 20643. This represents a large loss of potential revenue and a significant disposal liability if the material is not recycled.

The dust masses collected for each of the main process periods has been plotted in Figure 58. The inter heat periods were very short on the trial day and very few samples were collected during the ‘prior to scrap’ period or the ‘post tapping’ period. It should be noted that the blow was interrupted during heat 32505, due to oxygen in the BOS gas recovery system, but there was no such interruption for the other heats during this period.

There was variation in the exact masses collected for different heats, which is expected for such a large manufacturing process, but the main periods of dust collection observed were the ‘blow start to blow end’ period and the ‘blow end to tap end'. The large mass of dust produced during the blow period was expected but the large dust masses produced in the post blow period were not expected, especially heat 32504 which produced 22,523 kg in that period alone.

Table 25: Dust mass compositions compared to previous hold trial heats

	Zero WOB trial 32502	Zero WOB trial 32504	Zero WOB trial 32505	Hold trial Control 18795	Hold trial Hold 20643
Dust mass (kg)	15,546	30,613	14,055	6,991	8,692
Zinc mass (kg)	27	25	28	603	206
Zinc %	0.2	0.1	0.2	8.6	2.4
Iron mass (kg)	12,405	26,312	10,263	3,756	5,406
Iron %	79.8	86.0	73.0	53.7	62.1
Calcium mass (kg)	934	773	1,100	683	529
Calcium %	6.0	2.5	7.8	9.8	6.1

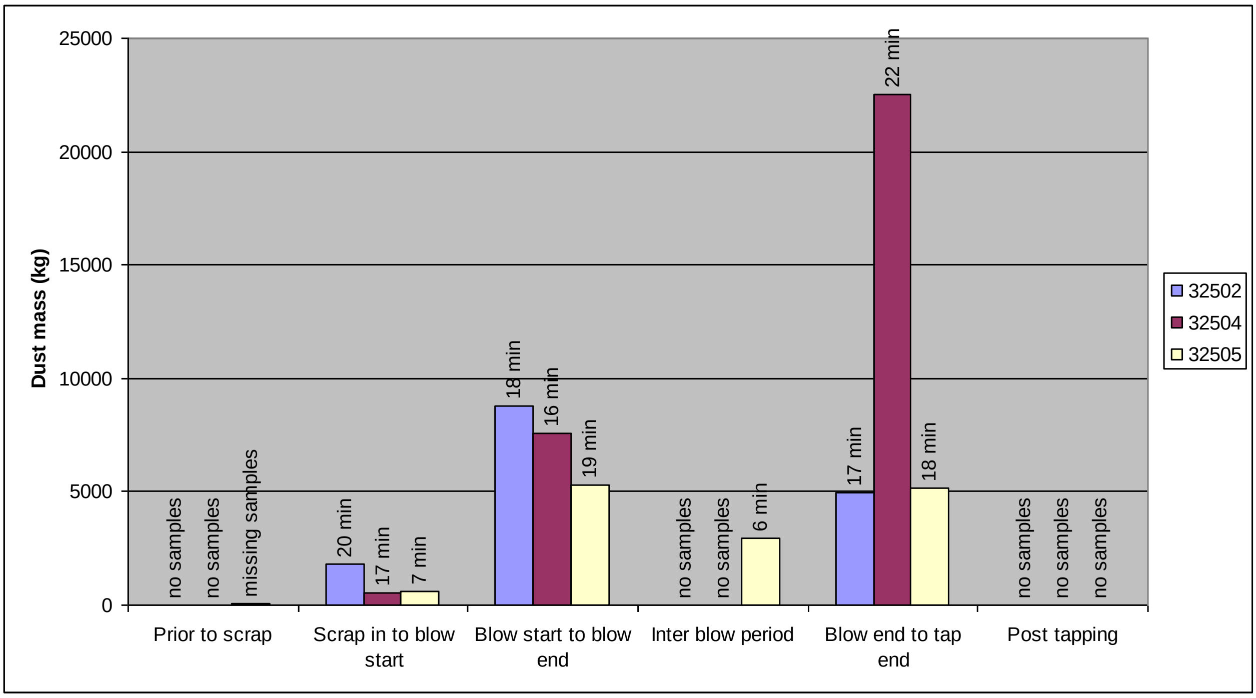


Figure 58: Dust mass generation during the main process periods

In an effort to explain the reason for the large dust masses observed outside the blow period, the dust mass flows have been plotted against the ID fan speed in Figure 59. However, there does not appear to be a correlation between the extra dust and increases in the ID fan speed, in fact the ID fan was at its lowest running speed when some of the largest dust peaks were measured.

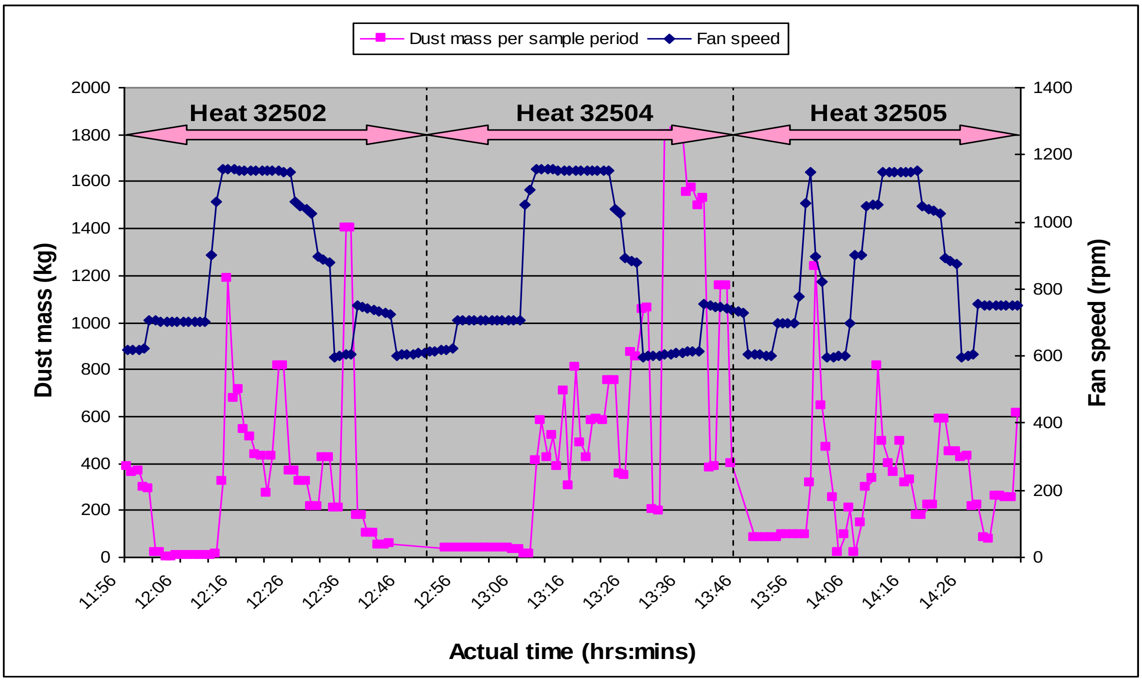


Figure 59: Induced draft fan speed plotted with the dust mass liberated

The lance height and oxygen flow rate could potentially alter the dust mass flow by generating more dust if the lance was close to the molten metal surface or the flow rate was increased during the process. Although the 32505 heat had an interrupted blow period, the plots shown in Figure 60 exhibit no significant differences for both parameters and hence no obvious reason that would explain the post blow dust masses.

Another possibility for the increased dust through the OG system would be nitrogen purging which is initiated when a radar sensor records dust accumulation, positioned on the hood, and exceeds 3%.

In Figure 61, the radar readings on the day of the trial were very low for most of the day corresponding to when the converter was not operational during the reline maintenance period. At the end of the trial heats there was a steep increase up to 2% before a sharp drop off. However, at no point during the trial heats was the radar reading above 0.2% suggesting that the additional dust mass collected outside of the blow periods was not due to accumulated dust breaking off.

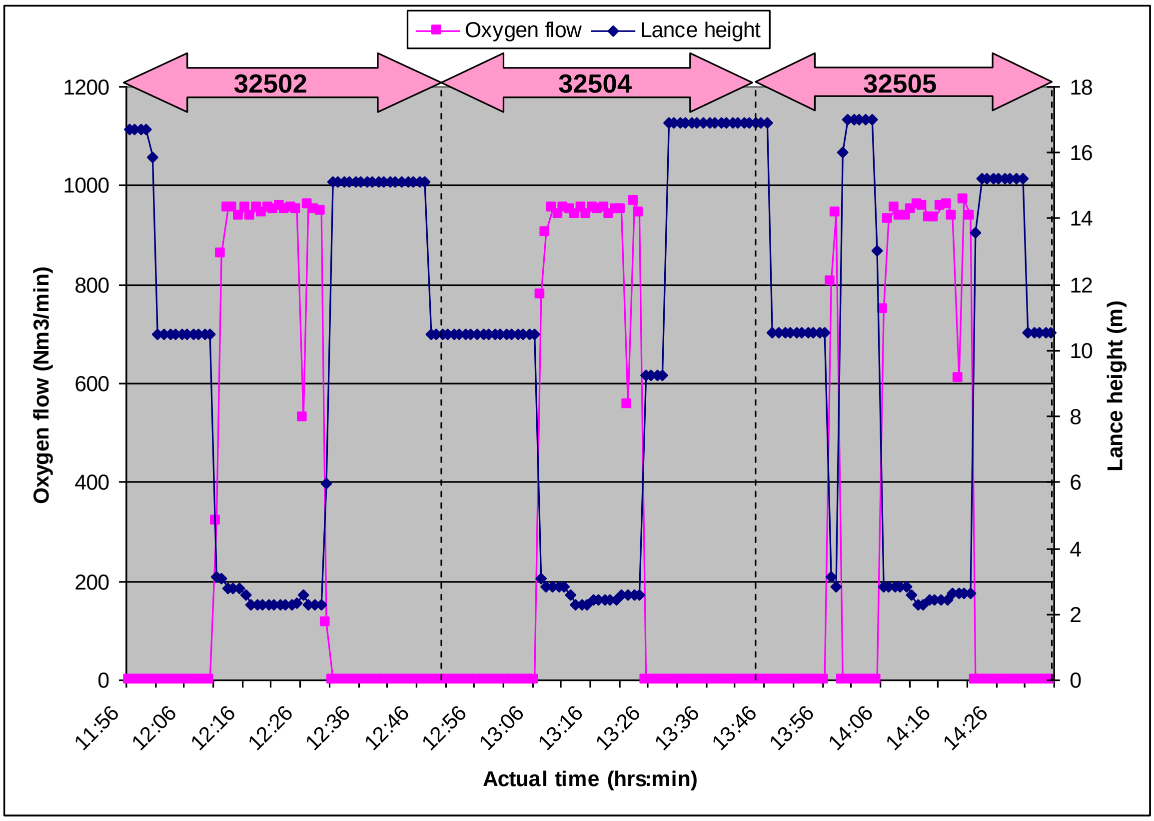


Figure 60: Lance height plotted with oxygen flow

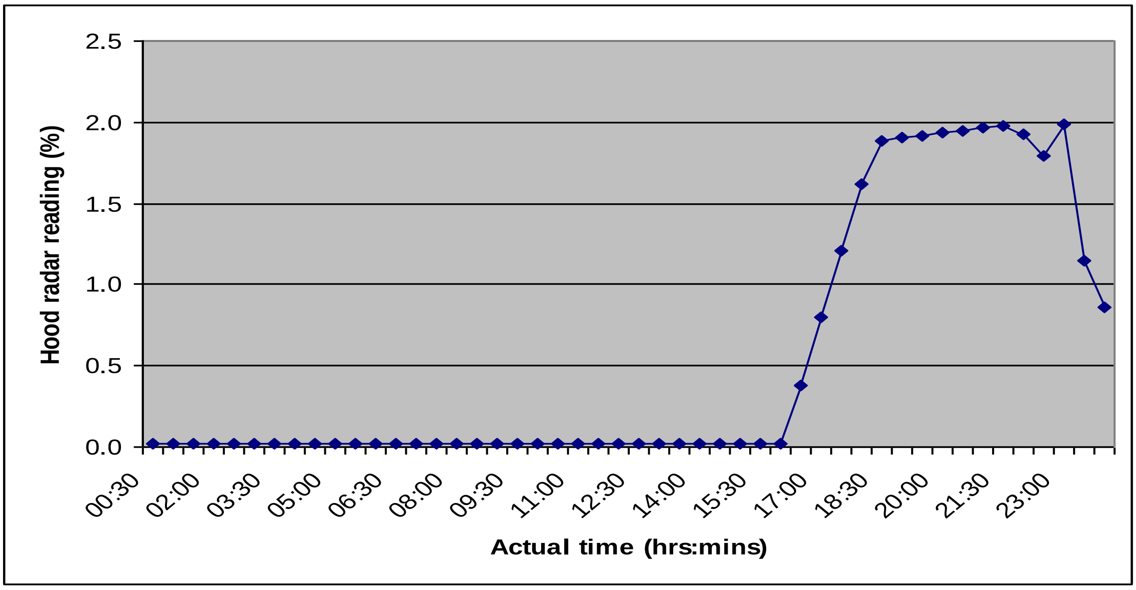


Figure 61: Hood radar readings for the entire trial day

It is possible that during the reline period dust material may have settled in the seal tanks and sumps. For this reason Figure 62 plots the seal tank agitation flow rate during the trial period, which is normally around 600 L/min, alongside the dust mass liberated for that period. For the trial, the agitation flow rate was much lower than usual, but the values obtained from the PI system look uncharacteristically linear. For this reason it cannot be certain that the agitation figures can be relied on.

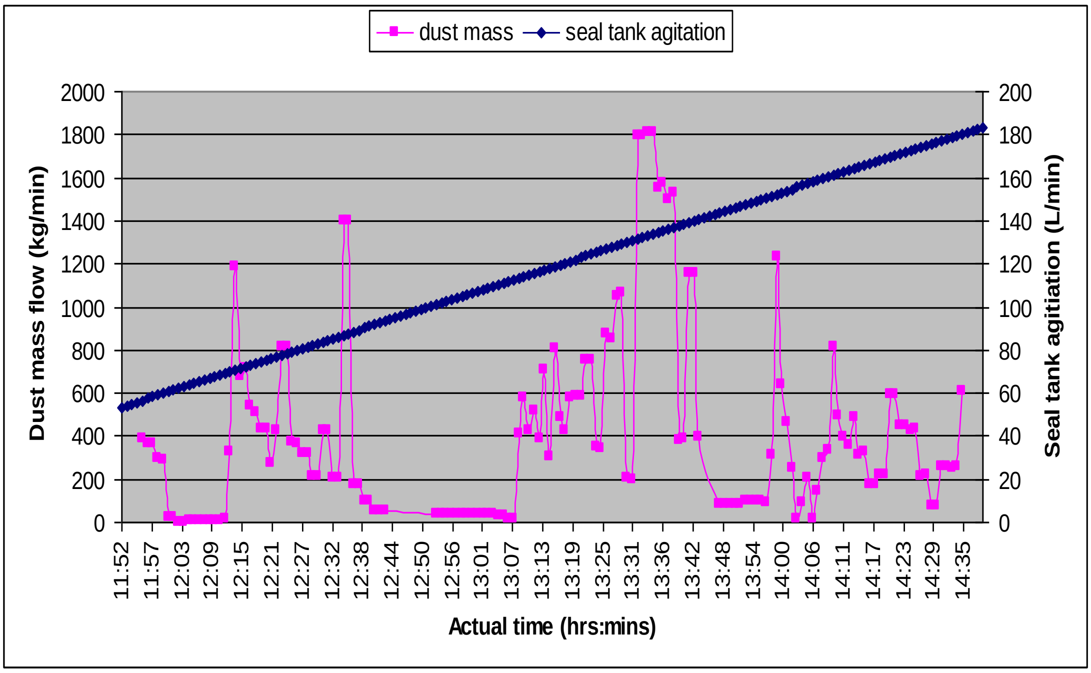


Figure 62: Seal tank agitation compared to dust mass flow

5.2.9 BOS grit

A sample of BOS grit was collected over a number of heats during the trial to determine the efficacy of the BOS degritter. The BOS grit collection area was cleared at 10:30 and a loading machine, equipped with a bucket and load cell, returned at 14:40 to collect, weigh and sample the BOS grit collected for that period.

The 'wet' BOS grit mass collected over the time period of 4.5heats was 7.97t with a moisture content of 11.3% giving 7.07t (oven dried) which calculates as 1.57t per heat. The BOS grit ICP data shown in Table 26 was high in iron content and low in zinc content which is typical of previous analysis of BOS grit. When comparing the three zero WOB trials and the BOS grit sample the compositions are very similar suggesting the dust collected during the trials is BOS grit like material.

Table 26: BOS grit ICP elemental composition

Sample	**Iron (%)**	**Zinc (%)**	**Calcium (%)**
BOS grit	79.5	0.2	5.9
Heat 32502	79.8	0.2	6.0
Heat 32504	86.0	0.1	2.5
Heat 32505	73.0	0.2	7.8

5.2.10 Particle size analysis

A particle size classification, for a composite sample of each heat, was determined by wet sieving. Each sample was obtained by combining the portions of the collected samples in the measured proportions of the total dust. The results in Table 27 show the majority of the dust particles, for each of the three heats, was made up of coarse particles classified in the 106-850μm.

Figure 63 shows the absolute dust mass proportions for the wet sieved particle size range classification. It shows the dust mass averages for the three heats of the zero WOB trial (4/11/10) and the heat averages for the previous hold control trial (13/10/09) and the hold trial (4/12/09). The results for the zero WOB trial show higher dust masses for the coarse and mid range particles, consistent with the total mass observed, but lower quantities of fine particles.

Table 27: Wet sieved particle size classification

	Particle size distribution			
Sample	**<63(µm)**	**63-106 (µm)**	**106-850 (µm)**	**>850 (µm)**
Heat 32502	15.9%	5.4%	75.0%	3.6%
Heat 32504	10.4%	5.7%	83.3%	0.6%
Heat 32505	25.2%	9.2%	64.7%	0.9%
BOS grit	14.5%	13.8%	70.3%	1.4%

Discussions with the Tata Slurry Project Group indicate that potentially if the slurry dust content from the clarifier and filter press system is high, slurry can be returned via the overflow of the clarifier into the water return tank and potentially increasing the dust content measured for each heat. If this was the case it might explain how so much dust was sampled outside blow periods.

If the large dust masses measured were due to additional dust returned into the water system, it would still be expected that similar quantities of the fine dust would be produced as measured during the many previous trials. However, this was not the case and only approximately half the amount of the fine dust (<38µm) was produced.

The theory that additional dust mass could be returned from the clarifiers or filter presses does not explain why less of the fine dust was collected or why the dust was ‘grit like’ in character. It is still not clear from the information provided what caused the large dust masses.

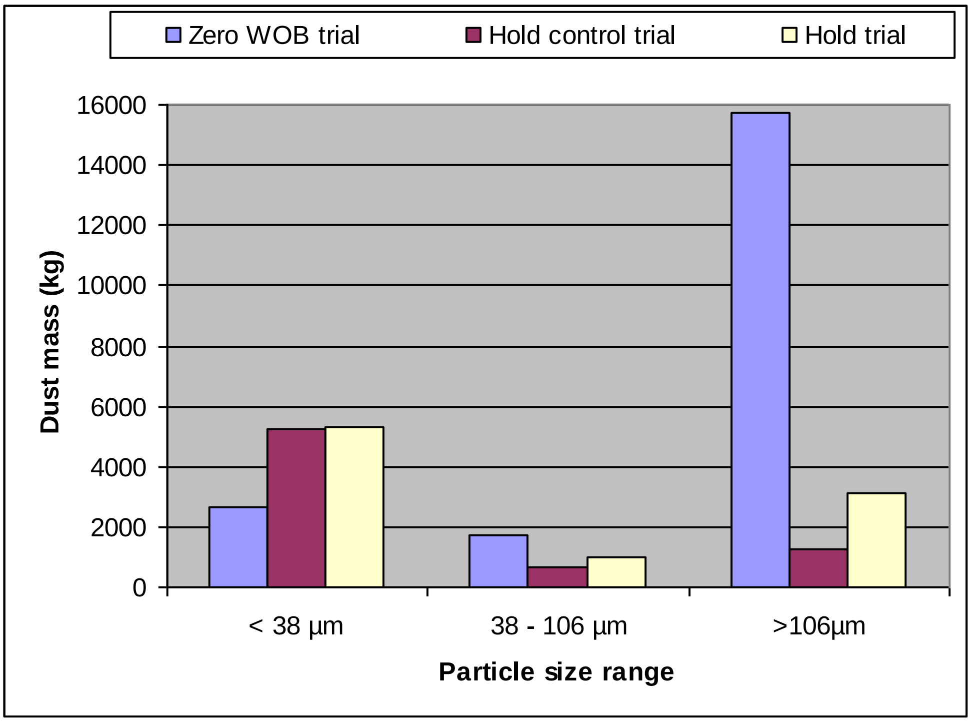


Figure 63: Wet sieved particle size classification for average trial dust masses

5.2.11 Mass verification trials

Because of the large dust masses recorded for the trial heats, and the additional material observed in the clarifiers and filter presses, some further work was requested by the Tata waste group to verify the dust masses observed.

The aim of this work was to determine the total dust mass per heat over a wider period of time to compare its variability and determine if there is still an issue with dust collection outside of the blow period. Two separate trials, consisting of two heats per trial, were conducted on the 20th January and 3rd February 2011.

The dust mass profiles shown in Figure 64 for the two trials were much more consistent with expectations for the process. The main dust mass liberation occurred at the beginning of the blow and tapered off during this period. The large dust masses previously measured outside the blow period, as shown in Figure 54, were absent from these heats.

The total dust mass collected over the trial periods, is shown in Table 28, ranging from 4,654kg to 6,590kg which was much lower than the zero WOB trial which ranged from 14,055kg to 30,613kg. In particular, much less dust was collected outside the blow period which ranged from 568kg to 1,699kg, compared to the zero WOB trials which ranged from 6,790kg to 23,032kg.

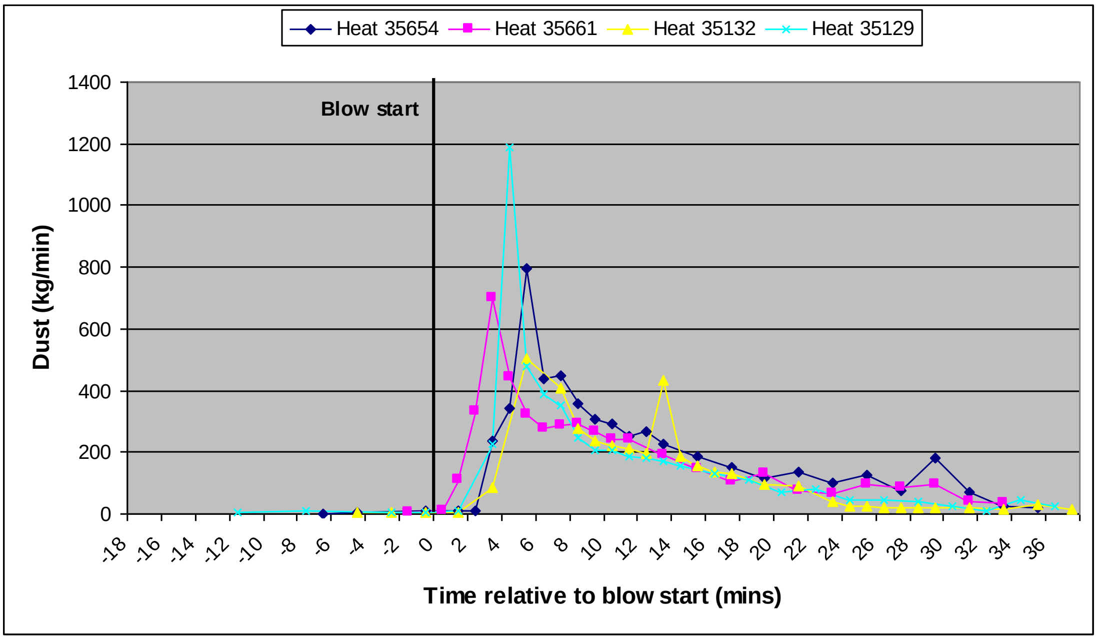


Figure 64: Dust mass profile comparison

It was not clear, from the information supplied, what changes resulted in much lower dust masses for the mass verification trials. Whether this was due to less water leaks on the converter or maybe the smaller iron ore additions (less than 4t compared up to 12t) it was not clear.

Table 28: Dust masses collected during mass verification trials

	Mass trial 1 **(20/1/11)**		**Mass trial 2** **(3/2/11)**	
Heat number	**35129**	**35132**	**35654**	**35661**
Scrap to tap process time (minutes)	44	39	50	54
Dust mass collected over blow period				
Dust mass (kg)	4,536	4,086	4,891	4,451
Time (minutes)	19	19	19	17
Dust mass collected outside blow period				
Dust mass (kg)	955	568	1,699	1,434
Time (minutes)	22	23	23	18
Dust mass collected over entire sampling period				
Dust mass (kg)	5,491	4,654	6,590	5,885
Time (minutes)	41	42	42	35

5.2.12 Conclusion zero WOB and mass verification trials

Zinc contamination in the primary BOS dust slurry was reduced to an extremely low level by eliminating zinc galvanised scrap.

Potentially all of the primary dust collected during the zero WOB trials was recoverable through the Sinter Plant/Blast Furnace. For the entire sample period of each heat the zinc mass collected was consistently below 30kg per heat. This compares to the previous trials where it ranged between 206kg to 603kg.

The dust masses were much larger than expected and ranged between 14,055kg to 30,613kg. It has not been established exactly why such a large mass of material was collected, but it has been suggested by Tata that potentially BOS dust slurry can be returned into the dust extraction water return tank. This might explain how so much dust was sampled outside blow periods. However if this were the case, quantities of fine dust similar to previous trials would still have been expected to be produced and measured, but this was not observed.

Potential process parameters that might have caused the additional dust do not account for the size of the dust masses measured. None of the parameters investigated such as: oxygen flow rate; lance height; process additions; ID fan speed; seal tank agitation; or OG dust accumulation readings, explain the dust masses outside of the blow period adequately.

Iron ore additions between 11t to 12t were added during and after the blow period, and it would be expected that some would have been collected in the dust extraction system. However, the levels of dust outside the blow were up to 23t, double the amount of ore added. Also, the dust samples collected during that period had higher iron contents compared to iron ore, ranging from 70% to 99% compared to 65% for the ore.

The composite samples of the zero WOB heats had a very similar composition to the BOS grit collected with concentrations around 80% of iron, 0.2% zinc and 6% calcium. The wet sieve particle size profile for the dust also looks like BOS grit. The three heats had between 65% to 83% coarse particles in the size range of 106µm to 850µm when compared to the BOS grit sample with 70% in the same range. In comparison, the BOS slurry from the previous trials had only 24.6% in this range.

The mass verification trials, carried out to collect more information on the dust masses, indicate that the BOS process and converter setup during the trials produced dust masses ranging between 4,654kg to 6,590kg. These levels are in line with those previously measured.

5.3 Max WOB trials

5.3.1 Aims

The aim of the trials was to investigate the effect of high levels of WOBs on the zinc levels and the amount of dust generated during each heat.

5.3.2 Objectives

As with the previous trials, the objective was to take samples from the primary dust collection system at regular intervals. The mass and composition of dust produced during each trial heat was measured to verify the quantities and composition of dust compared to previous trials.

5.3.3 Methodology

5.3.3.1 Trial protocol and conditions

The trial was designed to cause a minimum of disruption to the operation of the BOS plant and essentially it consisted of normal BOS process operation conditions. To achieve the objectives the following set of additional requirements were requested for each trial heat.

- Using a zinc free scrap charge for each heat.
- Maximum amount of waste oxide briquettes (WOBs) to be added.

5.3.4 Results and discussion Max WOB trial

5.3.4.1 Introduction

The Max WOBs trial took place in April 2011 which involved sampling three heats, 37437 on 6th April and on the 8th April heats 37509 and 37510.

Since the aim of the trials was to investigate the effect of high levels of WOBs on the dust and zinc levels generated during each heat a high quantity of added WOBs and a minimum of zinc contaminated scrap was the ideal sampling scenario. In that way the zinc added to the converter is solely from the WOBs, and can be clearly identified. But since WOB additions are dependent on the ratio of hot metal to scrap, and the temperature of the incoming hot metal, a high quantity of WOBs could not be guaranteed. It was also not possible to control the levels of galvanised scrap input into each heat because of the scrap availability and steel quality requirements.

5.3.4.2 Process additions

As mentioned there were difficulties controlling the WOB and scrap charge, however some interesting process conditions were sampled. On the first sampling day 6th April 2011 heat 37437 had a very low Mill Products charge (which is typically high in galvanised scrap) so the input of galvanised scrap should also be relatively low providing that the Over Size Cobbles did not contain galvanised scrap returns. On the second sampling day 8th April 2011 we were able to rapidly swap the kit from converter 2 to converter 1 to sample heat 37509 which was a hot metal reblow so the only zinc input would be the WOBs. A reblow typically occurs if the measured carbon content is not as predicted and additional oxygen is required. (Stubbles, 2015) The third heat 37510 was sampled from converter 2 and had a high WOB charge as required. (Table 29)

Table 29: WOB charge and zinc containing scrap Max WOB trial

Heat number	**37437**	**37509**	**37510**
WOB input	10.5t	3.7t	9.9t
Comments	3t mill's prod's (should be low zinc input from scrap)	reblow (no scrap)	32t mill's products

5.3.4.3 Dust masses

The dust mass analyses of all three of the Max WOB trial heats show profiles regarded as more typical of the BOS heats with peaks at the blow start followed by a tapering off at the end of the blow. (Figure 65) Particularly of interest is that there were no dust mass peaks outside of the blow period, this compares to previous high dust mass trials such as the zero WOB trial and the hold control trials, where peaks were measured before and after the blow period.

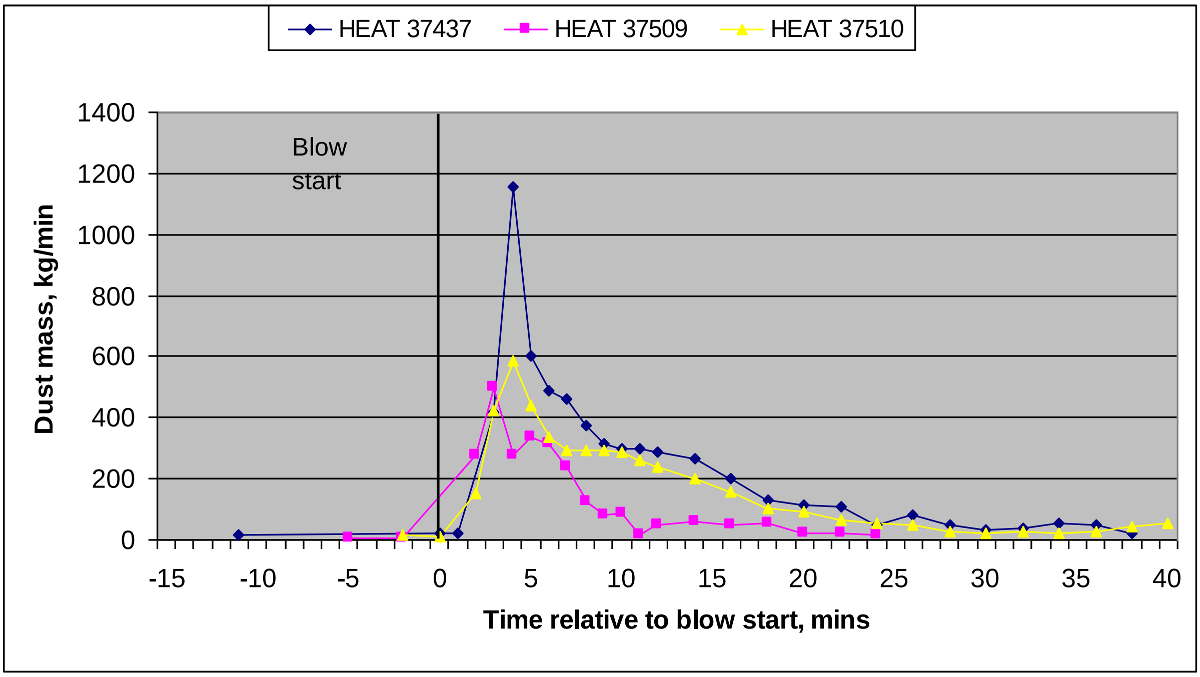


Figure 65: Dust masses Max WOB trial

The data listed in Table 30 shows results more typical of the expected masses with the majority of the dust collected during the blow period. Note that the heat 37509 was a reblow with a short blow time and corresponding lower total dust mass.

Table 30: Dust masses Max WOB trial

	37437	**37509**	**37510**
Dust mass collected over entire sampling period			
Dust mass (kg)	7779	2823	5718
Sample period (mins)	49	29	42
Dust mass collected over blow period			
Dust mass (kg)	6409	2080	4576
Time (mins)	20	9	18

5.3.4.4 Zinc concentrations

The zinc concentrations measured on the samples, and the WOBs used in the trials, were used to calculate the total mass of zinc collected in the dust, and the total mass of zinc input as WOBs. In all three heats the amount of zinc collected in the dust was far greater than the amount of zinc input via the WOBs. (Table 31)

For heats 37437 and 37510 it was expected that the difference between the zinc input and collected would be due to the zinc from the scrap input. However, heat 37509 was a reblow of steel from the caster and had zero scrap input.

Because of this the data was scrutinising and other potential sources of zinc inputs including the hot metal charge were considered. However it was not possible to discover the additional zinc source.

Table 31: Zinc collected vs. Zinc in WOBs

	37437	**37509**	**37510**
Dust mass collected over entire sampling period			
Dust mass (kg)	7779	2823	5718
Zinc mass (kg)	494	270	451
Sample period (min's)	49	29	42
WOB zinc concentration (%)	2.7	2.3	2.3
WOB zinc mass content (kg)	285	87	229

Figure 66 to Figure 68 shows the zinc liberation into the dust during the three heats. Also the timings of the WOB additions are marked. As seen in the previous trials there is an initial zinc peak in the dust caused by the liberation of the zinc contained in the scrap and the first WOB addition. In all three Heats from the Max WOB trial there can also be seen a second smaller zinc peak in the dust caused by the second WOB addition. Taking into account the three minutes residence time of the sampling system, it can be seen that the zinc contained in the WOBs almost immediately volatilises into the dust.

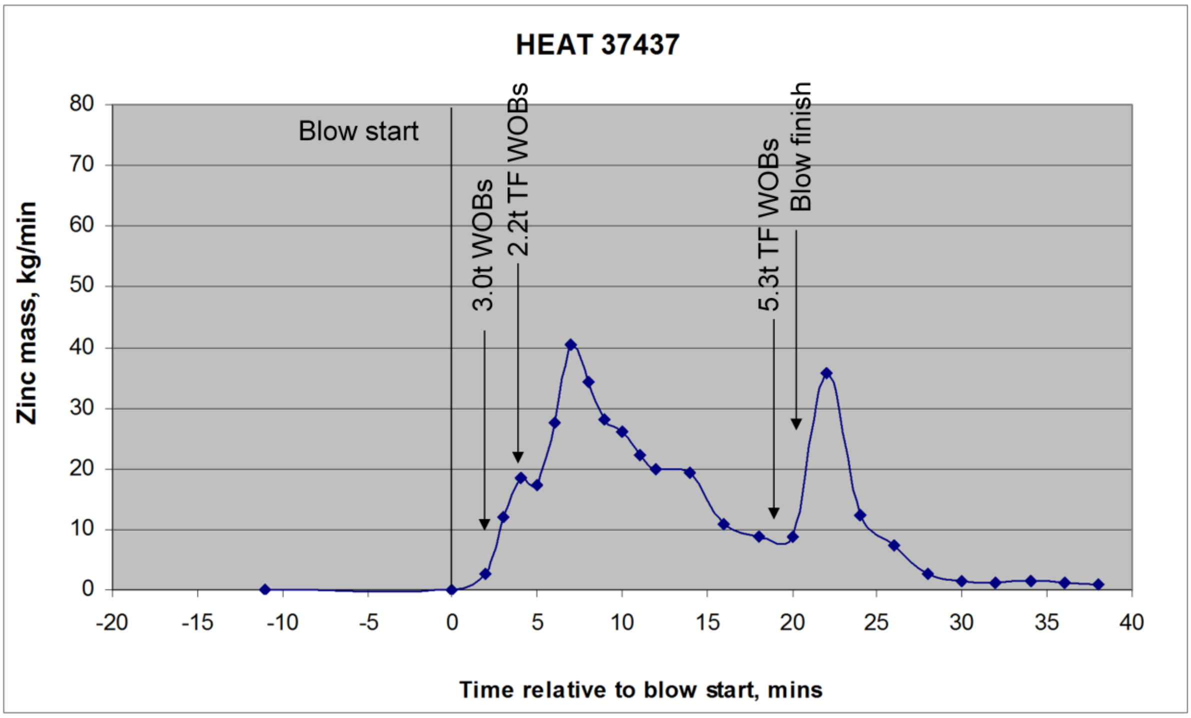


Figure 66: Zinc mass Heat 37437

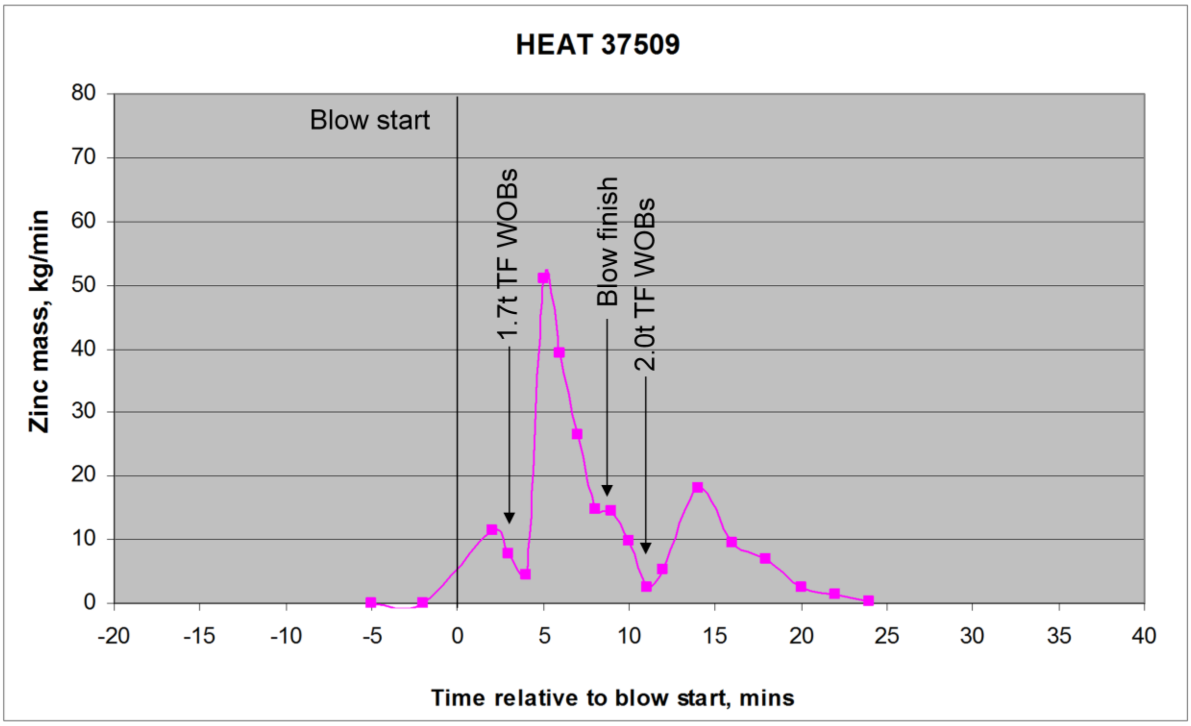


Figure 67: Zinc mass Heat 37509

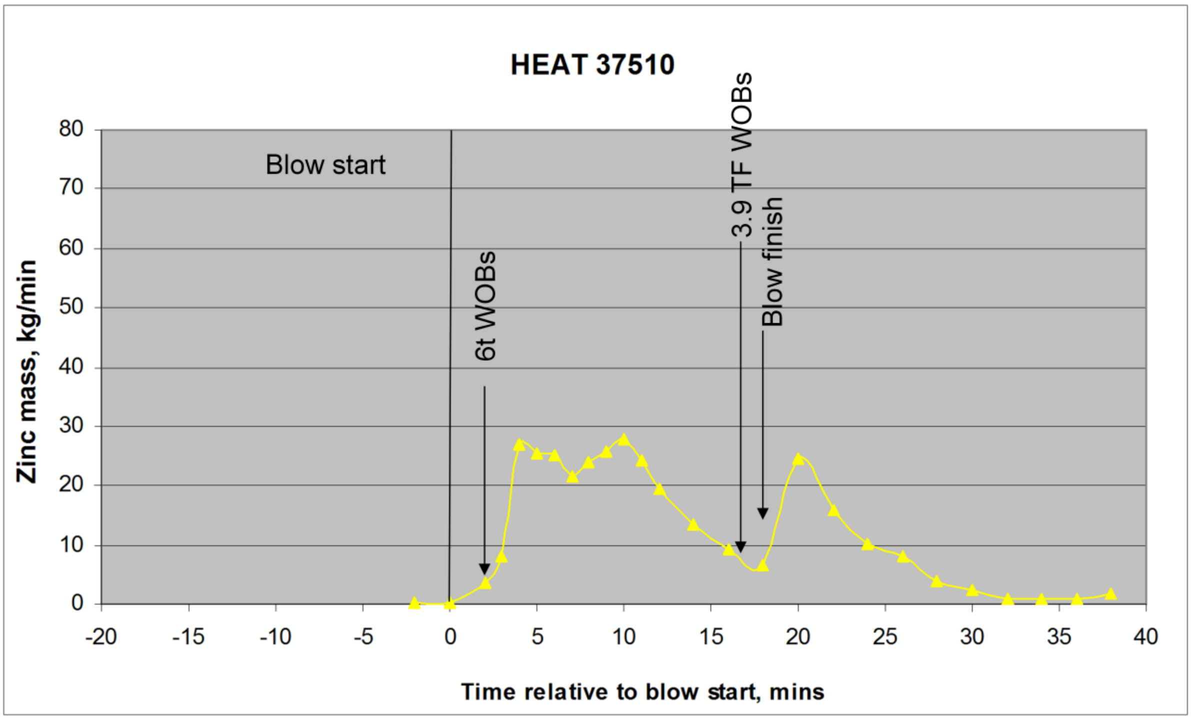


Figure 68: Zinc mass Heat 37510

5.3.4.5 Summary Max WOB trial

A summary of all the trial heats sampled in the project has been plotted in Figure 69.

Based on the trials so far there does not appear to be a relationship between the WOB input and any increased dust levels.

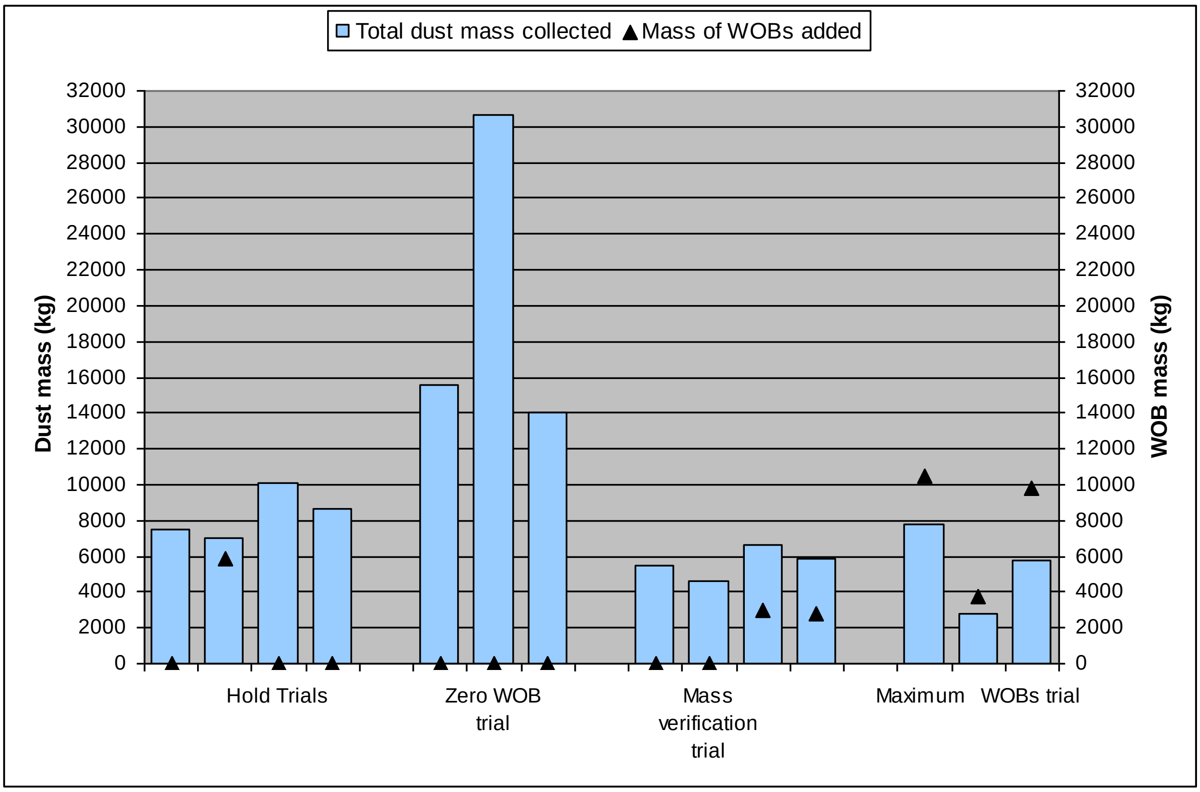


Figure 69: Dust masses collected all trials

Figure 70 shows a plot of the dust masses per blow to allow like for like comparisons of the heats over comparable sample periods. It shows the dust mass collected during the blow period, which is a similar length of time for most heats, between 16 to 20minutes, except for the recycle heat.

The dust masses for all the heats varied from 4086kg to 8752kg over this period. This is a significant mass range and suggests that it is not only the length of time that affects the dust mass produced, but also other process variables.

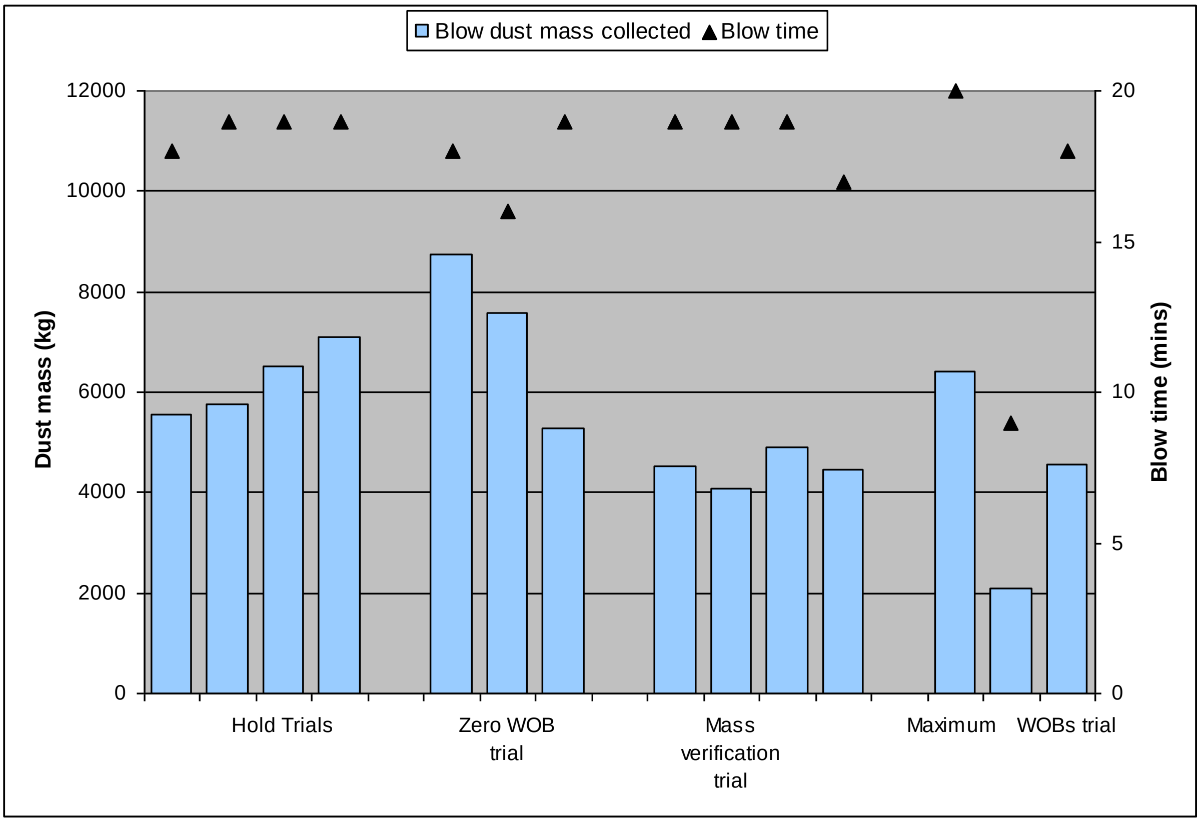


Figure 70: Dust masses collected during blow all trials

There are limitations to comparing dust masses over comparable time scales, because of the irregular way that dust is generated during each heat, and the length of time of each heat. Most dust mass peaks can be correlated to different parts of the process (blow; additions; or tapping etc), however not all heats show the same peak profile during these process periods. For this reason, the absolute figure obtained for the heat period sampled are more indicative of the dust levels that might eventually be stockpiled.

6 Statistical evaluation of BOS trials

6.1 Introduction

After sampling 14 heats it was of particular interest, which of the measured factors affected the dust generation, and how the scrap and the WOB charge affected the zinc levels in the dust.

In order to detect dependencies and correlations between the generated dust and the BOS process, a statistical evaluation of the data obtained from all four BOS trials was conducted. The goal of this task was to analyse what effect various process conditions have on the dust mass and composition and if predictions for the dust can be made if the process conditions are known. For the statistical calculations the PASW Statistics 18 package was used.

The two statistical methods used for this evaluation were the Pearson product-moment correlation coefficient (PPMCC) and regression analysis. PPMCC is a measure for linear dependency between two factors. (Laerd statistics, 2015) The value of PPMCC, called r-value, ranges between +1 which indicates a perfect linear correlation where the increase of the one variable leads to an increase in the other and -1 indicating a perfect linear correlation where the increase of the one variable leads to a decrease in the other. A r-value of zero indicates no linear correlation between the two factors. The hypothesis which needs to be answered is if the r value of two variables equals zero, thus there is no correlation between them. The alternative hypothesis is that the r value is not zero; therefore there is a correlation between the variables.

The p-value is the probability value, it indicates if a result occurred just by chance. If this value is less than the significance level quoted, 0.05 or 0.01, then the r-value is significant and a correlation in the variables is statistically likely.

With the regression analysis more than two variables can be examined. It gives an indication how the dependable variable, in this case the dust, changes, when one of the independent variables, in this case the BOS process conditions, is altered whilst the other independent variables stay constant.

6.2 Dust mass

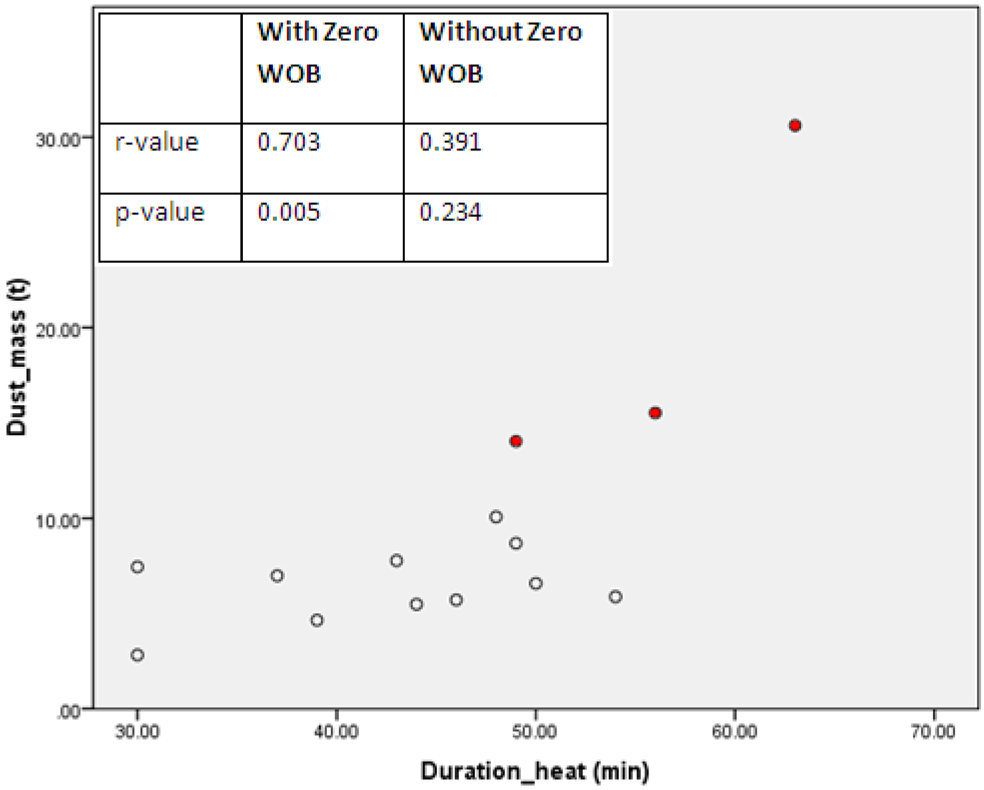
The first objective was to find correlations between the dust mass and various BOS process conditions, converter loadings and timings. This enables to understand what effect these variables have on the produced dust masses.

6.2.1 Duration

The first factors which were analysed were the duration of the heat and of the blow. Figure 71 shows the relation between dust mass in tonnes and the duration of the heat in minutes. Each dot in the scatter plot represents a trial heat. The three red dots image the three heats from the zero WOB trials. Because of the significantly larger dust masses produced in those three heats, the data set was analysed twice, once including the three heats and another time with them being separated. Since it is certain that the larger dust mass in the zero WOB trials are not due to the duration of the heat, the statistical evaluation including the zero WOB trials is in this case ignored. Evaluating the numbers without the zero WOB trials, the r-value of 0.391 indicates no relation between the dust mass and the duration of the heat. The p-value of 0.234 shows that the r-value does not significantly differ from zero, thus the null hypothesis cannot be rejected. Duration of the heat does not influence the dust generation. This is in line with what has been observed during various trials, with the majority of the dust being produced during the blow period and dust being just occasionally liberated at the start or end of the heat.

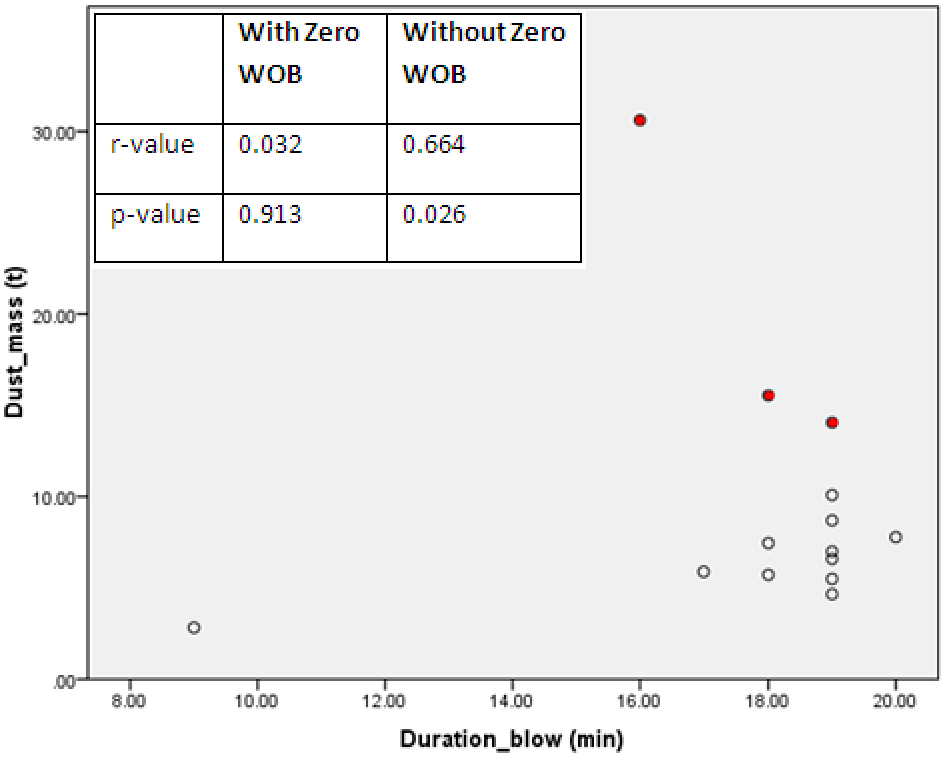
Figure 72 shows the correlation between dust mass and blow time. If the zero WOB trial data is excluded, the significant r-value of 0.664 shows that there is a linear correlation between both factors, indicating the longer the blow period, the higher the overall dust mass. This finding is expected, and indicates the majority of the dust being produced during the blow period.

Figure 73 shows the relation between dust during the blow and blow time and as expected, when excluding the zero WOB trials, a strong correlation can be seen. Also by looking at the data from the zero WOB trials, it shows that during two of the three heats additional dust was generated during the blow period.



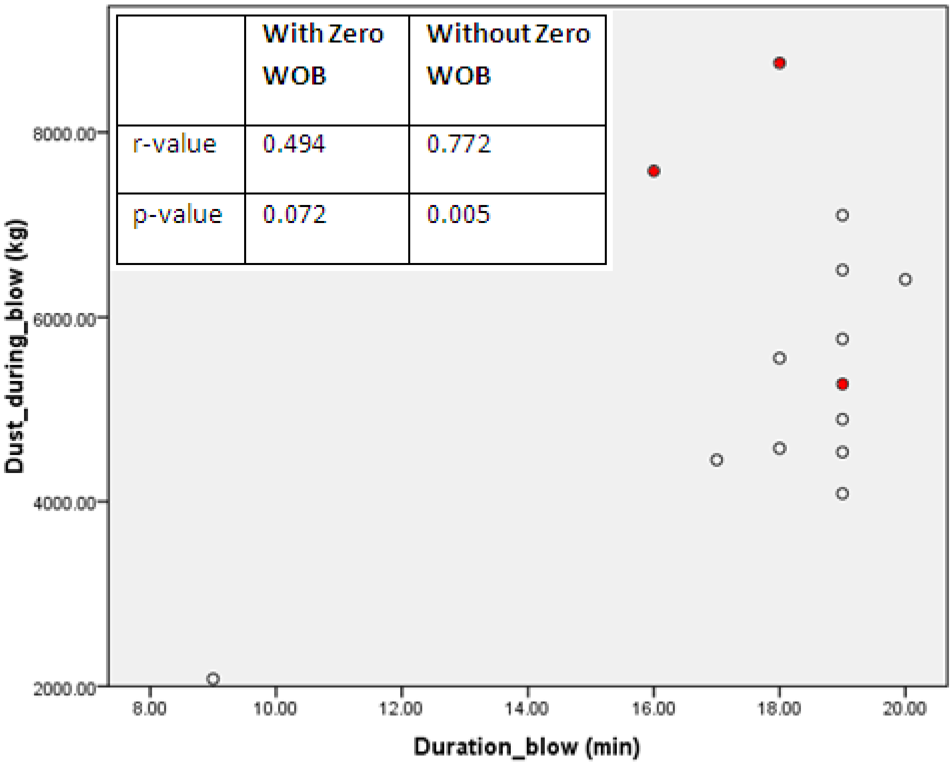
	With Zero WOB	Without Zero WOB
r-value	0.703	0.391
p-value	0.005	0.234

Figure 71: Duration heat and dust mass



	With Zero WOB	Without Zero WOB
r-value	0.032	0.664
p-value	0.913	0.026

Figure 72: Duration blow and dust mass

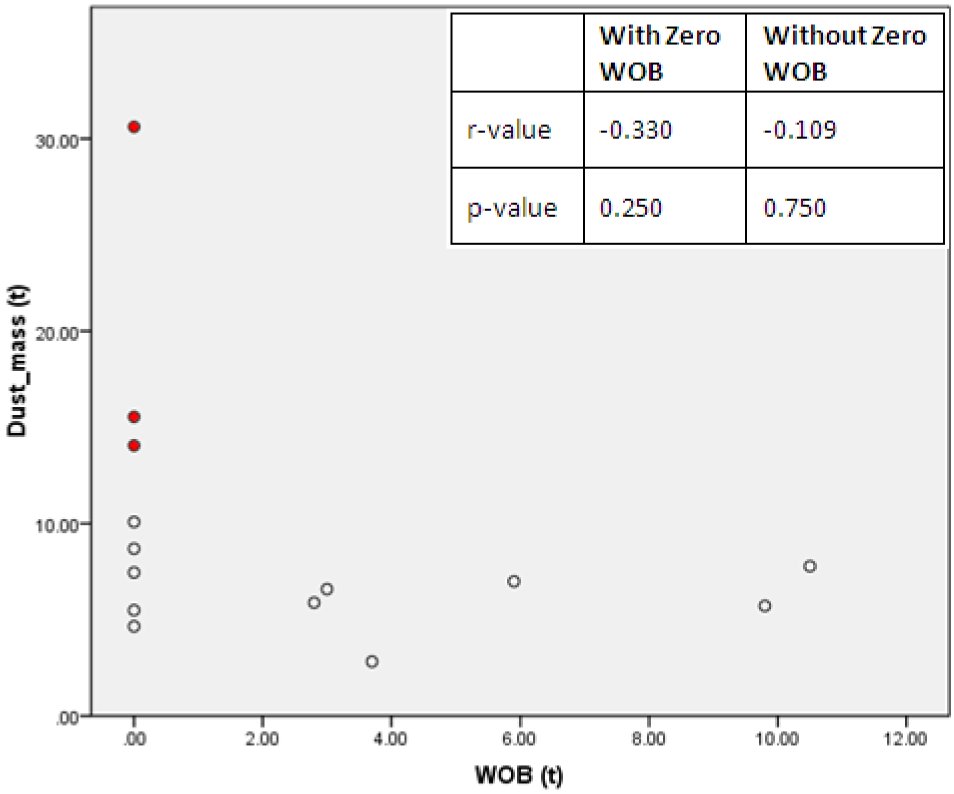


	With Zero WOB	Without Zero WOB
r-value	0.494	0.772
p-value	0.072	0.005

Figure 73: Duration blow and dust during blow

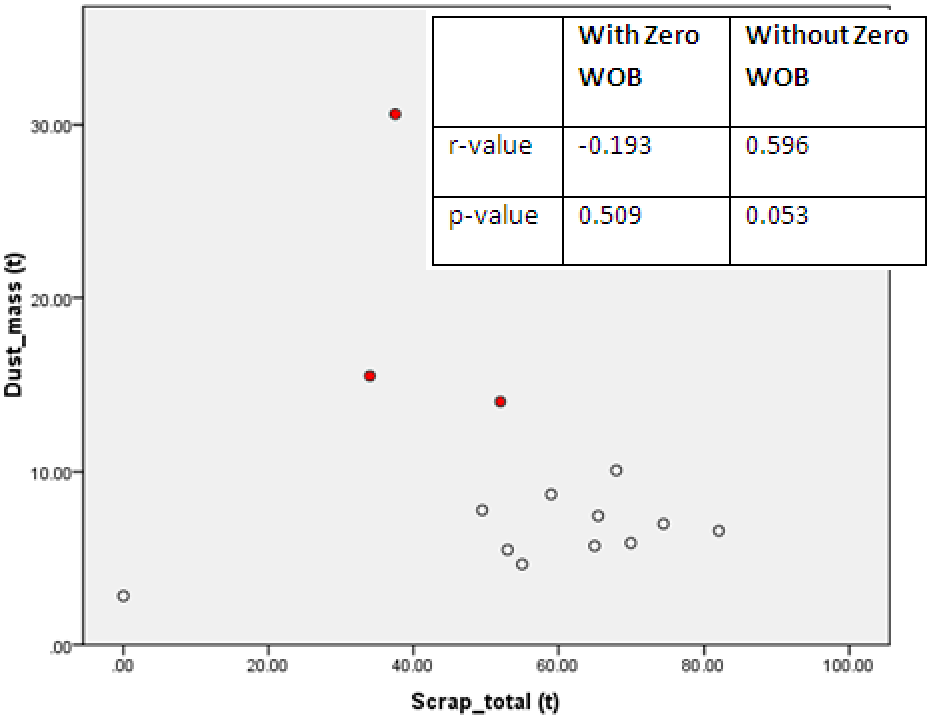
6.2.2 Converter loading

Also the converter loading was analysed. Objective was to find indications that certain additions would generate an invcreased dust production. Figure 74 shows the relation between dust mass and WOB input. It can be seen, no matter if the evaluation in- or excludes the zero WOB trials, there is no correlation between WOB input and dust mass. Identical results are obtained when analysing dust mass with scrap input (Figure 75), total additions (Figure 76) or hot metal input (Figure 77).



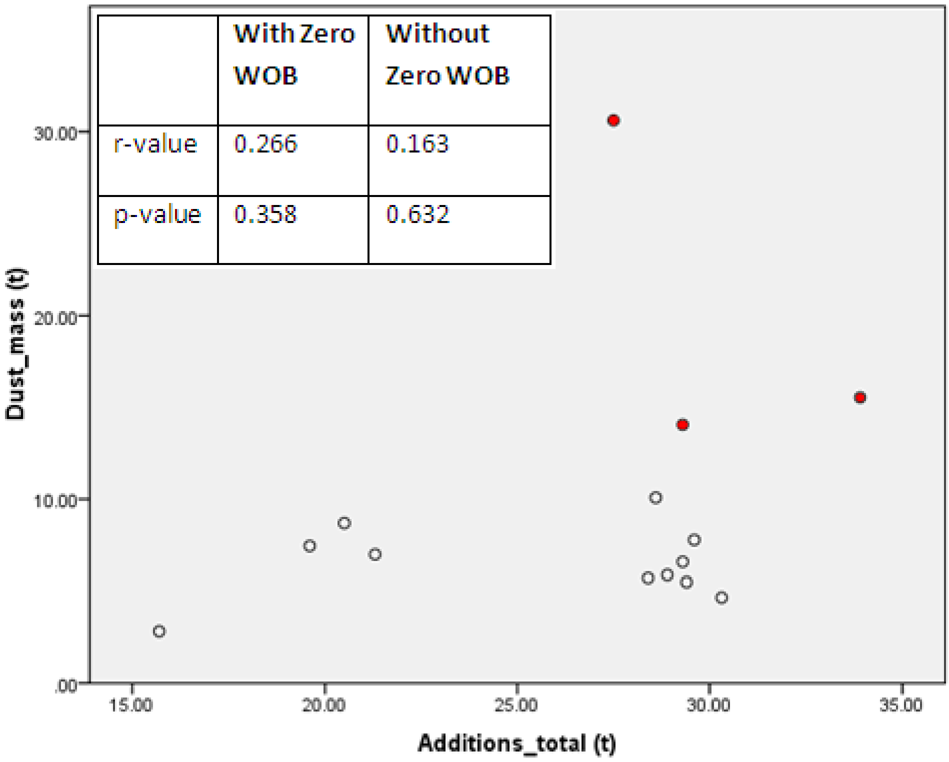
	With Zero WOB	Without Zero WOB
r-value	-0.330	-0.109
p-value	0.250	0.750

Figure 74: WOB input and dust mass



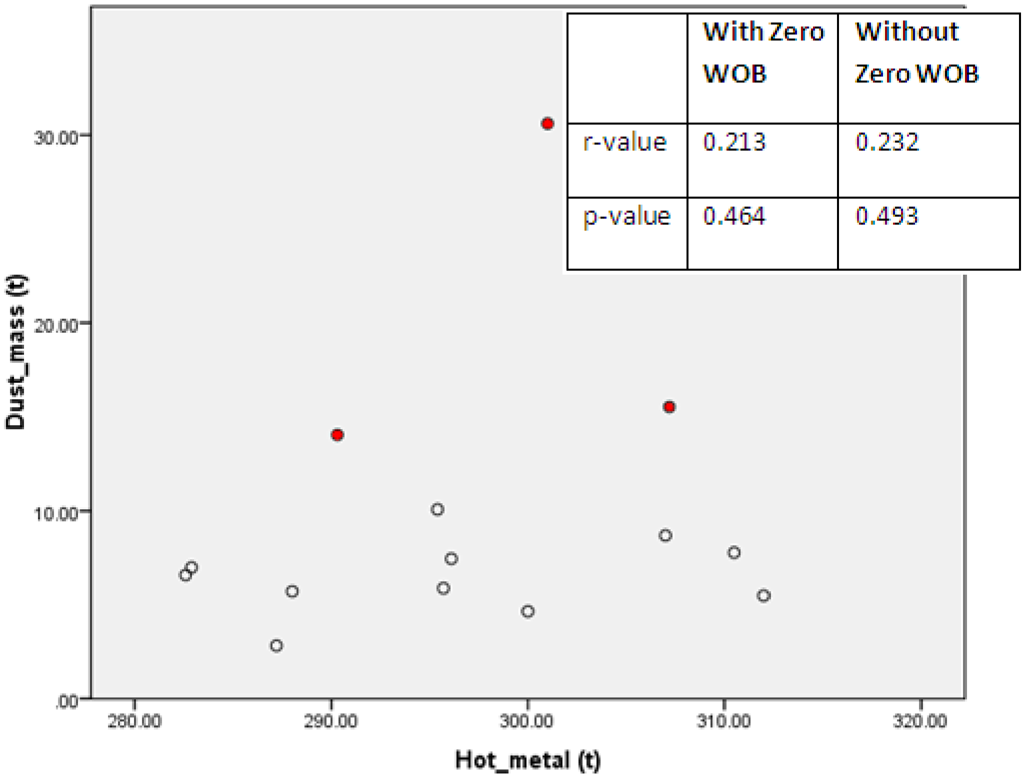
	With Zero WOB	Without Zero WOB
r-value	-0.193	0.596
p-value	0.509	0.053

Figure 75: Scrap total and dust mass



	With Zero WOB	Without Zero WOB
r-value	0.266	0.163
p-value	0.358	0.632

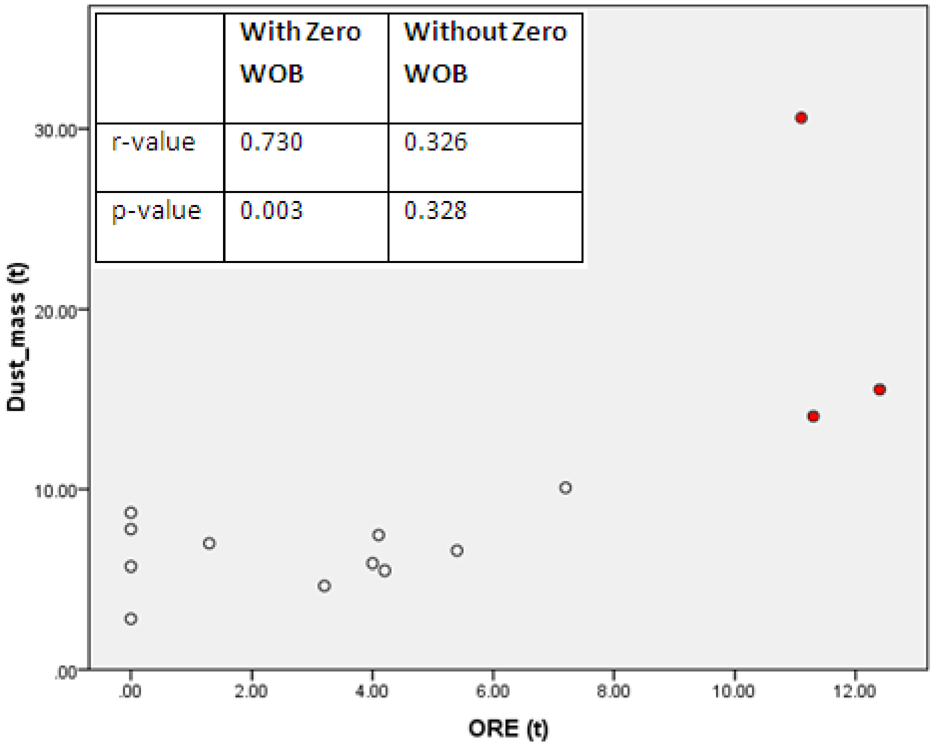
Figure 76: Additions total and dust mass



	With Zero WOB	Without Zero WOB
r-value	0.213	0.232
p-value	0.464	0.493

Figure 77: Hot metal and dust mass

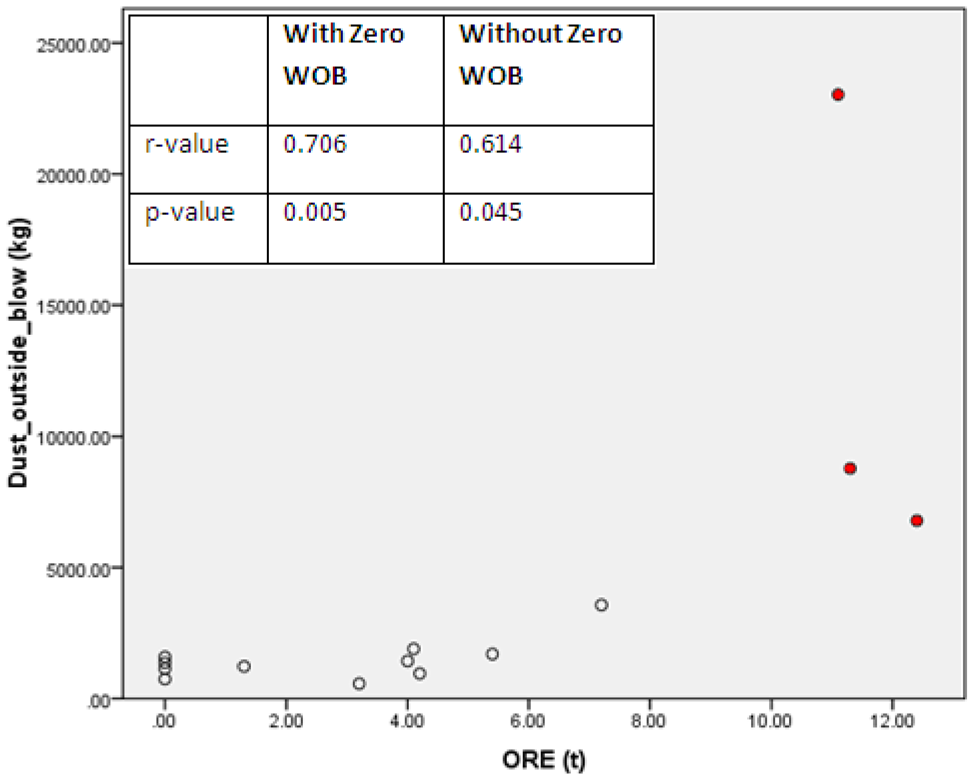
Figure 78 shows the correlation between ore input and dust production. It shows that during the Zero WOB Trials the ore input was higher than during the other trials, indicating that this increased input may have had an effect on the large dust masses produced. But looking at the data without the zero WOB trials this effect cannot be seen, indicating that the ore has no influence on the amount of dust produced.



	With Zero WOB	Without Zero WOB
r-value	0.730	0.326
p-value	0.003	0.328

Figure 78: Ore input and dust mass

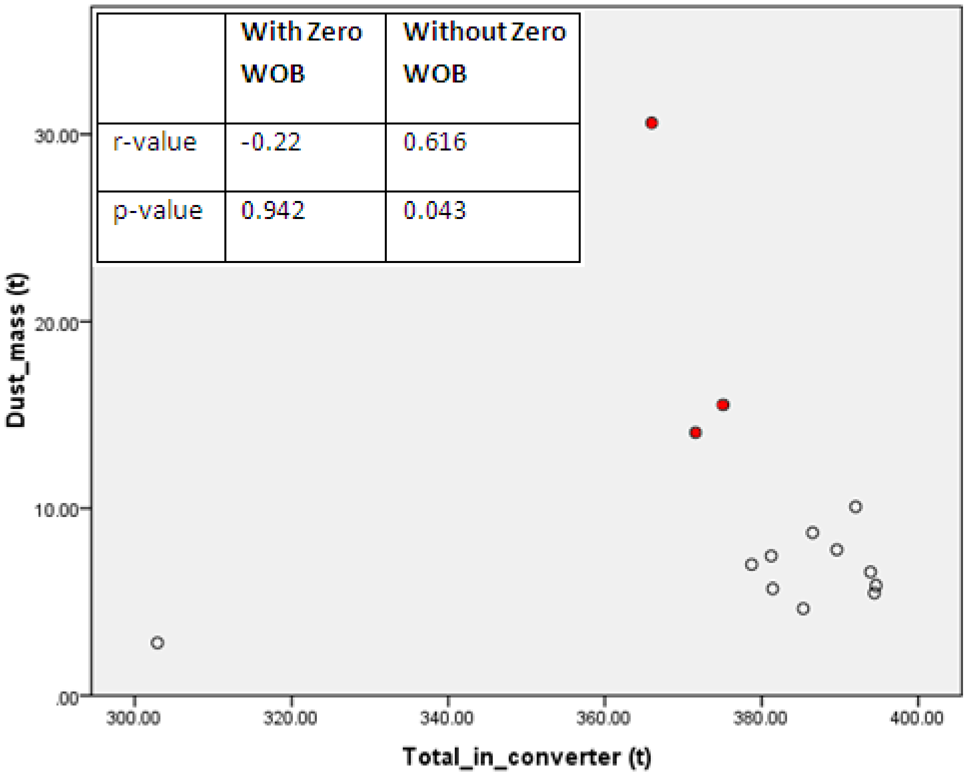
In order to investigate the role of the iron ore additions on the dust production further the amount of ore added was compared to the amount of dust produced outside the blow period. As seen in Figure 79 a correlation between these two factors can be found. Therefore ore additions as an answer for additional dust outside blow period cannot be dismissed.



	With Zero WOB	Without Zero WOB
r-value	0.706	0.614
p-value	0.005	0.045

Figure 79: Ore input and dust outside blow

Also the total converter loading was analysed. As seen in Figure 80, a positive correlation between converter loading and dust mass for trials without zero WOB can be seen. Looking at the zero WOB trials, the converter was not as full as usual, which is against the above stated trend thinking at the additional dust masses generated.



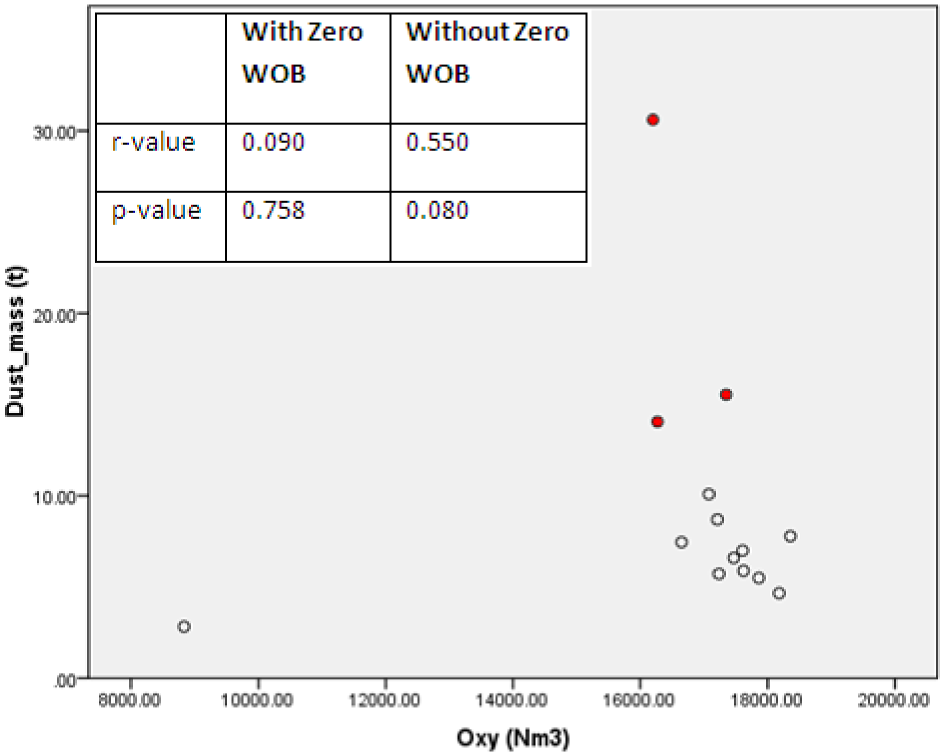
	With Zero WOB	Without Zero WOB
r-value	-0.22	0.616
p-value	0.942	0.043

Figure 80: Total in converter and dust mass

6.2.3 Process conditions

After looking at the duration of the blow and heat and the loading of the converter, the process conditions were analysed.

First the effect of the amount of oxygen injected into the converter was analysed (Figure 81). It can be seen that it has no influence on the dust mass.



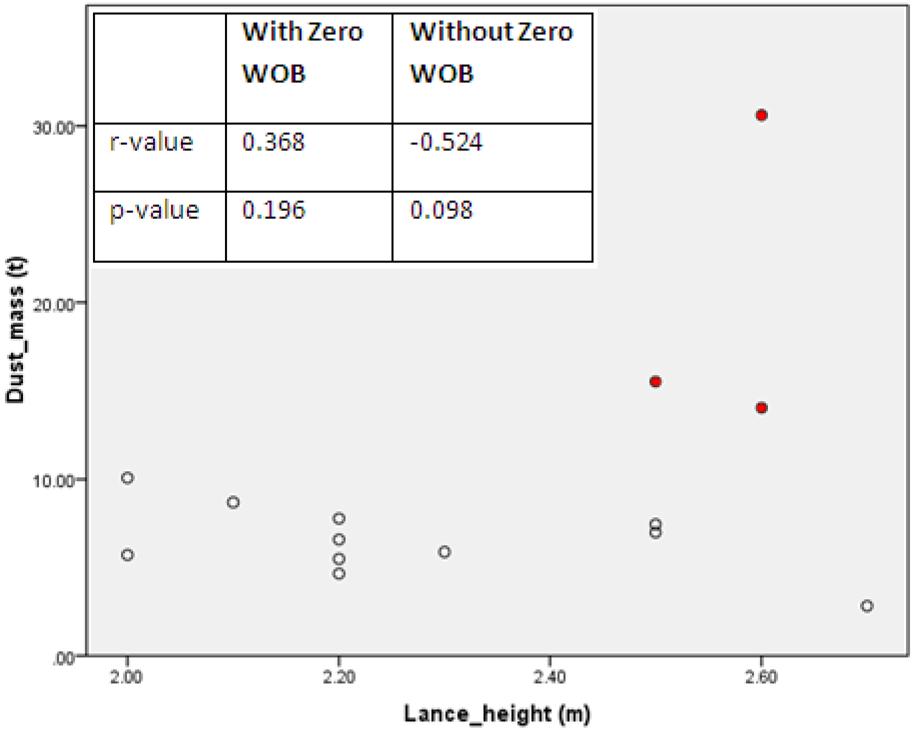
	With Zero WOB	Without Zero WOB
r-value	0.090	0.550
p-value	0.758	0.080

Figure 81: Oxygen input and dust mass

Next the position of the oxygen lance was looked at (Figure 82). It is seen that the position has no influence on the amount of dust produced. Looking at the data from the zero WOB trials the lance was high compared to the other trials. Figure 80 shows that the converter was during the zero WOB trials not as full as in the other trials. Therefore it had to be analysed if this meant an increased distance between bath surface and the tip of the oxygen lance.

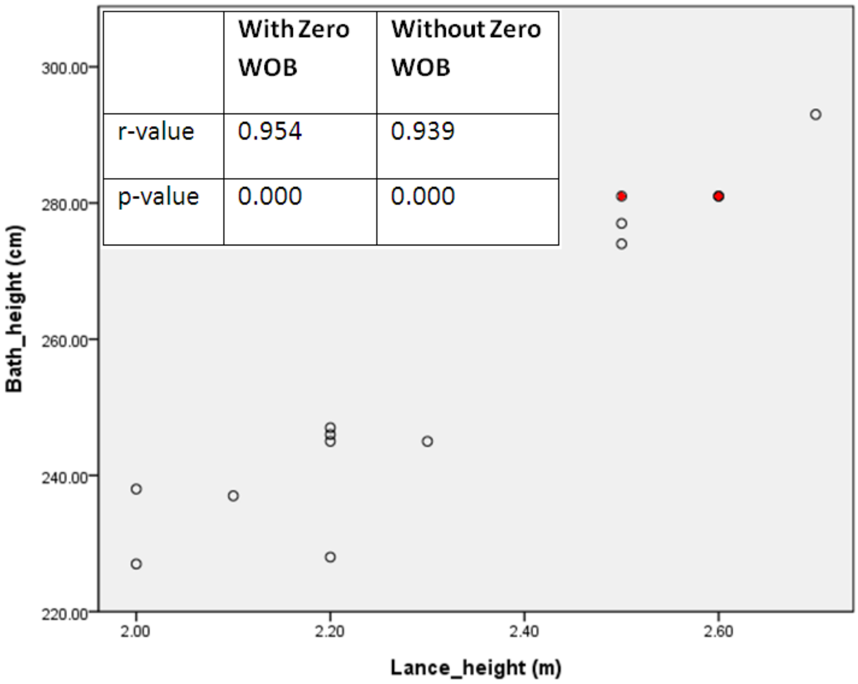
In order to examine the distance between Lance and bath surface in the converter, bath height and lance height was analysed in Figure 83. It is seen that there is a positive correlation between the two factors and the values of the zero WOB trials were no outliers.

Furthermore as seen in Figure 84, the distance between bath surface and the tip of the lance has no influence on the dust production.



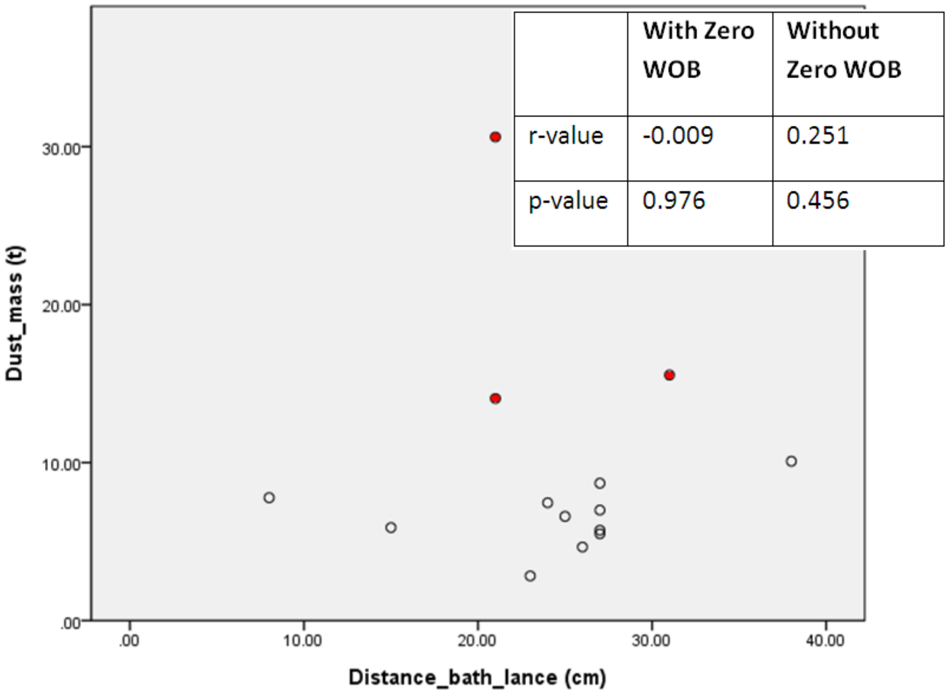
	With Zero WOB	Without Zero WOB
r-value	0.368	-0.524
p-value	0.196	0.098

Figure 82: Lance height and dust mass



	With Zero WOB	Without Zero WOB
r-value	0.954	0.939
p-value	0.000	0.000

Figure 83: Lance height and bath height

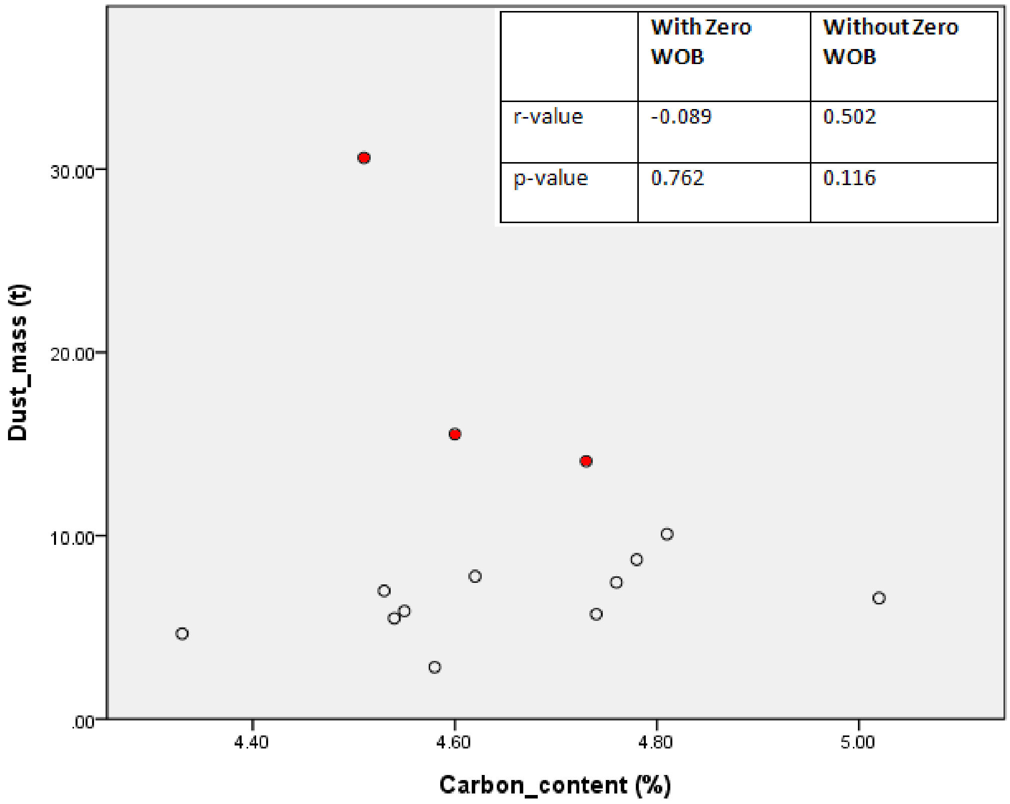


	With Zero WOB	Without Zero WOB
r-value	-0.009	0.251
p-value	0.976	0.456

Figure 84: Dust mass and Distance bath lance

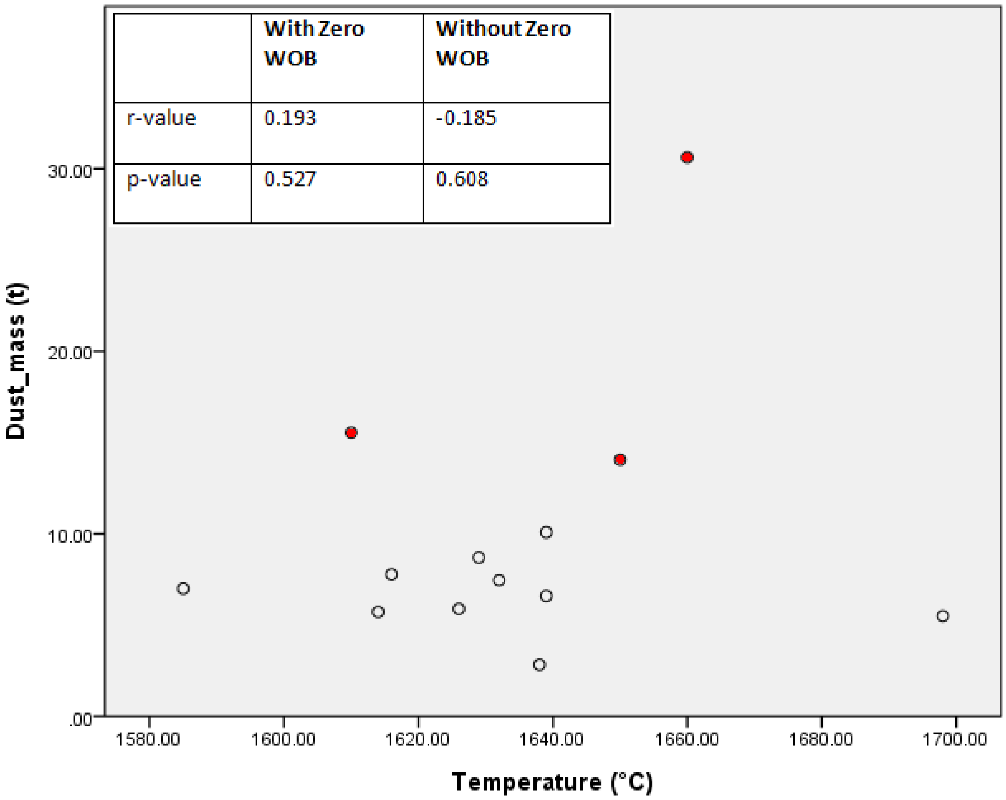
Next it was analysed if the amount of carbon in the hot metal had an impact on the produced dust masses. As seen in Figure 85, there is no correlation between the two parameters and therefore the carbon content has no influence on the dust masses produced.

Also the temperature of the hot metal was analysed, and as seen in Figure 86, it had no influence on the produced dust masses.



	With Zero WOB	Without Zero WOB
r-value	-0.089	0.502
p-value	0.762	0.116

Figure 85: Carbon content and dust mass



	With Zero WOB	Without Zero WOB
r-value	0.193	-0.185
p-value	0.527	0.608

Figure 86: Temperature and dust mass

6.2.4 Summary dust mass

The findings from statistically evaluating the 14 trial heats are:

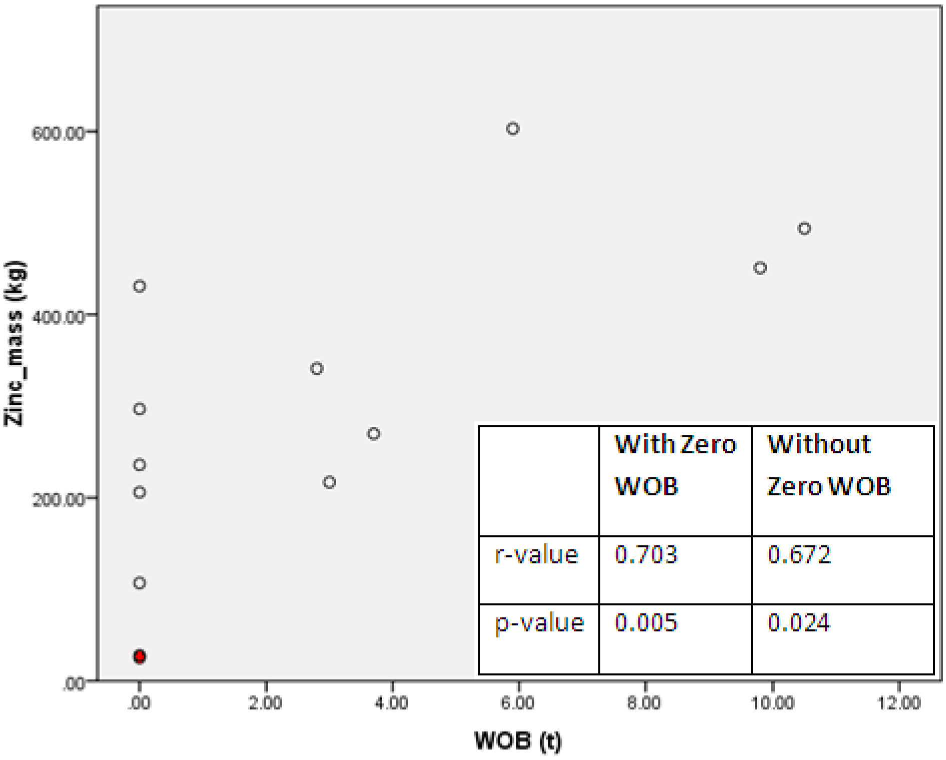
- The longer the blow time the more dust gets produced
- Duration of the heat has no influence on the dust mass
- The higher the total converter loading the more dust gets produced
- Increased Ore input leads to increased dust production outside the blow period. Reason may not be the tonnage but the late addition during the blow.
- WOBs, scrap, additions and hot metal input have, looking at it independently, no influence on dust mass
- Lance height and BAPs have no impact on dust generation

These findings are all expected. The author was hoping by doing this analysis to find certain differences between the Zero WOB trials and the other trials in order to give an explanation for the additional dust masses produced. But with the data obtained from the trials this question cannot be answered.

One interesting thing to note is the addition of WOBs. From this analysis they have no significant impact on the generation of dust. This may be due to the fact that the predictor variables are looked at independently and other variables affect the dust generation at the same time, therefore making the WOBs not significant. But still, more data should be generated, because if the WOBs do not significantly increase the dust levels, than this is a potential way to recycle the dust, until it reaches high zinc levels which makes it attractive to zinc smelters.

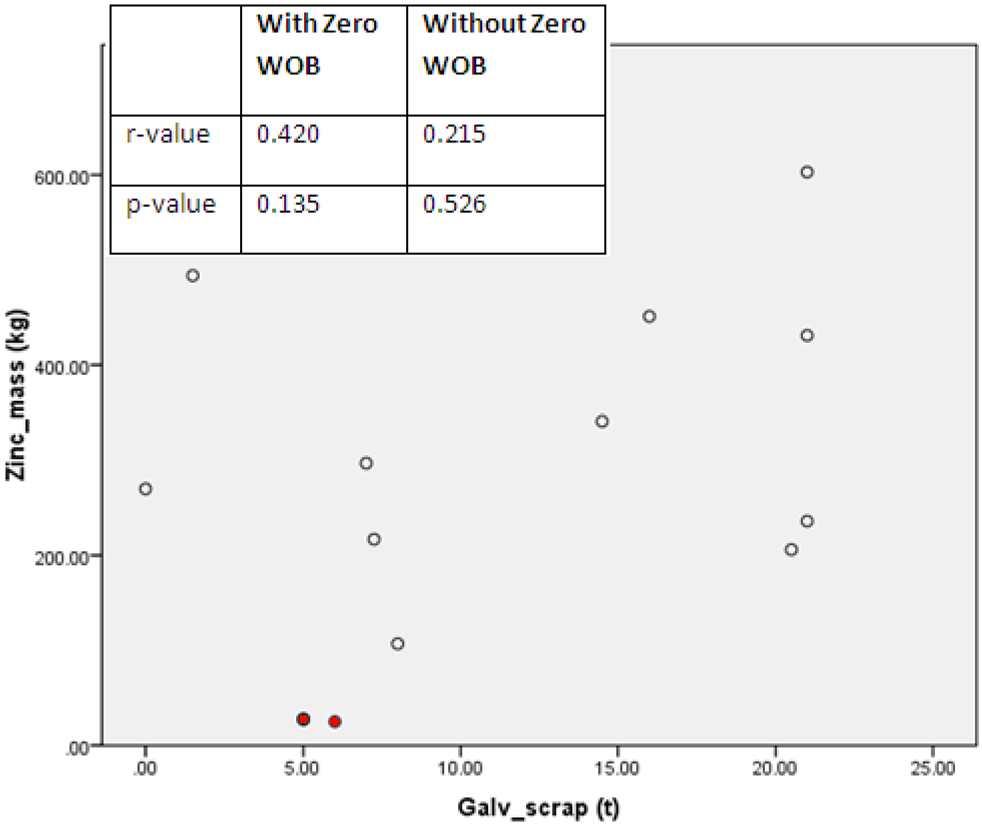
6.3 Zinc mass

It was investigated how and if the amount of WOBs and galvanised scrap added to the converter influence the zinc concentration in the dust. As seen in Figure 87 the WOBs have a strong positive correlation with the zinc mass in the dust. This is somehow obvious since the more WOBs, the more zinc gets added to the converter. However looking at the correlation between the galvanized scrap input and the zinc mass in the dust (Figure 88), no correlation can be found. The reason for this is that both WOBs and galvanized scrap have an impact on the zinc masses. Therefore they have to be looked at together.



	With Zero WOB	Without Zero WOB
r-value	0.703	0.672
p-value	0.005	0.024

Figure 87: WOB input and Zinc mass



	With Zero WOB	Without Zero WOB
r-value	0.420	0.215
p-value	0.135	0.526

Figure 88: Galvanised scrap input and Zinc mass

6.3.1 Regression analysis

A regression analysis was undertaken to analyse what effect the WOB and galvanised Scrap input have on the Zinc mass in the dust. For heats, where the galvanised proportion in the mills product was unknown, a proportion of 50% was assumed.

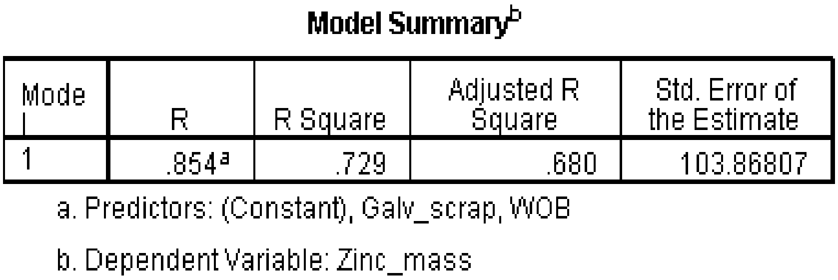
The R value of 0.854 for the zinc mass linear regression model, shown in Table xxx, indicates a strong correlation between the predictor variables and the zinc mass contained in the BOS dust. The R Square value indicates that 73% of the variance of zinc in the dust mass is predicted by the amount of WOBs and galvanised scrap.

The results in Table 32 compare the associated relationship of WOBs and galvanised scrap input to the zinc mass in the dust. The significance values for the two predictor values are both below 0.05 which shows that both were statistically reliable. Using the values of Table 33 a regression equation can be formed:

(Zinc mass(kg)) = 46.058 + 36.737*(WOB(t))+11.556*(Galvanised scrap(t))

The result indicate that by adding a tonne of galvanised scrap in the initial charge, the zinc mass in the dust is increased by 11.6 kg. Adding a tonne of WOBs to the charge leads to a much higher increase in zinc (36.7 kg).

Table 32: Regression model



Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.854[a]	.729	.680	103.86807

a. Predictors: (Constant), Galv_scrap, WOB

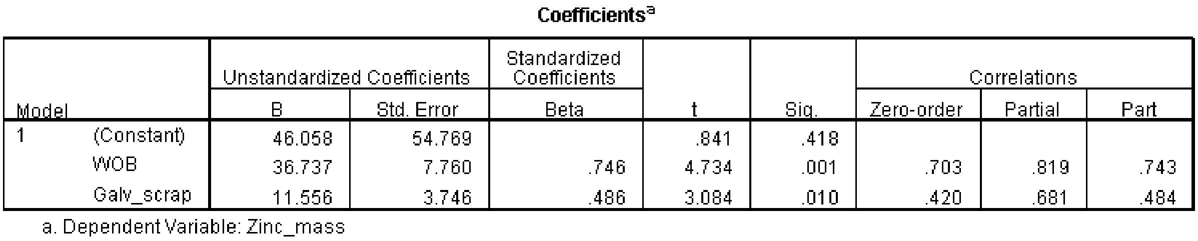
b. Dependent Variable: Zinc_mass

R: correlation between the observed and predicted values of dependent variable

R square: This is the proportion of variance in the dependent variable which can be explained by the independent variables

Adjusted R square: This is an adjustment of the R-squared that penalizes the addition of extraneous predictors to the model

Table 33: Regression coefficients



Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations		
		B	Std. Error	Beta			Zero-order	Partial	Part
1	(Constant)	46.058	54.769		.841	.418			
	WOB	36.737	7.760	.746	4.734	.001	.703	.819	.743
	Galv_scrap	11.556	3.746	.486	3.084	.010	.420	.681	.484

a. Dependent Variable: Zinc_mass

6.3.2 Summary zinc mass

A strong linear positive correlation between WOB input and zinc mass in the dust was found. This is expected and can also be seen looking at peaks in the zinc mass profile during a blow right after WOBs were added.

Combined the addition of WOBs and galvanised scrap account for 72 % of the zinc mass variance in the dust. This value is not as high as expected since WOBs and galvanized scrap are the main source of zinc in the dust. This may be due to the fact that the zinc content in the galvanized scrap is not as uniform as expected.

7 Discussion

7.1 Zinc liberation

A first zinc level increase in the dust was identified one minute after blow start. Taking into account the three to four minutes residence time between the converter mouth and the sampling location, it indicated zinc evaporation, immediately after the hot metal charging. Zinc was further liberated during the first ten minutes of the blow and then quickly decreased.

Rapid vaporisation of zinc is favourable, to facilitate separating the dust into a zinc rich fraction during the early stages and a zinc low fraction during the later stages of the blow. Zinc in galvanised scrap is present as pure zinc and zinc-iron alloys. A typical hot dip galvanised coating consists of five different zinc-iron alloy layers with varying iron concentration (Marder, 2000). With increasing iron concentration the boiling temperature increases, potentially lengthening the zinc removal from the converter (Inaba, Semura, & Horikawa, 2008). Also zinc, trapped in slow melting, densely compacted bales may cause this effect (Koros, Hellickson, & Dudek, 1995). An increased use of the bath agitation system, enhancing the diffusion in liquid to the phase boundary, (Nedar, 1996) could potentially increase the rate of vaporisation. Further research regarding these factors would be of benefit.

The addition of WOBs during the blow had a huge effect on the zinc levels at the later stages of the blow. In the second half of the blow of control heat 2, zinc levels in excess of 4% were measured which compared to more than double the amount of a similar heat without WOB addition. With decreasing carbon content in the melt, and the formation of a filtering slag, (Gritzan & Neuschutz, 2001), less metal droplets are ejected and therefore less dust is produced over blowing time. Because of this, late zinc liberation from WOBs addition, has a big impact on zinc levels during the second half of the blow.

7.2 Zinc reaction in off-gas system

After zinc volatilises from the converter, the zinc vapour gets transported away by the off gases. Temperature and CO_2/CO concentration ratio of the gas determine the oxidisation behaviour of zinc (Pluschkell & Janke, 1992). The measured BOS gas had an average ratio of 14% CO_2 and 65% CO. Due to the closed hood off gas system on site, the ratio changed only marginally during a blow, shifting from 25% CO_2 and 55% CO at the beginning of the blow to 12% CO_2 and 75% CO at the end. The slightly higher oxidisation potential of the gas at the later stages of the blow has only a marginal impact on the oxidisation behaviour.

A CO_2/CO ratio at this order of magnitude causes zinc vapour to oxidise in the area of 400˚C and 600˚C, and suppress oxidisation at higher temperatures (Pluschkell & Janke, 1992). With lower gas temperatures after hot metal charging early zinc oxidisation is most likely, whereas the higher temperatures during blowing will suppress oxidisation causing zinc to stay longer in its vapour phase.

This trend was verified by the SEM analysis, illustrating that after hot metal charging, zinc was predominantly present as individual grains, physically attached to other particles, indicating oxidisation of the zinc vapour prior to attachment. During blowing, no individual zinc grains were seen, suggesting a surface reaction of zinc vapour with the iron oxides, causing the formation of zinc ferrites.

XRD phase analysis of the dust is a suitable way to further investigate the reaction behaviour of zinc. Previous research indicated zinc to be present predominately as franklinite (ZnO, Fe_2O_3) and to a lesser extent as zincite (ZnO) (Krzton, 2010). The samples taken after hot metal charging and immediately after blow start showed as expected zinc to be in the form of zincite (ZnO). However, during the blow no zinc containing phases could be identified. This may be due to the dropping zinc levels, making it unable to differentiate zinc containing phases from the XRD background scatter.

7.3 Particle size

The wet sieving and SEM analysis identified a zinc rich particle size fraction below 60 microns accounting for 75% of the dust. The remaining 25% was a coarse dust predominantly made up of iron spheres, with little zinc contamination on the particles surface. Some zinc rich fines may agglomerate to particles above 60 micron but they are a minority group. During the control heats with high zinc input, the coarse grain dust had zinc levels of 0.7%. This value drops under normal operating conditions and makes it suitable for recycling via the blast furnace.

Zinc did not exist as an individual grain in the fine dust; therefore it cannot be further separated by particle size separation equipment.

7.4 Hold trials

During control heat 1, the primary dust system collected 426kg and the secondary system collected 20kg during the heat. The total zinc mass output of 446kg is consistent with the estimated zinc input and indicates the dust collection system captured the expected zinc mass. The second control trial showed an increased zinc mass due to the addition of 5.9t of WOBs. Zinc content of the WOBs was 3% therefore contributing with an additional 177kg of zinc. The primary dust system collected 603kg and the secondary system collected 20kg during the heat. The total zinc mass output of 623kg is also consistent with the estimated zinc input, indicating the dust collection system captured the expected zinc mass.

The zinc mass flows shown for hold heat 1 and 2 had no WOBs and the same zinc input as the first control trial. With 234kg and 206kg of zinc in its primary dust, there was a marked decrease in zinc contamination compared to the control trial heats, indicating a successful diversion of zinc.

Thus, the residual heat of the converter and a holding time above 10 minutes seems to be sufficient to volatilise approximately 50% of the zinc contained in the scrap. It is suggested that zinc trapped in the centre of the galvanised scrap bales and the zinc-iron alloys present are not affected by the residual heat and the hold time and still find its way into the primary dust.

Tilting of the converter and ramping up the secondary extraction fans successfully diverted the volatilised zinc; however a zinc increase in the secondary dust silo was not measured. Potential reason might be: the hold trial being carried out when two converters were running in the BOS plant, which diluted the measured zinc contents because of additional dust mass from the second converter. Also the residence time was in the region of 45 minutes making it difficult to correlate changes in zinc contents with changes in the process. Furthermore it was not possible to arrange an empty holding silo at the beginning and end of the trials to correlate accurately with the start and finish of the trial. And most importantly, the high oxidisation potential of the off gas in the secondary dust extraction system might have caused zinc to condense on the cold extraction system ducts, therefore not being transported to the sampling point. To successfully implement this technique, an extraction system specifically designed for this purpose would need to be installed.

7.5 Zero WOB trials

The three low zinc trial heats each had a low zinc charge of less than 6t of galvanised scrap, which was reflected in the zinc mass flows. The liberated zinc masses shown in Figure 8 had promisingly low values, indicating less than 30kg of zinc in the dust. The results demonstrated that a low galvanised scrap charge makes it is possible to produce a low zinc content dust which can be recovered through the sinter plant and blast furnace.

7.6 Max WOB trials

The Max WOB trials have shown what a big effect the addition of WOBs has on the zinc levels in the dust. Zinc present in the WOBs is immediately volatilised causing a spike in the zinc levels of the dust. But interestingly the overall dust levels are not significantly increased by the WOB addition. This means that a repeated recycling of BOS dust via the use of WOBs will increase the zinc levels of the dust but not significantly the amount. This could potentially make it possible to increase the zinc levels in the dust in order to sell it to zinc smelters. But in order to confirm this more data needs to be collected.

8 Conclusion

The current treatment and recycling options (pyrometallurgy, hydrometallurgy, physical separation, direct recycling) have been investigated, its limitations have been illustrated and zinc as the main problem for recycling has been identified.

Literature described that a coarse zinc free fraction can be separated from a fine zinc rich fraction by means of physical separation. This study confirms this, indicating that 75% of the BOS dust is zinc rich and the remaining 25% of the dust is coarse with little zinc contamination. The zinc levels in the zinc rich fraction can be as high as 7 % depending on the added galvanized scrap charge whereas the zinc levels in the coarse fraction are below 1% making it suitable for recycling via the blast furnace. Wet sieving and SEM work of this study has shown that the cut off between the two fractions is at about 60 microns. The coarse particle fraction is predominantly made up of iron spheres which indicate that this material is produced from spitting of the steel bath. Further physical separation of the zinc from the sub 60 micron fraction is not possible. The Port Talbot BOS plant has a closed hood off gas system with a stable CO_2 to CO ratio. This ratio determines the oxidization behavior of zinc. In Port Talbot, the measured CO_2/ CO ratio causes zinc to oxidise at 400 - 600°C and suppresses oxidisation at higher temperatures. The temperature in the off gas system varies. The hottest temperature is of course above the converter (1600°C) but temperatures are still relatively high in the turnover section in the third floor (800 -1000°C). This has the result that zinc vapour leaves the converter and then reacts with the surface of other dust particles. At lower temperatures zinc will oxidise and then attach to other particles. Therefore zinc is not present as individual grain in the dust, prohibiting further physical separation of the zinc rich fraction.

With no treatment options in place for the majority of the dust, the steel industry is facing a real problem.

This study wanted to clarify, if zinc contamination in the BOS dust can be reduced by holding the galvanised scrap in the hot converter in an inert nitrogen atmosphere prior to the hot metal addition, to volatilise the zinc. In that way, the volatilized zinc can be sucked away by the secondary dust collection system and does not come in contact with dust which is produced after the hot metal is added. This would ideally result in a zinc free dust which could be recycled via the blast furnace.

In order to evaluate this large scale experiment, a robust sampling device was fabricated, which allowed isokinetic sampling of the BOS slurry. The sampling point was chosen to be as close to the converter as possible (residence time ca. 3 mins), therefore changes in the dust levels could be instantly seen. Also the sampling device allowed taking samples every 30 seconds, which resulted in a detailed characterization how the dust changes during a heat. The data obtained allowed not only to answer the question if zinc can be volatilized in the hot converter prior to the blow, it also gave great insight into general aspects of the dust.

The obtained data showed that zinc is liberated from the converter immediately after hot metal charging, with zinc liberation being high during the first 10 minutes of the blow, and then it attenuates. This finding theoretically allows cutting off a zinc rich dust at the start of the blow from a zinc low dust at the end of the blow.

Separating the dust in this way leads in the best scenario to a separation where half of the dust can be recycled via the blast furnace.

The data also showed that adding WOBs during the blow causes an increase of zinc contamination. This was expected. But the data also showed the zinc peaks straight after the addition of the WOBs which indicates immediate vaporisation. When adding the WOBs during the later stages of the blow, where less dust is produced, high zinc levels in the dust can therefore be seen. Thus, when the idea of separating the dust during the heat is followed on, the WOBs have to be added at blow start.

The data obtained during the hold trials showed the following:

By holding the scrap for more than ten minutes in the nitrogen purged converter, utilising its residual heat, approximately 50% of the zinc contained in the scrap is volatilised and can be diverted away using the secondary dust collection system. This resulted in halving the zinc contamination in the primary dust extraction system during the hold trials compared to the control trials. This is not enough to directly recycle the dust vial the blast furnace. Even though zinc as a boiling of 907°C and the temperature in the converter is expected to be much higher, the holding time was not enough to volatilise all of the zinc. Zinc in galvanised scrap is present as pure zinc and zinc-iron alloys. Increased iron concentration in these alloys increases its boiling temperature. This could be the explanation why not all of the zinc was volatilised.

It was not possible to collect the zinc which was volatilized prior to hot metal addition in the secondary dust extraction system. The temperature in this system is much lower than in the primary system which leads to oxidization of the zinc and attaching to the ducts.

Follow up trials which had the aim to get a greater insight into the process showed that charging the converter with a reduced amount of galvanised scrap makes it possible to produce a dust with low zinc contamination which can be recovered through the sinter plant and blast furnace. Currently there are two clarifiers at the BOS plant in Port Talbot. This gives the potential option to direct slurry produced from heats with galvanised scrap to clarifier one and slurry produced from heats without or little galvanised scrap into clarifier two. In that way the dust from clarifier two could be recycled through the blast furnace.

9 Limitations

One limitation of this study is the number of heats sampled. If a greater amount of heats could have been sampled and analysed, the findings could have been strengthened and verified. There is one main reason for the limited number: the study was not conducted in a laboratory environment. With the need to make various changes to the Tata production schedule including changing the scrap menu and production timings, leadtime for planning and organising was needed.

10 Bibliography

Federal Interagency Sedimentation Project. (1941). *Laboratory investigations of suspended sediment samplers.* Iowa City.

Afonina, A. N., Krichevtsov, E. A., Kulikova, L. P., Laletin, V. G., & Smirnov, L. A. (1980). Morphology of Basic Oxygen Furnace Dust. *Journal of Steel in the USSR, Vol.4* , 181-182.

Alonso, D. F., Azzopardi, B. J., Gonçalves, J., & Coury, J. R. (2001). Drop Size Measurements in a Laboratory Scale Venturi Scrubber. *Journal of the Brazilian Society of Mechanical Sciences* .

Bogdandy, L., & Pantke, H. D. (1958). *Stahl und Eisen 78* , 792-798.

Bounds, C. O., & Pusateri, J. F. (1988). The Flame Reactor-Process - A Solution for Lead/Zinc Industry Problems. *Paper presented at the TMS Annual Meeting.* Phoenix.

British Standard. (2006). Water quality - vocabulary, BS ISO 6107-02:2006. *British Standard* . London.

Delhaes, C., Hauck, A., & Neuschutz, D. (1993). Mechanisms of dust generation in a stainless steelmaking converter. *Steel Research , 64* (1), 22-27.

Dressel, W. M., Barnard, P. G., & Fine, M. M. (1974). *Removal of Lead and Zinc and the Production of Prereduced Pellets from Iron and Steelmaking Wastes.* NTIS Report NO. Pb-234.

Drinker, P., & Hatch, T. (1936). *Industrial dust.* McGraw-Hill Book Company.

Duyvesteyn, W. P., & Jha, M. C. (1986). Two-Stage Leaching Process for Steel Plant Dusts. US: Patent 4,610,721.

European commission. (2001). *Best Available Techniques Reference Document on the Production of Iron and Steel.* Joint research centre; Institute for prospective technological studies.

Ferguson, R., & Church, M. (2004). A simple universal equation for grain settling velocity. *Journal of Sedimentary Research , 74* (6), 933-937.

Flowline Manufacturing Ltd. (2011). Retrieved July 13, 2011, from Flowline Manufacturing Ltd Web site: http://flowline.co.uk/products/product/moredetails/flo-dar.id69.html#download

Franzen, A., & Pluschkell, W. (2000). Removal of zinc layers from coated steel strip by evaporation. *Steel Research , 70* (12), 508-512.

Garcia, M. H. (Ed.). (2008). *Sedimentation engineering: processes, measurements, modeling and practice.* Reston: American society of civil engineers.

Gleim, V. T. (1953). *Applied Chemistry 26* , 1099-1106.

Goldstein, J. L., Porter, J. R., & Keyser, N. H. (1982). *Characterization, Recovery and Recycling of Electric Arc Furnace Flue Dust.* Lehigh University, Bethlehem: Final Report, US department of Commerce.

Gritzan, A., & Neuschutz, A. (2001). Rates and mechanisms of dust generation in oxygen steelmaking. *Steel Research , 72* (9), 324-330.

Gulliver, J. S. (2010). *Stormwater Treatment: Assessment and Maintenance.* (A. Erickson, & P. Weiss, Eds.) Minneapolis, MN: University of Minnesota, St. Anthony Falls Laboratory; http://stormwaterbook.safl.umn.edu/.

Hay, S. M., & Rankin, W. J. (1994). Recovery of Iron and Zinc from Blast Furnace and Basic Oxygen Furnace Dusts: A Thermodynamic Evaluation. *Minerals Engineering, Vol.7, No.8* , 985-1001.

Heijwegen, C. P. (1985). Process of Treating Dust which Contains Zinc and Lead and which is Derived from an Iron or Steelmaking Process. *European Patent 0 040 870 B1* .

Higley, L. W., & Fukubayashi, H. H. (1974). Method for Recovery of Zinc and Lead from Electric Furnace Dusts. *Proc. of the 4th Symp. on Mineral Utilisation*, (pp. 295-302).

Hill, P., Pickin, G., Butt, J., & Turner, M. (1991). *Recycling of zinc coated scrap in the BOS vessel.* Welsh laboratories, British Steel Technical Report.

Hoeffer, E. (1994). The ups and downs of recycling coated scrap. *New Steel* , 53-56.

Hogan, J. C. (1974). Waste Oxide Recycling in Steel Plants. In W. K. Lu. Hamilton: MacMaster University.

Holden, C. (1959). Factors affecting fuming in open hearth furnaces. *J. Iron Steel Inst. 193* , 93-102.

Holowaty, M. O. (1971). A Process for Recycling of Zinc-Bearing Steelmaking Dusts. *Meeting of American Iron and Steel Institute* , 149-173.

http://www.malvern.com. (2015). Retrieved April 11, 2015, from http://www.malvern.com/en/products/product-range/mastersizer-range/mastersizer-2000/default.aspx

Inaba, T., Semura, K., & Horikawa, K. (2008). Behavior of zinc in BOF with charging zinc coated scrap. *4th International Congress on the Science and Technology of Steelmaking.*

Industrial Efficiency Technology Database. (n.d.). Retrieved April 09, 2015, from http://ietd.iipnetwork.org/content/bof-heat-and-gas-recovery

IZA Europe. (1999). *Zinc recycling.*

Kern, P. L., Joo, L. A., & Gee, J. T. (1988). The Beneficial Reuse of Electric Arc Furnace Dust through the Waelz Process. *20th Mid-Atlantic Industrial Waste Conference*, (pp. 158-166).

Knaggs, K., & Slater, J. M. (1959). Some factors affecting fume evoluition in molten steel during oxugen injection. *J. Iron Steel Inst. 193* , 211-2216.

Kohlmeyer, E. J. (1944). Ueber die Vergasung von Eisen : (Mitteilg aus d. Inst. f. Metallhüttenwesen d. Techn. Hochschule Berlin) / Ernst Justus Kohlmeyer ; Hans Spandau. 1-6.

Kola, R. (1990). The Processing of Steelmaking Waste. *Lead-Zinc 90, Eds.Mackey T.S. and Prengaman R.D., The Minerals, Metals & Materials Society* , 453-464.

Koros, P. J., Hellickson, D. A., & Dudek, F. J. (1995). Issues in Recycling Galvanized Scrap. *Galvatech 95.* Chicago.

Kosmider, H., Neuhaus, H., & Kratzenstein, H. (1954). Die Abgasverhältnisse im Thomasstahlwerk bei Anwendung verschiedener Frischgase. *Stahl u. Eisen. [Jg.] 74. 1954* , 73-82.

Krishnan, E. R. (1983). *Environmental Progress, 2* , 184.

Krzton, H. (2010). Quantitative Phase Composition of Steelmaking Dust from polish Steel Industtry. *Diffusion and Defect Data Pt. B: Solid State Phenomena , 163*, 31-37.

Laerd statistics. (2015). *https://statistics.laerd.com*. Retrieved April 08, 2015, from https://statistics.laerd.com/statistical-guides/pearson-correlation-coefficient-statistical-guide.php

Law, S. L. (1983). *Characterization of Steelmaking Dusts from Electric Arc Furnaces.* US Bureau of Mines Report 8750.

Lee, Y., Smith, S., & Nassaralla, C. L. (1997). Recycling and Recovering of Steelmaking Dusts and Chromium-Based Refractory in the Iron and Steel Industries. *Proc. of 4th Int. Conf. on Env.Conscious Design and Manufacturing*, (pp. 67-78).

Lenntech.com. (2015). Retrieved April 10, 2015, from http://www.lenntech.com/library/clarification/clarification/centrifugation.htm

Maczek, H., & Kola, R. (1980). Recovery of zinc and lead from electric furnace steel making dust at Berzelius. *Journal of Metals 32* , 53-58.

Marder, A. R. (2000). Metallurgy of zinc-coated steel. *Progress in Material Science , 45* (3), 191-271.

Metal Price Report. (1990). *Finding value in waste.* Scrap supplement.

Morris, J. P., Riott, J. P., & Illig, E. G. (1966). A study of fumes from oxygen refining of steels. *J. Metals 18* , 803-810.

Nedar, L. (1996). Dust formation in a BOF converter. *Steel Research , 67* (8), 320-327.

Nicolle, R., & Lu, W. K. (1974). A review on the behaviour of zinc in blast furnaces and zinc removal in the preparatory processes. *McMaster Symp. on Iron and Steelmaking* , 12-1 / 12-25.

Nyirenda, R. L. (1991). The processing of steelmaking flue dust: a review. *Minerals Engineering , 4* (7-11), 1003-1025.

Ozturk, B., & Fruehan, R. J. (1996). Vaporization of Zinc from Steel Scrap. *ISIJ International , 36* (SUPPL), 239-242.

Pasztor, L., & Floyd, S. B. *Managing and Disposing of Residues from Environmental Control Facilities in the Steel Industry.* 1976: NTIS Report: PB-260 477.

Pazdej, R., & Steiler, J. M. (1980). New Treatment Possibilities of BF/BOF Zinc 9and Lead) Bearing Dusts. *1st Process Technology Conference on Recycling in the Steel Industry.* Washington, D.C.

Pedersen, T., Aune, J. A., & Cundall, R. H. (1990). The Elkem Multi-Purpose urna ace@ for the Recovery of Zinc and Lead from Waste Materials. *Lead-Zinc* , 857.

Piddington, C. R. (2001). The recycling of basic oxygen steelmaking dust. *PhD Thesis, University of Wales, Division of materials and minerals* . Cardiff.

Piret, N. L., & Castle, J. F. (1990). Review of secondary zinc treatment process options. *Recycling of metalliferrous materials Conference proceedings .* Birmingham, England: Institution of Mining and Metallurgy.

Pluschkell, W., & Janke, D. (1992). Thermodynamics of zinc reactions in the BOF steelmaking process. *Steelmaking conference proceedings*, (pp. 717-722). Toronto.

Pooley, F. D., & Wheatley, B. I. (1990). Production of Zinc Powder from Arc and Smelter Flue dusts. *Recycling of Metalliferous Materials* , 515-518.

Pugh, J. L., & Fletcher, L. N. (1974). Waste Oxide Recycling in Steel Plants. In W. K. Lu.

Ray, S. K., Chattopadhyay, G., & Ray, A. K. (1997). Evaluation of Dust Generated from Basic Oxygen Furnace Steel Making. *Journal of the Air and Waste Management Association, Vol.47* , 716-721.

Reinke, N., Vossnacke, A., Schuetz, W., Koch, M. K., & Unger, H. (2001). Aerosol Generation by Bubble Collapse at Ocean Surfaces. *Water, Air and Soil Pollution: Focus VOL1* , 333-340.

Rhee, P. C. (1974). Waste Oxide Recycling in Steel Plants. *MacMaster University* , 14-1.

Satyendra, K. S. (2015). Retrieved April 09, 2015, from http://ispatguru.com/basic-oxygen-furnace-gas-recovery-and-cleaning-system/

Schaukens, A. (1997). *The Enviroplas TM Process for the ecovery of Zinc, Chromium and Nickel from Steel-PLant Dusts.* Mintek Co. Publications.

Schuermann, E., Ploch, A., Pflipsen, H. D., & Herwig, U. (1995). Chemische Zusammensetzung, Entstehungsmechanismus und Bildungsrate von Konverterstaub . *Stahl und Eisen 115* , 55-62.

Simonyan, L. M., & Govorova, N. M. (2011). Features of dust formation in the oxygen-blowing of melts and possible uses of captured dust. *Metallurgist , 55* (5-6), 450-458.

Steel dust recycling. (2015). Retrieved April 10, 2015, from http://www.steeldust.com/waelz.htm

Stubbles, J. (2015). *www.steel.org*. Retrieved April 08, 2015, from https://www.steel.org/Making%20Steel/How%20Its%20Made/Processes/Processes%20Info/The%20Basic%20Oxygen%20Steelmaking%20Process.aspx

Szekely, J. (1995). A Research Program for the Minimization and Effective Utilization of Steel Plant Wastes. *Iron and Steelmaker Vol.2* , 25-29.

Tata steel. (2008). BOS off gas system guidebook.

Tata steel. (2015). *Tata steel Basic Oxygen Furnace*. Retrieved April 11, 2015, from http://resources.schoolscience.co.uk/Corus/14-16/steel/msch4pg2.html

Tsujino, R., Hirai, M., Ohno, T., Ishiwata, N., & Inoshita, T. (1989). Mechanism of Dust Generation in a Converter with Minimum Slag. *ISIJ International , 29* (4), 291-299.

Turkdogan, E. T., & Leake, L. E. (1959). *J. Iron Steel Inst. 192* , 162-170.

Water Institute of Southern Africa. (2002). *Handbook for the operation of waste water treatment plants.*

West, N. (1976). Recycling Ferruginous Wastes: practice and trends. *Iron and Steel international* , 173-185.

World Steel Association. (2011). *WORLD STEEL IN FIGURES.*

Zhao, B. (2013). Retrieved April 09, 2015, from Lead and Zinc Sintering: http://cdn.intechopen.com/pdfs-wm/42561.pdf

11 Appendix

Table A 1: **BOS slurry flow rates - control heat 18793**

Time	Velocity (m/s)	Level (mm)	Flow (l/m)
11:07	2.858	241	18069.2
11:08	2.858	238	17718.5
11:09	2.858	238	17718.5
11:10	2.858	239	17788.6
11:11	2.854	239	17762.5
11:12	2.854	238	17692.5
11:13	2.885	239	17959.4
11:14	2.875	237	17719.5
11:15	2.875	237	17684.3
11:16	2.875	237	17684.3
11:17	2.875	237	17684.3
11:18	2.781	237	17106.5
11:19	2.781	237	17106.5
11:20	2.797	237	17238.0
11:21	2.856	237	17599.1
11:22	2.856	235	17459.3
11:23	2.862	237	17639.3
11:24	2.862	237	17674.3
11:25	2.864	238	17720.9
11:26	2.866	244	18330.5
11:27	2.907	246	18810.0
11:28	2.907	246	18845.8
11:29	2.926	246	18933.4
11:30	2.907	247	18953.3
11:31	2.889	247	18870.7
11:32	2.882	248	18860.6
11:33	2.882	249	19002.8
11:34	2.882	252	19323.2
11:35	2.882	252	19323.2
11:36	2.882	254	19501.4
11:37	2.846	252	19083.1
11:38	2.846	252	19083.1
11:39	2.846	252	19080.0
11:40	2.846	253	19188.7
11:41	2.846	252	19044.8
11:42	2.766	252	18475.3
11:43	2.766	250	18270.4
11:44	2.845	249	18684.3
11:45	2.763	246	17942.2
11:46	2.818	246	18298.7
11:47	2.835	244	18201.0
11:48	2.835	243	18061.5
11:49	2.835	242	17957.0
11:50	2.86	242	18116.1
11:51	2.86	242	18119.0
11:52	2.86	242	18119.0
11:53	2.86	242	18116.1

Table A 2: **BOS slurry flow rates - control heat 18795 (part1)**

Time	Velocity (m/s)	Level (mm)	Flow (l/m)
12:48	2.809	235	17174.9
12:49	2.811	235	17151.9
12:50	2.828	235	17256.9
12:51	2.811	234	17048.8
12:52	2.811	237	17289.5
12:53	2.858	237	17578.5
12:54	2.865	237	17691.5
12:55	2.905	244	18577.5
12:56	2.929	244	18735.1
12:57	2.929	244	18735.1
12:58	2.929	244	18735.1
12:59	2.83	241	17892.8
13:00	2.83	241	17892.8
13:01	2.83	243	18031.9
13:02	2.839	243	18085.2
13:03	2.839	243	18050.3
13:04	2.866	243	18227.8
13:05	2.866	243	18227.8
13:06	2.803	243	17825.5
13:07	2.803	248	18377.8
13:08	2.803	249	18447.0
13:09	2.803	249	18447.0
13:10	2.895	248	18981.6
13:11	2.895	249	19053.0
13:12	2.763	237	17028.7
13:13	2.894	235	17692.5
13:14	2.876	235	17581.6
13:15	2.876	243	18357.6
13:16	2.876	243	18357.6
13:17	2.876	243	18357.6
13:18	2.875	243	18354.7
13:19	2.872	243	18336.9
13:20	2.865	240	17972.6
13:21	2.865	240	17972.6
13:22	2.841	240	17858.7
13:23	2.812	240	17677.4
13:24	2.812	240	17677.4
13:25	2.797	242	17718.3
13:26	2.799	242	17730.1
13:27	2.799	242	17730.1
13:28	2.879	242	18239.8
13:29	2.861	239	17876.1
13:30	2.861	239	17876.1
13:31	2.861	239	17876.1
13:32	2.861	239	17876.1
13:33	2.841	239	17754.1
13:34	2.816	239	17597.1
13:35	2.841	239	17754.1

Table A 3: **BOS slurry flow rates - control heat 18795 (part2)**

Time	Velocity (m/s)	Level (mm)	Flow (l/m)
13:36	2.809	238	17447.3
13:37	2.809	238	17447.3
13:38	2.818	238	17470.5
13:39	2.818	238	17470.5
13:40	2.781	238	17239.9
13:41	2.818	238	17470.5
13:42	2.821	238	17490.7
13:43	2.774	237	17131.5
13:44	2.821	238	17490.7
13:45	2.821	237	17421.6
13:46	2.821	239	17559.9
13:47	2.883	236	17659.5
13:48	2.905	239	18083.8
13:49	2.883	238	17906.7

Table A 4: **BOS slurry flow rates - hold heat 20641**

Time	Velocity (m/s)	Level (mm)	Flow (l/m)
10:32	2.735	243	17424.39
10:33	2.735	242	17357.16
10:34	2.735	240	17189.20
10:35	2.726	240	17069.66
10:36	2.726	239	17036.21
10:37	2.75	239	17116.97
10:38	2.75	239	17116.97
10:39	2.75	239	17116.97
10:40	2.75	239	17184.43
10:41	2.74	238	16988.99
10:42	2.74	240	17190.65
10:43	2.74	237	16921.84
10:44	2.746	240	17228.58
10:45	2.746	237	16959.17
10:46	2.746	238	17026.48
10:47	2.741	237	16924.71
10:48	2.741	237	16891.14
10:49	2.741	236	16824.02
10:50	2.741	236	16824.02
10:51	2.741	235	16689.89
10:52	2.741	235	16689.89
10:53	2.737	235	16700.71
10:54	2.734	235	16714.29
10:55	2.734	235	16680.84
10:56	2.734	235	16714.29
10:57	2.734	235	16714.29
10:58	2.767	248	18105.84
10:59	2.77	249	18226.58
11:00	2.77	249	18226.58
11:01	2.767	249	18174.08
11:02	2.751	249	18070.22
11:03	2.748	251	18252.32
11:04	2.748	251	18252.32
11:05	2.751	253	18511.92

Table A 5: **BOS slurry flow rates - hold heat 20643**

Time	Velocity (m/s)	Level (mm)	Flow (l/m)
11:43	2.74	239	17053.28
11:44	2.742	239	17067.76
11:46	2.765	239	17209.60
11:47	2.734	239	17018.55
11:48	2.765	239	17209.60
11:49	2.714	239	16894.07
11:50	2.753	239	17137.23
11:51	2.753	239	17137.23
11:52	2.753	239	17137.23
11:53	2.745	239	17082.23
11:54	2.753	241	17373.75
11:55	2.747	241	17332.67
11:56	2.745	241	17317.99
11:57	2.747	239	17164.08
11:58	2.747	238	16995.70
11:59	2.747	238	16995.70
12:00	2.748	238	17038.01
12:01	2.748	238	17038.01
12:02	2.749	238	17043.78
12:03	2.749	238	17043.78
12:04	2.749	236	16872.56
12:05	2.735	236	16789.76
12:06	2.739	240	17148.28
12:07	2.739	240	17148.28
12:08	2.749	241	17344.41
12:09	2.793	245	18035.37
12:10	2.793	245	18035.37
12:11	2.793	246	18104.16
12:12	2.778	246	18007.69
12:13	2.778	251	18487.45
12:14	2.778	251	18487.45

Table A 6: **BOS slurry solid contents - control heat 18793**

Sample ID	Sample time	Solids content (mass %)	Liquid volume ml	Solids content (g/L)
C260	11:07	0.36	9524	3.63
C261	11:09	0.15	9863	1.54
C262	11:11	0.15	10801	1.53
C263	11:13	0.81	9576	8.18
C264	11:15	0.53	7249	5.33
C265	11:17	0.11	10187	1.07
C266	11:19	0.30	10009	3.00
C267	11:21	0.49	8349	4.92
C268	11:22	0.16	7643	1.57
C269	11:23	n/a	4954	n/a
C270	11:24	2.56	5968	26.26
C271	11:25	2.87	7189	29.52
C272	11:26	1.98	6531	20.25
C273	11:27	2.26	6883	23.17
C274	11:28	n/a	6319	n/a
C275	11:29	3.25	6491	33.55
C276	11:30	1.80	6830	18.28
C277	11:31	1.95	7180	19.89
C278	11:32	1.61	7449	16.37
C279	11:33	1.54	7051	15.69
C280	11:34	1.28	7643	12.97
C281	11:35	1.16	7727	11.70
C282	11:36	1.26	6984	12.80
C283	11:37	1.40	7233	14.23
C284	11:38	1.15	6249	11.60
C285	11:39	0.90	7943	9.11
C286	11:40	0.65	7461	6.54
C287	11:41	0.27	7538	2.71
C288	11:42	0.33	7295	3.34
C289	11:43	0.35	6964	3.47
C290	11:45	0.50	8105	5.07
C291	11:47	0.32	7460	3.20
C292	11:49	0.12	8011	1.18
C293	11:51	0.36	8596	3.63
C294	11:53	0.13	8166	1.31

Table A 7: **BOS slurry solid contents - control heat 18793**

Sample ID	Sample time	Solids content (mass %)	Liquid volume ml	Solids content (g/L)
C296	12:50	0.04	9565	0.42
C297	12:52	0.04	8726	0.44
C298	12:53	0.20	9174	1.97
C299	12:54	6.95	7601	74.66
C300	12:55	1.63	7477	16.54
C301	12:56	0.11	8429	1.06
C302	12:57	2.77	7487	28.51
C303	12:58	2.29	7676	23.44
C304	12:59	2.29	8224	23.48
C305	13:00	2.12	7871	21.64
C306	13:01	1.86	8138	18.97
C307	13:02	1.84	8735	18.78
C308	13:03	1.97	8248	20.15
C309	13:04	1.49	8375	15.14
C310	13:05	1.43	8358	14.51
C311	13:06	1.04	8442	10.54
C312	13:07	1.07	8230	10.84
C313	13:08	1.09	8487	10.98
C314	13:09	0.59	7121	5.95
C315	13:10	0.77	7416	7.73
C316	13:11	0.65	7313	6.57
C317	13:12	0.79	8280	7.94
C318	13:13	0.38	7522	3.85
C319	13:14	0.02	7717	0.22
C320	13:15	0.37	7209	3.67
C321	13:16	0.20	8551	2.04
C322	13:18	0.64	8667	6.39
C323	13:20	0.93	9511	9.36
C324	13:22	0.05	8348	0.47

Table A 8: **BOS slurry solid contents – hold heat 20641**

Sample ID	Time	Solids content (mass %)	Liquid volume (ml)	Solids content (g/litre)
C343	10:32:00	1.08	9596	10.85
C344	10:35:00	0.27	9545	2.66
C345	10:37:00	0.12	9663	1.24
C346	10:39:00	0.08	10748	0.84
C347	10:41:00	0.10	9944	1.03
C348	10:43:00	0.10	9973	0.95
C349	10:45:00	0.09	9974	0.93
C350	10:47:00	0.08	10103	0.79
C351	10:49:00	0.11	10283	1.05
C352	10:51:00	0.12	10715	1.20
C353	10:53:00	0.11	10078	1.12
C354	10:54:00	0.11	9946	1.11
C355	10:55:00	0.14	9172	1.40
C356	10:56:00	2.32	9030	23.75
C357	10:56:30	2.41	9283	24.64
C358	10:57:00	3.19	8803	32.93
C359	10:58:00	3.79	9217	39.35
C360	10:58:30	3.36	8155	34.65
C361	10:59:00	2.71	8538	27.81
C362	10:59:30	2.48	8267	25.40
C363	11:00:00	2.77	8657	28.41
C364	11:00:30	2.58	8840	26.41
C365	11:01:00	2.22	8565	22.66
C366	11:01:30	2.78	7987	28.53
C367	11:02:00	2.32	8605	23.72
C368	11:03:00	2.44	9222	24.98
C369	11:04:00	1.94	9481	19.75
C370	11:05:00	1.56	9405	15.86
C371	11:06:00	2.27	9060	23.16
C372	11:07:00	1.63	8970	16.51
C373	11:08:00	1.96	8994	19.94
C374	11:09:00	1.57	9203	15.96
C375	11:10:00	1.43	8844	14.48
C376	11:11:00	1.21	9163	12.26
C377	11:12:00	1.28	9449	12.97
C378	11:13:00	1.04	9536	10.53
C379	11:14:00	0.54	9251	5.38
C380	11:15:00	1.10	10221	11.13
C381	11:16:00	0.56	9259	5.65
C382	11:17:00	1.57	9766	15.91
C383	11:18:00	0.21	8980	2.13
C384	11:19:00	0.31	10278	3.13
C385	11:20:00	0.35	9617	3.55
C386	11:21:00	0.31	9664	3.13
C387	11:22:00	2.16	8900	22.04
C388	11:23:00	0.52	9925	5.24
C389	11:24:00	3.58	9751	37.03
C390	11:25:00	2.71	9358	27.85

Table A 9: **BOS slurry solid contents - hold heat 20643**

Sample ID	Time	Solids content (mass %)	Liquid volume (ml)	Solids content (g/litre)
C391	11:43:00	1.49	9770	15.15
C392	11:45:00	0.27	9087	2.75
C393	11:47:00	0.18	9688	1.78
C394	11:49:00	0.09	9723	0.92
C395	11:51:00	0.16	9716	1.65
C396	11:53:00	0.16	9214	1.56
C397	11:55:00	0.11	9535	1.10
C398	11:57:00	0.11	9436	1.12
C399	11:59:00	0.11	8837	1.12
C400	12:01:00	0.11	9653	1.12
C401	12:03:00	0.13	9140	1.29
C402	12:04:00	0.14	8975	1.42
C403	12:05:00	0.10	9539	1.01
C404	12:06:00	0.69	8996	6.95
C405	12:06:30	2.82	8474	28.98
C406	12:07:00	3.20	8930	32.97
C407	12:07:30	2.77	9067	28.42
C408	12:08:00	8.10	8817	88.01
C409	12:08:30	5.56	9648	58.71
C410	12:09:00	4.00	9285	41.55
C411	12:09:30	3.32	9266	34.33
C412	12:10:00	3.12	9662	32.10
C413	12:10:30	2.85	8575	29.25
C414	12:11:00	2.51	9866	25.67
C415	12:11:30	2.47	9443	25.25
C416	12:12:00	2.54	9012	26.03
C417	12:12:30	2.51	9561	25.71
C418	12:13:00	2.33	9654	23.78
C419	12:13:30	2.29	9421	23.38
C420	12:14:00	2.24	9688	22.91
C421	12:15:00	2.10	10270	21.41
C422	12:16:00	1.93	9151	19.63
C423	12:17:00	1.92	9651	19.56
C424	12:18:00	1.61	9587	16.38
C425	12:19:00	1.58	9399	16.01
C426	12:20:00	1.31	9119	13.25
C427	12:21:00	1.19	8817	11.98
C428	12:22:00	0.78	9781	7.88
C429	12:23:00	0.85	9468	8.54
C430	12:24:00	0.44	9288	4.43
C431	12:25:00	0.36	10167	3.61
C432	12:26:00	0.26	9941	2.60
C433	12:27:00	0.25	9502	2.52
C434	12:28:00	0.27	9852	2.70
C435	12:29:00	0.28	10725	2.79

Table A 10: **Dust mass flow - control heat 18793**

Sample ID	Sample time	Solids content (g/L)	Flow (L/m)	Dust mass flow (kg/min)	Cumulative mass of dust (kg)
C260	11:07	3.63	18069.2	65.7	0.0
	11:08	3.63	17718.5	64.4	65.7
C261	11:09	1.54	17718.5	27.2	130.1
	11:10	1.54	17788.6	27.3	157.3
C262	11:11	1.53	17762.5	27.3	184.7
	11:12	1.53	17692.5	27.2	211.9
C263	11:13	8.18	17959.4	146.9	239.1
	11:14	8.18	17719.5	144.9	385.9
C264	11:15	5.33	17684.3	94.2	530.8
	11:16	5.33	17684.3	94.2	625.0
C265	11:17	1.07	17684.3	18.9	719.2
	11:18	1.07	17106.5	18.3	738.1
C266	11:19	3.00	17106.5	51.3	756.4
	11:20	3.00	17238.0	51.7	807.7
C267	11:21	4.92	17599.1	86.6	859.4
C268	11:22	1.57	17459.3	27.3	946.0
C269	11:23	1.57	17639.3	27.6	973.3
C270	11:24	26.26	17674.3	464.1	1000.9
C271	11:25	29.52	17720.9	523.1	1465.0
C272	11:26	20.25	18330.5	371.2	1988.1
C273	11:27	23.17	18810.0	435.8	2359.3
C274	11:28	23.17	18845.8	436.7	2795.1
C275	11:29	33.55	18933.4	635.2	3231.8
C276	11:30	18.28	18953.3	346.5	3867.0
C277	11:31	19.89	18870.7	375.3	4213.4
C278	11:32	16.37	18860.6	308.8	4588.8
C279	11:33	15.69	19002.8	298.1	4897.6
C280	11:34	12.97	19323.2	250.5	5195.7
C281	11:35	11.70	19323.2	226.1	5446.2
C282	11:36	12.80	19501.4	249.6	5672.2
C283	11:37	14.23	19083.1	271.5	5921.8
C284	11:38	11.60	19083.1	221.3	6193.3
C285	11:39	9.11	19080.0	173.8	6414.7
C286	11:40	6.54	19188.7	125.6	6588.5
C287	11:41	2.71	19044.8	51.5	6714.1
C288	11:42	3.34	18475.3	61.6	6765.6
C289	11:43	3.47	18270.4	63.3	6827.2
	11:44	3.47	18684.3	64.7	6890.5
C290	11:45	5.07	17942.2	90.9	6955.3
	11:45	5.07	18298.7	92.7	7046.2
C291	11:47	3.20	18201.0	58.3	7138.9
	11:48	3.20	18061.5	57.9	7197.2
C292	11:49	1.18	17957.0	21.1	7255.0
	11:50	1.18	18116.1	21.3	7276.2
C293	11:51	3.63	18119.0	65.7	7297.5
	11:52	3.63	18119.0	65.7	7363.3
C294	11:53	1.31	18116.1	23.6	7429.0
				Total	7452.6

Table A 11: **Dust mass flow – control heat 18795**

Sample ID	Sample time	Solids content (g/L)	Flow (L/m)	Dust mass flow (kg/min)	Cumulative mass of dust (kg)
C295	12:48	0.60	17174.9	10.2	0.0
	12:49	0.60	17151.9	10.2	10.2
C296	12:50	0.42	17256.9	7.2	20.5
	12:51	0.42	17048.8	7.1	27.6
C297	12:52	0.44	17289.5	7.6	34.7
C298	12:53	1.97	17578.5	34.7	42.3
C299	12:54	74.66	17691.5	1320.8	77.0
C300	12:55	16.54	18577.5	307.2	1397.8
C301	12:56	1.06	18735.1	19.8	1705.0
C302	12:57	28.51	18735.1	534.1	1724.8
C303	12:58	23.44	18735.1	439.1	2258.9
C304	12:59	23.48	17892.8	420.1	2698.0
C305	13:00	21.64	17892.8	387.1	3118.1
C306	13:01	18.97	18031.9	342.1	3505.2
C307	13:02	18.78	18085.2	339.6	3847.3
C308	13:03	20.15	18050.3	363.7	4186.9
C309	13:04	15.14	18227.8	275.9	4550.5
C310	13:05	14.51	18227.8	264.5	4826.4
C311	13:06	10.54	17825.5	187.8	5090.9
C312	13:07	10.84	18377.8	199.3	5278.7
C313	13:08	10.98	18447.0	202.5	5478.0
C314	13:09	5.95	18447.0	109.8	5680.5
C315	13:10	7.73	18981.6	146.7	5790.3
C316	13:11	6.57	19053.0	125.2	5937.0
C317	13:12	7.94	17028.7	135.3	6062.2
C318	13:13	3.85	17692.5	68.2	6197.5
C319	13:14	0.22	17581.6	3.9	6265.7
C320	13:15	3.67	18357.6	67.3	6269.6
C321	13:16	2.04	18357.6	37.4	6336.9
	13:17	2.04	18357.6	37.4	6374.3
C322	13:18	6.39	18354.7	117.4	6411.7
	13:19	6.39	18336.9	117.2	6529.1
C323	13:20	9.36	17972.6	168.2	6646.3
	13:21	9.36	17972.6	168.2	6814.5
C324	13:22	0.47	17858.7	8.3	6982.7
				Total	6991.0

Table A 12: **Dust mass flow - hold heat 20641**

Time	Solids content (g/litre)	Flow volume in sample period (litre)	Dust mass per sample period (kg)	Cumulative dust mass(kg)
10:32:00	10.85	51831	562.3	0.0
10:35:00	2.66	34554	91.9	562.3
10:37:00	1.24	34554	42.8	654.3
10:39:00	0.84	34554	28.9	697.0
10:41:00	1.03	34554	35.4	726.0
10:43:00	0.95	34554	33.0	761.4
10:45:00	0.93	34554	32.3	794.4
10:47:00	0.79	34554	27.4	826.7
10:49:00	1.05	34554	36.3	854.0
10:51:00	1.20	34554	41.4	890.4
10:53:00	1.12	17277	19.3	931.7
10:54:00	1.11	17277	19.2	951.0
10:55:00	1.40	17277	24.2	970.2
10:56:00	23.75	8639	205.2	994.4
10:56:30	24.64	8639	212.9	1199.6
10:57:00	32.93	17277	568.8	1412.4
10:58:00	39.35	8639	339.9	1981.3
10:58:30	34.65	8639	299.4	2321.2
10:59:00	27.81	8639	240.2	2620.6
10:59:30	25.40	8639	219.4	2860.8
11:00:00	28.41	8639	245.4	3080.2
11:00:30	26.41	8639	228.2	3325.6
11:01:00	22.66	8639	195.7	3553.8
11:01:30	28.53	8639	246.5	3749.5
11:02:00	23.72	17277	409.9	3996.0
11:03:00	24.98	17277	431.5	4405.9
11:04:00	19.75	17277	341.3	4837.4
11:05:00	15.86	17277	273.9	5178.7
11:06:00	23.16	17277	400.1	5452.7
11:07:00	16.51	17277	285.2	5852.8
11:08:00	19.94	17277	344.4	6138.0
11:09:00	15.96	17277	275.8	6482.4
11:10:00	14.48	17277	250.1	6758.2
11:11:00	12.26	17277	211.7	7008.3
11:12:00	12.97	17277	224.1	7220.0
11:13:00	10.53	17277	182.0	7444.1
11:14:00	5.38	17277	93.0	7626.1
11:15:00	11.13	17277	192.3	7719.0
11:16:00	5.65	17277	97.6	7911.3
11:17:00	15.91	17277	274.9	8009.0
11:18:00	2.13	17277	36.8	8283.9
11:19:00	3.13	17277	54.1	8320.7
11:20:00	3.55	17277	61.4	8374.8
11:21:00	3.13	17277	54.0	8436.2
11:22:00	22.04	17277	380.8	8490.2
11:23:00	5.24	17277	90.4	8871.0
11:24:00	37.03	17277	639.7	8961.4
11:25:00	27.85	17277	481.1	9601.2
			Total	**10082.3**

Table A 13: **Dust mass flow - hold heat 20643**

Time	Solids content (g/litre)	Flow volume in sample period (litre)	Dust mass per sample period (kg)	Cumulative dust mass(kg)
11:43:00	15.15	34630.0	524.61	0.0
11:45:00	2.75	34630.0	95.12	524.61
11:47:00	1.78	34630.0	61.48	619.73
11:49:00	0.92	34630.0	31.95	681.21
11:51:00	1.65	34630.0	57.03	713.16
11:53:00	1.56	34630.0	54.12	770.19
11:55:00	1.10	34630.0	38.13	824.31
11:57:00	1.12	34630.0	38.90	862.44
11:59:00	1.12	34630.0	38.80	901.35
12:01:00	1.12	34630.0	38.74	940.14
12:03:00	1.29	17315.0	22.36	978.89
12:04:00	1.42	17315.0	24.50	1001.24
12:05:00	1.01	17315.0	17.57	1025.75
12:06:00	6.95	8657.5	60.15	1043.32
12:06:30	28.98	8657.5	250.91	1103.46
12:07:00	32.97	8657.5	285.46	1354.38
12:07:30	28.42	8657.5	246.09	1639.83
12:08:00	88.01	8657.5	761.93	1885.92
12:08:30	58.71	8657.5	508.32	2647.85
12:09:00	41.55	8657.5	359.71	3156.17
12:09:30	34.33	8657.5	297.17	3515.88
12:10:00	32.10	8657.5	277.94	3813.05
12:10:30	29.25	8657.5	253.20	4091.00
12:11:00	25.67	8657.5	222.20	4344.20
12:11:30	25.25	8657.5	218.58	4566.39
12:12:00	26.03	8657.5	225.36	4784.97
12:12:30	25.71	8657.5	222.60	5010.33
12:13:00	23.78	8657.5	205.85	5232.93
12:13:30	23.38	8657.5	202.45	5438.78
12:14:00	22.91	17315.0	396.68	5641.24
12:15:00	21.41	17315.0	370.76	6037.92
12:16:00	19.63	17315.0	339.93	6408.68
12:17:00	19.56	17315.0	338.65	6748.61
12:18:00	16.38	17315.0	283.55	7087.26
12:19:00	16.01	17315.0	277.30	7370.81
12:20:00	13.25	17315.0	229.40	7648.11
12:21:00	11.98	17315.0	207.41	7877.51
12:22:00	7.88	17315.0	136.47	8084.92
12:23:00	8.54	17315.0	147.95	8221.39
12:24:00	4.43	17315.0	76.69	8369.34
12:25:00	3.61	17315.0	62.47	8446.04
12:26:00	2.60	17315.0	45.03	8508.51
12:27:00	2.52	17315.0	43.55	8553.53
12:28:00	2.70	17315.0	46.75	8597.09
12:29:00	2.79	17315.0	48.27	8643.83
Total				8692.11

Mass of zinc in 20t of galvanised scrap

Galvanised scrap is assumed to represent 20 tonnes of the 70 tonne scrap charge. Various zinc coatings exist for different industrial applications. Common hot dip galvanised steel sheets have zinc coatings within the range of 90 – 1200g/m^2, causing zinc levels to get as high as 4%. Zinc content of galvanised scrap is assumed to be 150g/m^2. Assume density of steel to be 7.8 kg/m^3, assume average gauge 1.2mm. Therefore a 1m^2 panel would have a volume of 1200cm^3 and a mass of 9.36kg.Total mass of galvanised panel 9.36+0.15=9.51kg. Zinc mass by percentage = 0.15/9.51=1.58%

Assumed zinc in 20t galvanised scrap charge =316kg.

Zinc atomic weight 65.38, Oxygen 16. 316kg of Zn in vessel will require 77.28 kg oxygen to fully oxidise.

Before purge, vessel at 1000^{0}C will only contain 15.8kg of oxygen.

If all Zn was converted to ZnO total mass is 393.28kg.

Error! Reference source not found. lists the zinc contents of 20tonnes of galvanised scrap for a range of different gauges calculated in a Tata internal report (Hill, Pickin, Butt, & Turner, 1991).

Table A 14: **Average zinc content contained in 20t of galvanised scrap**

Identity	Gauge (mm)	Approx. weight of zinc (kg)
A1	0.61	425
A2	0.35	1828
A3	1.19	88
A4	0.65	1089
Unmarked	0.69	622
Unmarked	2.95	288
B2	1.14	635
B5	0.67	195
B6	1.17	430
C1	1.18	135
C9	1.89	612
C10	0.73	321
D1	0.65	1131
D6	1.98	519
	Average	**594kg**

Therefore the two calculated figures for the zinc content in 20tonnes of galvanised scrap give a range of 316 to 594kg. Data from a scrap sampling study indicated that zinc content of steel scrap can be expected to be in the region of 2.39% (Koros, Hellickson, & Dudek, 1995). This figure converts to 478kg of zinc for the 20t galvanised scrap charge used during the trials, and is within the mentioned range.

Table A 15: **pH of BOS dust slurry water - control heat 18793**

Heat	Sample ID	Time	Gross Weight (kg)	pH
	C260	11:07	9.849	10.03
	C261	11:09	10.168	10.43
	C262	11:11	11.108	10.63
Scrap Charge	C263	11:13	9.944	10.75
	n/a	n/a	n/a	n/a
	C264	11:15	7.578	10.69
	n/a	n/a	n/a	n/a
	C265	11:17	10.488	10.57
Hot metal	C266	11:19	10.329	10.81
Blow	C267	11:21	8.68	10.99
	C268	11:22	7.945	10.46
	C269	11:23	5.244	10.21
	C270	11:24	6.415	12.55
	C271	11:25	7.692	12.5
	C272	11:26	6.954	11.98
	C273	11:27	7.333	10.82
	C274	11:28	6.609	10.04
	C275	11:29	6.999	10.71
	C276	11:30	7.245	10.11
	C277	11:31	7.613	10.04
	C278	11:32	7.861	9.57
	C279	11:33	7.452	9.75
	C280	11:34	8.032	9.42
	C281	11:35	8.108	9.36
	C282	11:36	7.364	9.55
	C283	11:37	7.626	9.75
	C284	11:38	6.612	9.32
	C285	11:39	8.305	9.16
	C286	11:40	7.8	8.52
Tapping	C287	11:41	7.848	9.03
	C288	11:42	7.609	9.58
	C289	11:43	7.278	9.79
	C290	11:45	8.436	10.08
	C291	11:47	7.774	10.95
	C292	11:49	8.31	11.1
Scrap Charge	C293	11:51	8.917	11.04
	n/a	n/a	n/a	n/a
	C294	11:53	8.467	10.79

Table A 16: **pH of BOS dust slurry water control heat 18795**

Heat	Sample ID	Time	Gross Weight (kg)	pH
Scrap Charge	no sample	n/a	n/a	n/a
	no sample	n/a	n/a	n/a
	no sample	n/a	n/a	n/a
	no sample	n/a	n/a	n/a
	no sample	n/a	n/a	n/a
	no sample	n/a	n/a	n/a
Hot metal	C295	12:48	10.163	11.42
Blow	C296	12:50	9.859	11.23
	C297	12:52	9.02	11.21
	C298	12:53	9.482	10.74
	C299	12:54	8.46	12.73
	C300	12:55	7.891	12.61
	C301	12:56	8.728	12.36
	C302	12:57	7.991	11.89
	C303	12:58	8.146	11.27
	C304	12:59	8.707	11.46
	C305	13:00	8.332	11.89
	C306	13:01	8.583	11.77
	C307	13:02	9.189	11.76
	C308	13:03	8.704	11.77
	C309	13:04	8.792	10.99
	C310	13:05	8.77	10.53
	C311	13:06	8.821	10.16
	C312	13:07	8.609	10.02
	C313	13:08	8.87	10.04
	C314	13:09	7.453	9.8
	C315	13:10	7.763	9.58
	C316	13:11	7.651	9.4
	C317	13:12	8.636	9.82
	C318	13:13	7.841	10.35
	C319	13:14	8.009	10.51
Tapping	C320	13:15	7.525	10.52
	C321	13:16	8.858	10.35
	C322	13:18	9.013	10.77
	C323	13:20	9.89	11.4
	C324	13:22	8.642	11.34

Table A 17: **pH of BOS dust slurry water - hold heat 20641**

Pulpit observations	Sample ID	Time	Sample gross weight (kg)	pH
	C343	10:32:00	9968	10.4
	C344	10:35:00	9838	10
Scrap addition	C345	10:37:00	9942	9.5
	C346	10:39:00	11023	9.4
	C347	10:41:00	10221	9.4
	C348	10:43:00	10250	9.9
	C349	10:45:00	10250	9.2
Hot Iron addition	C350	10:47:00	10377	9.3
	C351	10:49:00	10560	9.9
	C352	10:51:00	10994	9.3
Start Blow	C353	10:53:00	10356	9.6
	C354	10:54:00	10224	9.7
	C355	10:55:00	9453	9.6
	C356	10:56:00	9513	9.7
	C357	10:56:30	9780	9.7
	C358	10:57:00	9362	12
	C359	10:58:00	9848	12
	C360	10:58:30	8707	12
	C361	10:59:00	9045	11.8
	C362	10:59:30	8747	11.6
	C363	11:00:00	9172	11.4
	C364	11:00:30	9342	10.9
	C365	11:01:00	9028	10.6
	C366	11:01:30	8485	10.9
	C367	11:02:00	9078	11.3
	C368	11:03:00	9721	10.4
	C369	11:04:00	9936	10.1
	C370	11:05:00	9822	9.8
	C371	11:06:00	9539	9.8
	C372	11:07:00	9387	n/a
	C373	11:08:00	9442	9.6
	C374	11:09:00	9618	9.8
	C375	11:10:00	9241	9.8
	C376	11:11:00	9544	9.7
End Blow	C377	11:12:00	9839	9.7
	C378	11:13:00	9904	9.6
	C379	11:14:00	9569	9.7
	C380	11:15:00	10601	9.8
Start Tapping	C381	11:16:00	9579	10
	C382	11:17:00	10189	10
	C383	11:18:00	9268	9.9
	C384	11:19:00	10576	10.1
	C385	11:20:00	9918	10.2
	C386	11:21:00	9961	10.2
	C387	11:22:00	9365	10.4
	C388	11:23:00	10244	10.2
End Tapping	C389	11:24:00	10379	10.8
	C390	11:25:00	9886	10
	C391	11:43:00	10185	10.1

Table A 18: **pH of BOS dust slurry water - hold heat 20643**

Observations	Sample ID	Time	Gross Weight (kg)	pH
Scrap addition	C392	11:45:00	9380	9.9
	C393	11:47:00	9973	9.8
	C394	11:49:00	9999	9.2
	C395	11:51:00	9999	9.7
	C396	11:53:00	9497	9.3
	C397	11:55:00	9813	9.2
	C398	11:57:00	9714	9.2
Hot Iron addition	C399	11:59:00	9115	9.6
	C400	12:01:00	9931	9.6
Start Blow	C401	12:03:00	9420	9.6
	C402	12:04:00	9256	9.6
	C403	12:05:00	9816	9
	C404	12:06:00	9327	9.8
	C405	12:06:30	8989	9.8
	C406	12:07:00	9493	9.6
	C407	12:07:30	9593	11.7
	C408	12:08:00	9862	12.6
	C409	12:08:30	10482	12.6
	C410	12:09:00	9939	12
	C411	12:09:30	9852	12.1
	C412	12:10:00	10240	11.5
	C413	12:10:30	9095	11.7
	C414	12:11:00	10386	10.9
	C415	12:11:30	9949	10.6
	C416	12:12:00	9515	10.4
	C417	12:12:30	10074	10.3
	C418	12:13:00	10151	10.6
	C419	12:13:30	9909	10.3
	C420	12:14:00	10177	10.3
	C421	12:15:00	10756	10.1
	C422	12:16:00	9599	10.2
	C423	12:17:00	10107	9.7
	C424	12:18:00	10012	9.6
	C425	12:19:00	9818	9.9
	C426	12:20:00	9508	9.8
	C427	12:21:00	9192	9.8
End Blow	C428	12:22:00	10125	9.2
	C429	12:23:00	9817	9.2
	C430	12:24:00	9597	9.1
	C431	12:25:00	10470	9.5
	C432	12:26:00	10233	9.7
Start Tapping	C433	12:27:00	9793	9.6
	C434	12:28:00	10146	n/a
	C435	12:29:00	11020	9.7

Table A 19: **Dust mass cut-off with cumulative zinc content <0.5% - hold trial 20641**

Time	Cumulative dust mass(kg)	Cumulative zinc mass (kg)	Average cumulative zinc content (%)
10:32:00	0.0	0.00	0.00
10:35:00	562.3	0.99	0.18
10:37:00	654.3	1.15	0.18
10:39:00	697.0	1.30	0.19
10:41:00	726.0	1.39	0.19
10:43:00	761.4	1.52	0.20
10:45:00	794.4	1.62	0.20
10:47:00	826.7	1.73	0.21
10:49:00	854.0	1.85	0.22
10:51:00	890.4	1.97	0.22
10:53:00	931.7	2.57	0.28
10:54:00	951.0	4.56	0.48
10:55:00	970.2	6.21	0.64
10:56:00	994.4	8.11	0.82
10:56:30	1199.6	21.18	1.77
10:57:00	1412.4	37.05	2.62
10:58:00	1981.3	57.08	2.88
10:58:30	2321.2	70.66	3.04
10:59:00	2620.6	78.74	3.00
10:59:30	2860.8	89.29	3.12
11:00:00	3080.2	102.32	3.32
11:00:30	3325.6	114.84	3.45
11:01:00	3553.8	127.47	3.59
11:01:30	3749.5	139.37	3.72
11:02:00	3996.0	152.05	3.81
11:03:00	4405.9	175.43	3.98
11:04:00	4837.4	194.71	4.03
11:05:00	5178.7	200.50	3.87
11:06:00	5452.7	206.37	3.78
11:07:00	5852.8	211.56	3.61
11:08:00	6138.0	214.89	3.50
11:09:00	6482.4	219.16	3.38
11:10:00	6758.2	222.64	3.29
11:11:00	7008.3	225.18	3.21
11:12:00	7220.0	226.98	3.14
11:13:00	7444.1	227.90	3.06
11:14:00	7626.1	228.63	3.00
11:15:00	7719.0	229.23	2.97
11:16:00	7911.3	230.56	2.91
11:17:00	8009.0	231.27	2.89
11:18:00	8283.9	232.17	2.80
11:19:00	8320.7	232.51	2.79
11:20:00	8374.8	232.81	2.78
11:21:00	8436.2	233.06	2.76
11:22:00	8490.2	233.27	2.75
11:23:00	8871.0	233.98	2.64
11:24:00	8961.4	234.34	2.62
11:25:00	9601.2	235.50	2.45
Total	**10082.3**	**236.24**	**2.34**

Time	Cumulative dust mass (kg)	Cumulative zinc mass (kg)	Average cumulative zinc content (%)
11:25:00	0.00	0.00	0.00
11:24:00	481.14	0.74	0.15
11:23:00	1120.85	1.90	0.17
11:22:00	1211.30	2.26	0.19
11:21:00	1592.13	2.96	0.19
11:20:00	1646.13	3.18	0.19
11:19:00	1707.52	3.43	0.20
11:18:00	1761.63	3.73	0.21
11:17:00	1798.41	4.07	0.23
11:16:00	2073.32	4.97	0.24
11:15:00	2170.95	5.68	0.26
11:14:00	2363.27	7.01	0.30
11:13:00	2456.22	7.61	0.31
11:12:00	2638.18	8.34	0.32
11:11:00	2862.26	9.26	0.32
11:10:00	3074.00	11.06	0.36
11:09:00	3324.11	13.60	0.41
11:08:00	3599.90	17.08	0.47
11:07:00	3944.33	21.35	0.54
11:06:00	4229.52	24.68	0.58
11:05:00	4629.64	29.87	0.65
11:04:00	4903.58	35.74	0.73
11:03:00	5244.89	41.53	0.79
11:02:00	5676.41	60.81	1.07
11:01:30	6086.28	84.19	1.38
11:01:00	6332.77	96.87	1.53
11:00:30	6528.50	108.77	1.67
11:00:00	6756.68	121.40	1.80
10:59:30	7002.07	133.92	1.91
10:59:00	7221.51	146.95	2.03
10:58:30	7461.73	157.50	2.11
10:58:00	7761.09	165.58	2.13
10:57:00	8101.01	179.16	2.21
10:56:30	8669.85	199.19	2.30
10:56:00	8882.74	215.06	2.42
10:55:00	9087.92	228.13	2.51
10:54:00	9112.10	230.03	2.52
10:53:00	9131.26	231.68	2.54
10:51:00	9150.55	233.67	2.55
10:49:00	9191.92	234.27	2.55
10:47:00	9228.25	234.39	2.54
10:45:00	9255.61	234.51	2.53
10:43:00	9287.90	234.62	2.53
10:41:00	9320.88	234.72	2.52
10:39:00	9356.32	234.85	2.51
10:37:00	9385.26	234.94	2.50
10:35:00	9428.03	235.09	2.49
10:32:00	9519.97	235.25	2.47
Total	**10082.30**	**236.24**	**2.34**

Table A 20: **Dust mass cut-off with cumulative zinc content <0.5% - hold trial 20643**

Time	Cumulative dust mass(kg)	Zinc kg in Cumulative dust mass	Zinc % in Cumulative dust mass
11:43:00	0.0	0.00	0.00
11:45:00	524.6	0.68	0.13
11:47:00	619.7	0.89	0.14
11:49:00	681.2	1.13	0.17
11:51:00	713.2	1.26	0.18
11:53:00	770.2	1.43	0.19
11:55:00	824.3	1.58	0.19
11:57:00	862.4	1.69	0.20
11:59:00	901.3	1.81	0.20
12:01:00	940.1	1.94	0.21
12:03:00	978.9	2.05	0.21
12:04:00	1001.2	2.25	0.22
12:05:00	1025.7	2.51	0.24
12:06:00	1043.3	3.09	0.30
12:06:30	1103.5	4.93	0.45
12:07:00	1354.4	12.05	0.89
12:07:30	1639.8	19.68	1.20
12:08:00	1885.9	29.92	1.59
12:08:30	2647.8	36.86	1.39
12:09:00	3156.2	44.50	1.41
12:09:30	3515.9	55.36	1.57
12:10:00	3813.1	63.80	1.67
12:10:30	4091.0	75.20	1.84
12:11:00	4344.2	84.84	1.95
12:11:30	4566.4	93.45	2.05
12:12:00	4785.0	103.34	2.16
12:12:30	5010.3	113.83	2.27
12:13:00	5232.9	121.46	2.32
12:13:30	5438.8	129.35	2.38
12:14:00	5641.2	136.52	2.42
12:15:00	6037.9	148.53	2.46
12:16:00	6408.7	158.36	2.47
12:17:00	6748.6	170.07	2.52
12:18:00	7087.3	180.30	2.54
12:19:00	7370.8	188.04	2.55
12:20:00	7648.1	193.73	2.53
12:21:00	7877.5	198.01	2.51
12:22:00	8084.9	200.81	2.48
12:23:00	8221.4	202.67	2.47
12:24:00	8369.3	203.74	2.43
12:25:00	8446.0	204.53	2.42
12:26:00	8508.5	205.16	2.41
12:27:00	8553.5	205.51	2.40
12:28:00	8597.1	205.96	2.40
12:29:00	8643.8	206.17	2.39
Total	**8692.1**	**206.37**	**2.37**

Time	Cumulative dust mass (kg)	Cumulative zinc mass (kg)	Average cumulative zinc content (%)
12:29:00	0.00	0.00	0.00
12:28:00	48.27	0.20	0.42
12:27:00	95.02	0.41	0.43
12:26:00	138.57	0.86	0.62
12:25:00	183.60	1.21	0.66
12:24:00	246.07	1.84	0.75
12:23:00	322.77	2.63	0.81
12:22:00	470.71	3.70	0.79
12:21:00	607.18	5.56	0.91
12:20:00	814.60	8.36	1.03
12:19:00	1044.00	12.64	1.21
12:18:00	1321.30	18.33	1.39
12:17:00	1604.84	26.07	1.62
12:16:00	1943.50	36.30	1.87
12:15:00	2283.43	48.01	2.10
12:14:00	2654.19	57.84	2.18
12:13:30	3050.87	69.84	2.29
12:13:00	3253.33	77.02	2.37
12:12:30	3459.17	84.91	2.45
12:12:00	3681.78	92.54	2.51
12:11:30	3907.14	103.03	2.64
12:11:00	4125.72	112.92	2.74
12:10:30	4347.91	121.53	2.80
12:10:00	4601.11	131.17	2.85
12:09:30	4879.05	142.57	2.92
12:09:00	5176.22	151.00	2.92
12:08:30	5535.93	161.87	2.92
12:08:00	6044.26	169.51	2.80
12:07:30	6806.19	176.45	2.59
12:07:00	7052.27	186.69	2.65
12:06:30	7337.73	194.32	2.65
12:06:00	7588.64	201.44	2.65
12:05:00	7648.79	203.27	2.66
12:04:00	7666.36	203.86	2.66
12:03:00	7690.86	204.12	2.65
12:01:00	7713.22	204.32	2.65
11:59:00	7751.96	204.42	2.64
11:57:00	7790.76	204.55	2.63
11:55:00	7829.66	204.67	2.61
11:53:00	7867.80	204.78	2.60
11:51:00	7921.92	204.94	2.59
11:49:00	7978.95	205.11	2.57
11:47:00	8010.89	205.24	2.56
11:45:00	8072.37	205.47	2.55
11:43:00	8167.50	205.69	2.52
Total	**8692.11**	**206.37**	**2.37**

Table A 21: **Dust mass cut-off with cumulative zinc content <1% - hold trial 20641**

Time	Cumulative dust mass(kg)	Cumulative zinc mass (kg)	Average cumulative zinc content (%)
10:32:00	0.0	0.00	0.00
10:35:00	562.3	0.99	0.18
10:37:00	654.3	1.15	0.18
10:39:00	697.0	1.30	0.19
10:41:00	726.0	1.39	0.19
10:43:00	761.4	1.52	0.20
10:45:00	794.4	1.62	0.20
10:47:00	826.7	1.73	0.21
10:49:00	854.0	1.85	0.22
10:51:00	890.4	1.97	0.22
10:53:00	931.7	2.57	0.28
10:54:00	951.0	4.56	0.48
10:55:00	970.2	6.21	0.64
10:56:00	994.4	8.11	0.82
10:56:30	1199.6	21.18	1.77
10:57:00	1412.4	37.05	2.62
10:58:00	1981.3	57.08	2.88
10:58:30	2321.2	70.66	3.04
10:59:00	2620.6	78.74	3.00
10:59:30	2860.8	89.29	3.12
11:00:00	3080.2	102.32	3.32
11:00:30	3325.6	114.84	3.45
11:01:00	3553.8	127.47	3.59
11:01:30	3749.5	139.37	3.72
11:02:00	3996.0	152.05	3.81
11:03:00	4405.9	175.43	3.98
11:04:00	4837.4	194.71	4.03
11:05:00	5178.7	200.50	3.87
11:06:00	5452.7	206.37	3.78
11:07:00	5852.8	211.56	3.61
11:08:00	6138.0	214.89	3.50
11:09:00	6482.4	219.16	3.38
11:10:00	6758.2	222.64	3.29
11:11:00	7008.3	225.18	3.21
11:12:00	7220.0	226.98	3.14
11:13:00	7444.1	227.90	3.06
11:14:00	7626.1	228.63	3.00
11:15:00	7719.0	229.23	2.97
11:16:00	7911.3	230.56	2.91
11:17:00	8009.0	231.27	2.89
11:18:00	8283.9	232.17	2.80
11:19:00	8320.7	232.51	2.79
11:20:00	8374.8	232.81	2.78
11:21:00	8436.2	233.06	2.76
11:22:00	8490.2	233.27	2.75
11:23:00	8871.0	233.98	2.64
11:24:00	8961.4	234.34	2.62
11:25:00	9601.2	235.50	2.45
Total	**10082.3**	**236.24**	**2.34**

Time	Cumulative dust mass (kg)	Cumulative zinc mass (kg)	Average cumulative zinc content (%)
11:25:00	0.00	0.00	0.00
11:24:00	481.14	0.74	0.15
11:23:00	1120.85	1.90	0.17
11:22:00	1211.30	2.26	0.19
11:21:00	1592.13	2.96	0.19
11:20:00	1646.13	3.18	0.19
11:19:00	1707.52	3.43	0.20
11:18:00	1761.63	3.73	0.21
11:17:00	1798.41	4.07	0.23
11:16:00	2073.32	4.97	0.24
11:15:00	2170.95	5.68	0.26
11:14:00	2363.27	7.01	0.30
11:13:00	2456.22	7.61	0.31
11:12:00	2638.18	8.34	0.32
11:11:00	2862.26	9.26	0.32
11:10:00	3074.00	11.06	0.36
11:09:00	3324.11	13.60	0.41
11:08:00	3599.90	17.08	0.47
11:07:00	3944.33	21.35	0.54
11:06:00	4229.52	24.68	0.58
11:05:00	4629.64	29.87	0.65
11:04:00	4903.58	35.74	0.73
11:03:00	5244.89	41.53	0.79
11:02:00	5676.41	60.81	1.07
11:01:30	6086.28	84.19	1.38
11:01:00	6332.77	96.87	1.53
11:00:30	6528.50	108.77	1.67
11:00:00	6756.68	121.40	1.80
10:59:30	7002.07	133.92	1.91
10:59:00	7221.51	146.95	2.03
10:58:30	7461.73	157.50	2.11
10:58:00	7761.09	165.58	2.13
10:57:00	8101.01	179.16	2.21
10:56:30	8669.85	199.19	2.30
10:56:00	8882.74	215.06	2.42
10:55:00	9087.92	228.13	2.51
10:54:00	9112.10	230.03	2.52
10:53:00	9131.26	231.68	2.54
10:51:00	9150.55	233.67	2.55
10:49:00	9191.92	234.27	2.55
10:47:00	9228.25	234.39	2.54
10:45:00	9255.61	234.51	2.53
10:43:00	9287.90	234.62	2.53
10:41:00	9320.88	234.72	2.52
10:39:00	9356.32	234.85	2.51
10:37:00	9385.26	234.94	2.50
10:35:00	9428.03	235.09	2.49
10:32:00	9519.97	235.25	2.47
Total	**10082.30**	**236.24**	**2.34**

Table A 22: **Dust mass cut-off with cumulative zinc content <1% - hold trial 20643**

Time	Cumulative dust mass(kg)	Zinc kg in Cumulative dust mass	Zinc % in Cumulative dust mass
11:43:00	0.0	0.00	0.00
11:45:00	524.6	0.68	0.13
11:47:00	619.7	0.89	0.14
11:49:00	681.2	1.13	0.17
11:51:00	713.2	1.26	0.18
11:53:00	770.2	1.43	0.19
11:55:00	824.3	1.58	0.19
11:57:00	862.4	1.69	0.20
11:59:00	901.3	1.81	0.20
12:01:00	940.1	1.94	0.21
12:03:00	978.9	2.05	0.21
12:04:00	1001.2	2.25	0.22
12:05:00	1025.7	2.51	0.24
12:06:00	1043.3	3.09	0.30
12:06:30	1103.5	4.93	0.45
12:07:00	1354.4	12.05	0.89
12:07:30	1639.8	19.68	1.20
12:08:00	1885.9	29.92	1.59
12:08:30	2647.8	36.86	1.39
12:09:00	3156.2	44.50	1.41
12:09:30	3515.9	55.36	1.57
12:10:00	3813.1	63.80	1.67
12:10:30	4091.0	75.20	1.84
12:11:00	4344.2	84.84	1.95
12:11:30	4566.4	93.45	2.05
12:12:00	4785.0	103.34	2.16
12:12:30	5010.3	113.83	2.27
12:13:00	5232.9	121.46	2.32
12:13:30	5438.8	129.35	2.38
12:14:00	5641.2	136.52	2.42
12:15:00	6037.9	148.53	2.46
12:16:00	6408.7	158.36	2.47
12:17:00	6748.6	170.07	2.52
12:18:00	7087.3	180.30	2.54
12:19:00	7370.8	188.04	2.55
12:20:00	7648.1	193.73	2.53
12:21:00	7877.5	198.01	2.51
12:22:00	8084.9	200.81	2.48
12:23:00	8221.4	202.67	2.47
12:24:00	8369.3	203.74	2.43
12:25:00	8446.0	204.53	2.42
12:26:00	8508.5	205.16	2.41
12:27:00	8553.5	205.51	2.40
12:28:00	8597.1	205.96	2.40
12:29:00	8643.8	206.17	2.39
Total	8692.1	206.37	2.37

Time	Cumulative dust mass (kg)	Cumulative zinc mass (kg)	Average cumulative zinc content (%)
12:29:00	0.00	0.00	0.00
12:28:00	48.27	0.20	0.42
12:27:00	95.02	0.41	0.43
12:26:00	138.57	0.86	0.62
12:25:00	183.60	1.21	0.66
12:24:00	246.07	1.84	0.75
12:23:00	322.77	2.63	0.81
12:22:00	470.71	3.70	0.79
12:21:00	607.18	5.56	0.91
12:20:00	814.60	8.36	1.03
12:19:00	1044.00	12.64	1.21
12:18:00	1321.30	18.33	1.39
12:17:00	1604.84	26.07	1.62
12:16:00	1943.50	36.30	1.87
12:15:00	2283.43	48.01	2.10
12:14:00	2654.19	57.84	2.18
12:13:30	3050.87	69.84	2.29
12:13:00	3253.33	77.02	2.37
12:12:30	3459.17	84.91	2.45
12:12:00	3681.78	92.54	2.51
12:11:30	3907.14	103.03	2.64
12:11:00	4125.72	112.92	2.74
12:10:30	4347.91	121.53	2.80
12:10:00	4601.11	131.17	2.85
12:09:30	4879.05	142.57	2.92
12:09:00	5176.22	151.00	2.92
12:08:30	5535.93	161.87	2.92
12:08:00	6044.26	169.51	2.80
12:07:30	6806.19	176.45	2.59
12:07:00	7052.27	186.69	2.65
12:06:30	7337.73	194.32	2.65
12:06:00	7588.64	201.44	2.65
12:05:00	7648.79	203.27	2.66
12:04:00	7666.36	203.86	2.66
12:03:00	7690.86	204.12	2.65
12:01:00	7713.22	204.32	2.65
11:59:00	7751.96	204.42	2.64
11:57:00	7790.76	204.55	2.63
11:55:00	7829.66	204.67	2.61
11:53:00	7867.80	204.78	2.60
11:51:00	7921.92	204.94	2.59
11:49:00	7978.95	205.11	2.57
11:47:00	8010.89	205.24	2.56
11:45:00	8072.37	205.47	2.55
11:43:00	8167.50	205.69	2.52
Total	8692.11	206.37	2.37

Table A 23: **Recoverable dust mass calculated from measured zinc concentration**

HOLD TRIAL HEAT 20641			
Sample ID	**Time**	**Dust mass per sample period (kg)**	**Zinc %**
C343	10:32:00	562.32	0.18
C344	10:35:00	91.95	0.17
C345	10:37:00	42.77	0.34
C346	10:39:00	28.93	0.33
C347	10:41:00	35.44	0.36
C348	10:43:00	32.98	0.30
C349	10:45:00	32.29	0.36
C350	10:47:00	27.36	0.43
C351	10:49:00	36.32	0.34
C352	10:51:00	41.37	1.44
C353	10:53:00	19.29	10.34
C354	10:54:00	19.16	8.59
C355	10:55:00	24.19	7.85
C356	10:56:00	205.18	6.37
C357	10:56:30	212.89	7.46
C358	10:57:00	568.85	3.52
C359	10:58:00	339.92	4.00
C360	10:58:30	299.36	2.70
C361	10:59:00	240.21	4.39
C362	10:59:30	219.44	5.94
C363	11:00:00	245.39	5.10
C364	11:00:30	228.18	5.54
C365	11:01:00	195.73	6.08
C366	11:01:30	246.49	5.15
C367	11:02:00	409.88	5.70
C368	11:03:00	431.52	4.47
C369	11:04:00	341.30	1.70
C370	11:05:00	273.94	2.14
C371	11:06:00	400.11	1.30
C372	11:07:00	285.19	1.17
C373	11:08:00	344.43	1.24
C374	11:09:00	275.79	1.26
C375	11:10:00	250.11	1.02
C376	11:11:00	211.74	0.85
C377	11:12:00	224.08	0.41
C378	11:13:00	181.96	0.40
C379	11:14:00	92.95	0.64
C380	11:15:00	192.32	0.69
C381	11:16:00	97.63	0.72
C382	11:17:00	274.91	0.33
C383	11:18:00	36.79	0.93
C384	11:19:00	54.11	0.54
C385	11:20:00	61.39	0.41
C386	11:21:00	53.99	0.40
C387	11:22:00	380.84	0.18
C388	11:23:00	90.45	0.41
C389	11:24:00	639.71	0.18
C390	11:25:00	481.14	0.15
Mass <0.5% Zn =		3278.84	

HOLD TRIAL HEAT 20643			
Sample ID	**Time**	**Dust mass per sample period (kg)**	**Zinc %**
C391	11:43:00	524.61	0.13
C392	11:45:00	95.12	0.23
C393	11:47:00	61.48	0.38
C394	11:49:00	31.95	0.42
C395	11:51:00	57.03	0.30
C396	11:53:00	54.12	0.28
C397	11:55:00	38.13	0.29
C398	11:57:00	38.90	0.31
C399	11:59:00	38.80	0.34
C400	12:01:00	38.74	0.27
C401	12:03:00	22.36	0.91
C402	12:04:00	24.50	1.06
C403	12:05:00	17.57	3.31
C404	12:06:00	60.15	3.05
C405	12:06:30	250.91	2.84
C406	12:07:00	285.46	2.67
C407	12:07:30	246.09	4.16
C408	12:08:00	761.93	0.91
C409	12:08:30	508.32	1.50
C410	12:09:00	359.71	3.02
C411	12:09:30	297.17	2.84
C412	12:10:00	277.94	4.10
C413	12:10:30	253.20	3.81
C414	12:11:00	222.20	3.88
C415	12:11:30	218.58	4.52
C416	12:12:00	225.36	4.65
C417	12:12:30	222.60	3.43
C418	12:13:00	205.85	3.83
C419	12:13:30	202.45	3.54
C420	12:14:00	396.68	3.03
C421	12:15:00	370.76	2.65
C422	12:16:00	339.93	3.45
C423	12:17:00	338.65	3.02
C424	12:18:00	283.55	2.73
C425	12:19:00	277.30	2.05
C426	12:20:00	229.40	1.86
C427	12:21:00	207.41	1.35
C428	12:22:00	136.47	1.36
C429	12:23:00	147.95	0.72
C430	12:24:00	76.69	1.03
C431	12:25:00	62.47	1.02
C432	12:26:00	45.03	0.77
C433	12:27:00	43.55	1.03
C434	12:28:00	46.75	0.45
C435	12:29:00	48.27	0.42
Mass <0.5% Zn =		1073.91	

Table A 24: **Particle size distribution of control trial heat 18793**

Sample ID	Sample time	Mean particle size diameter (v,0.1)	Mean particle size diameter (v,0.5)	Mean particle size diameter (v,0.9)
C264	11.15	41.12	410.63	566.56
C267	11:21	290.58	446.19	566.19
C270	11:24	0.95	4.11	20.06
C271	11:25	0.68	3.86	24.28
C272	11:26	0.58	1.19	36.05
C273	11:27	0.61	1.56	22.01
C274	11:28	0.54	0.84	15.85
C275	11:29	0.58	1.27	27.92
C276	11:30	0.58	1.24	12.77
C277	11:31	0.64	2.87	21.97
C278	11:32	0.6	1.58	11.07
C279	11:33	0.63	1.83	15.09
C280	11:34	0.69	3.79	18.06
C281	11:35	0.94	3.22	18.47
C282	11:36	0.79	2.95	20.92
C283	11:37	0.75	3.13	28.06
C284	11:38	0.64	2.57	20.23
C285	11:39	0.63	2.41	20.89
C286	11:40	0.61	2.38	84.10
C288	11:42	0.74	7.76	43.28
C289	11:43	0.73	25.05	234.59
C290	11:45	0.78	26.59	276.78
C291	11:47	0.92	11.59	279.15
C293	11:51	0.7	7.58	198.52
C294	11:53	0.66	4.07	27.94

Table A 25: **BOS dust slurry water analysis - hold heat 20641**

Sample ID	Time	Zn (mg/L)	Ca (mg/L)	Total Zn mass (kg)	Total Ca mass (kg)
C343	10:32:00	0.0	4.1	0.0	0.1
C344	10:35:00	n/a	4.6	0.0	0.1
C345	10:37:00	0.0	5.2	0.0	0.1
C346	10:39:00	n/a	4.9	0.0	0.1
C347	10:41:00	0.0	5.1	0.0	0.1
C348	10:43:00	n/a	5.1	0.0	0.1
C349	10:45:00	0.0	6.1	0.0	0.1
C350	10:47:00	0.0	5.4	0.0	0.1
C351	10:49:00	0.0	5.0	0.0	0.1
C352	10:51:00	0.0	7.2	0.0	0.1
C353	10:53:00	0.1	7.2	0.0	0.1
C354	10:54:00	0.0	6.9	0.0	0.1
C355	10:55:00	0.0	7.8	0.0	0.1
C356	10:56:00	0.0	11.1	0.0	0.2
C357	10:56:30	0.0	7.3	0.0	0.1
C358	10:57:00	1.4	474.6	0.0	8.2
C359	10:58:00	4.2	324.7	0.1	5.6
C360	10:58:30	0.0	3.2	0.0	0.1
C361	10:59:00	0.0	1.9	0.0	0.0
C362	10:59:30	0.0	0.9	0.0	0.0
C363	11:00:00	0.0	2.7	0.0	0.0
C364	11:00:30	0.0	2.6	0.0	0.0
C365	11:01:00	0.0	2.8	0.0	0.0
C366	11:01:30	0.0	2.9	0.0	0.0
C367	11:02:00	0.2	4.1	0.0	0.1
C368	11:03:00	0.0	1.9	0.0	0.0
C369	11:04:00	0.0	2.4	0.0	0.0
C370	11:05:00	n/a	3.6	0.0	0.1
C371	11:06:00	n/a	n/a	0.0	0.0
C372	11:07:00	0.0	3.6	0.0	0.1
C373	11:08:00	n/a	3.0	0.0	0.1
C374	11:09:00	0.0	3.5	0.0	0.1
C375	11:10:00	n/a	3.8	0.0	0.1
C376	11:11:00	0.0	3.9	0.0	0.1
C377	11:12:00	n/a	n/a	0.0	0.0
C378	11:13:00	0.0	4.0	0.0	0.1
C379	11:14:00	n/a	n/a	0.0	0.0
C380	11:15:00	0.0	2.2	0.0	0.0
C381	11:16:00	n/a	7.6	0.0	0.1
C382	11:17:00	0.1	6.4	0.0	0.1
C383	11:18:00	n/a	n/a	0.0	0.0
C384	11:19:00	0.0	5.2	0.0	0.1
C385	11:20:00	n/a	5.6	0.0	0.1
C386	11:21:00	0.0	4.7	0.0	0.1
C387	11:22:00	n/a	4.6	0.0	0.1
C388	11:23:00	0.0	6.2	0.0	0.1
C389	11:24:00	n/a	4.6	0.0	0.1
C390	11:25:00	0.0	5.4	0.0	0.1

Table A 26: **BOS dust slurry water analysis hold heat 20643**

Sample ID	Time	Zn (mg/L)	Ca (mg/L)	Total Zn mass (kg)	Total Ca mass (kg)
C391	11:43:00	n/a	6.3	0.0	0.1
C392	11:45:00	0.0	4.7	0.0	0.1
C393	11:47:00	n/a	5.3	0.0	0.1
C394	11:49:00	0.0	5.4	0.0	0.1
C395	11:51:00	n/a	6.1	0.0	0.1
C396	11:53:00	0.0	5.4	0.0	0.1
C397	11:55:00	n/a	5.7	0.0	0.1
C398	11:57:00	0.0	5.5	0.0	0.1
C399	11:59:00	n/a	5.5	0.0	0.1
C400	12:01:00	0.0	6.1	0.0	0.1
C401	12:03:00	0.0	8.2	0.0	0.1
C402	12:04:00	0.0	8.6	0.0	0.1
C403	12:05:00	0.1	9.2	0.0	0.2
C404	12:06:00	0.0	12.4	0.0	0.2
C405	12:06:30	0.0	6.5	0.0	0.1
C406	12:07:00	0.0	11.5	0.0	0.2
C407	12:07:30	0.0	1.4	0.0	0.0
C408	12:08:00	2.4	699.4	0.0	12.1
C409	12:08:30	4.6	670.8	0.1	11.6
C410	12:09:00	4.1	394.4	0.1	6.8
C411	12:09:30	0.1	4.7	0.0	0.1
C412	12:10:00	0.0	6.7	0.0	0.1
C413	12:10:30	0.0	1.4	0.0	0.0
C414	12:11:00	0.0	3.3	0.0	0.1
C415	12:11:30	0.0	3.1	0.0	0.1
C416	12:12:00	0.0	2.7	0.0	0.0
C417	12:12:30	0.0	2.3	0.0	0.0
C418	12:13:00	0.0	2.5	0.0	0.0
C419	12:13:30	0.0	2.3	0.0	0.0
C420	12:14:00	0.0	n/a	0.0	0.0
C421	12:15:00	n/a	2.0	0.0	0.0
C422	12:16:00	0.0	2.6	0.0	0.0
C423	12:17:00	n/a	2.2	0.0	0.0
C424	12:18:00	0.0	2.7	0.0	0.0
C425	12:19:00	n/a	3.2	0.0	0.1
C426	12:20:00	n/a	n/a	0.0	0.0
C427	12:21:00	0.0	4.6	0.0	0.1
C428	12:22:00	n/a	5.1	0.0	0.1
C429	12:23:00	0.0	6.2	0.0	0.1
C430	12:24:00	0.0	6.6	0.0	0.1
C431	12:25:00	n/a	n/a	0.0	0.0
C432	12:26:00	n/a	3.5	0.0	0.1
C433	12:27:00	n/a	4.1	0.0	0.1
C434	12:28:00	0.0	7.7	0.0	0.1
C435	12:29:00	0.0	6.7	0.0	0.1

Table A 27: **BOS dust slurry flow rates – heat 32502**

Time	Velocity (m/s)	Level (mm)	Flow (L/m)
11:49	3.166	213	16940.0
11:50	3.166	213	16864.1
11:51	3.228	213	17271.0
11:52	3.166	215	17092.2
11:53	3.127	213	16656.0
11:54	3.127	214	16806.1
11:55	3.228	214	17348.5
11:56	3.127	213	16731.0
11:57	3.121	213	16661.2
11:58	3.18	213	16974.0
11:59	3.18	213	16974.0
12:00	3.121	212	16586.4
12:01	3.132	212	16640.7
12:02	3.18	212	16897.8
12:03	3.215	211	17008.5
12:04	3.132	211	16565.7
12:05	3.132	213	16753.4
12:06	3.221	213	17192.5
12:07	3.201	213	17126.7
12:08	3.163	213	16922.6
12:09	3.164	213	16889.6
12:10	3.201	213	17085.8
12:11	3.201	213	17085.8
12:12	3.164	212	16775.8
12:13	3.201	211	16932.3
12:14	3.243	211	17156.2
12:15	3.243	210	17039.7
12:16	3.246	210	17056.8
12:17	3.246	211	17173.4
12:18	3.245	212	17243.8
12:19	3.245	213	17321.6
12:20	3.245	213	17360.6
12:21	3.245	214	17438.5
12:22	3.238	214	17398.5
12:23	3.238	214	17398.5
12:24	3.235	214	17383.5
12:25	3.235	214	17383.5
12:26	3.232	214	17366.0
12:27	3.144	217	17196.1
12:28	3.144	217	17196.1
12:29	3.117	217	17051.1
12:30	3.117	216	16976.0
12:31	3.144	216	17120.4
12:32	3.159	216	17166.0
12:33	3.221	216	17502.1
12:34	3.237	216	17629.5
12:35	3.221	216	17502.1
12:36	3.214	216	17464.2
12:37	3.214	215	17348.3
12:38	3.214	213	17116.7
12:39	3.208	213	17084.5
12:40	3.214	213	17116.7
12:41	3.208	211	16969.2
12:42	3.232	212	17174.6
12:43	3.208	212	17046.1
12:44	3.232	212	17174.6
12:45	3.205	213	17149.1
12:46	3.205	215	17341.6
12:47	3.192	215	17271.1

Table A 28: **BOS dust slurry flow rates – heat 32504**

Time	Velocity (m/s)	Level (mm)	Flow (L/m)
12:48	3.145	215	17017.0
12:49	3.145	213	16828.1
12:50	3.145	214	16941.4
12:51	3.162	213	16917.6
12:52	3.207	213	17082.0
12:53	3.207	213	17082.0
12:54	3.162	212	16803.8
12:55	3.14	212	16687.7
12:56	3.14	213	16725.3
12:57	3.14	213	16725.3
12:58	3.259	214	17471.8
12:59	3.259	214	17471.8
13:00	3.259	214	17471.8
13:01	3.242	214	17384.6
13:02	3.196	212	16943.5
13:03	3.19	211	16873.2
13:04	3.19	212	16911.4
13:05	3.19	212	16911.4
13:06	3.165	213	16897.1
13:07	3.202	213	17090.7
13:08	3.202	214	17167.6
13:09	3.202	215	17360.0
13:10	3.167	215	17173.4
13:11	3.202	215	17360.0
13:12	3.212	215	17412.9
13:13	3.261	215	17601.8
13:14	3.261	215	17601.8
13:15	3.265	215	17626.9
13:16	3.297	215	17795.1
13:17	3.297	213	17597.2
13:18	3.209	213	17128.0
13:19	3.209	213	17128.0
13:20	3.209	213	17128.0
13:21	3.209	215	17320.6
13:22	3.25	216	17697.9
13:23	3.25	216	17737.0
13:24	3.25	216	17737.0
13:25	3.185	216	17381.6
13:26	3.185	217	17420.0
13:27	3.109	217	17005.3
13:28	3.185	217	17420.0
13:29	3.219	217	17608.3
13:30	3.219	217	17608.3
13:31	3.159	214	16935.7
13:32	3.159	214	16973.6
13:33	3.159	214	16973.6
13:34	3.151	214	16895.8
13:35	3.134	214	16843.6
13:36	3.118	214	16756.1
13:37	3.134	215	16956.6
13:38	3.134	215	16956.6
13:39	3.195	215	17322.1
13:40	3.195	215	17322.1
13:41	3.251	216	17663.9
13:42	3.251	216	17663.9
13:43	3.251	216	17663.9
13:44	3.251	215	17546.6
13:45	3.251	216	17663.9
13:46	3.251	214	17429.4

Table A 29: **BOS dust slurry flow rates – heat 32504**

Time	Velocity (m/s)	Level (mm)	Flow (L/m)
13:47	3.21	214	17212.5
13:48	3.198	214	17183.5
13:49	3.199	214	17188.5
13:50	3.21	214	17212.5
13:51	3.21	214	17251.0
13:52	3.199	213	17111.7
13:53	3.199	213	17111.7
13:54	3.192	213	17079.4
13:55	3.192	213	17079.4
13:56	3.192	213	17079.4
13:57	3.168	211	16757.6
13:58	3.228	211	17077.4
13:59	3.228	213	17271.0
14:00	3.216	213	17206.3
14:01	3.163	213	16920.1
14:02	3.216	213	17206.3
14:03	3.165	215	17087.1
14:04	3.162	215	17067.1
14:05	3.165	215	17163.3
14:06	3.27	215	17730.7
14:07	3.165	215	17163.3
14:08	3.267	214	17597.7
14:09	3.267	214	17597.7
14:10	3.257	213	17422.8
14:11	3.234	213	17303.3
14:12	3.238	213	17323.2
14:13	3.238	217	17790.6
14:14	3.234	217	17731.2
14:15	3.238	217	17751.6
14:16	3.238	217	17751.6
14:17	3.252	215	17551.6
14:18	3.227	215	17421.1
14:19	3.227	214	17382.3
14:20	3.192	214	17191.9
14:21	3.227	215	17498.7
14:22	3.227	215	17498.7
14:23	3.192	215	17307.0
14:24	3.192	215	17307.0
14:25	3.178	215	17228.8
14:26	3.178	217	17458.4
14:27	3.14	214	16876.1
14:28	3.178	216	17343.6
14:29	3.178	216	17343.6
14:30	3.188	215	17207.7
14:31	3.188	214	17131.1
14:32	3.188	214	17131.1
14:33	3.112	214	16686.3
14:34	3.138	214	16863.6
14:35	3.112	214	16686.3
14:36	3.112	214	16686.3
14:37	3.138	215	16939.0
14:38	3.14	215	16949.1
14:39	3.185	214	17116.1
14:40	3.185	214	17116.1

Table A 30: **BOS slurry solid contents – heat 32502**

Sample ID	Sample time	Solids Content (mass %)	Liquid volume (ml) @ 20^{o}C	Solids content (g/litre)
C482	11.56:30	2.3	9105	23.1
C483	11.57	2.1	8803	21.7
C484	11.59	1.7	7737	17.5
C485	12.01	0.1	8024	1.3
C486	12.03	0.0	8673	0.1
C487	12.05	0.0	8504	0.3
C488	12.07	0.0	8685	0.5
C489	12.09	0.1	8061	0.5
C490	12.11	0.0	7701	0.4
C491	12.12	0.1	9412	0.7
C492	12.13	1.9	9065	19.2
C493	12.14	6.5	7958	69.0
C494	12.15	3.8	9559	39.5
C495	12.16	4.0	8857	41.9
C496	12.17	3.1	8888	31.5
C497	12.18	2.9	9174	29.6
C498	12.19	2.5	9105	25.1
C499	12.20	2.4	9130	24.8
C500	12.21	1.5	8714	15.5
C501	12.22	2.4	8247	24.6
C502	12.23	4.5	8338	46.9
C503	12.25	2.1	8916	21.2
C504	12.27	1.8	8527	18.8
C505	12.29	1.2	8371	12.6
C506	12.31	2.4	8699	24.7
C507	12.33	1.2	9193	11.8
C508	12.35	7.4	8002	80.2
C509	12.37	1.0	9292	10.3
C510	12.39	0.6	8695	5.8
C511	12.41	0.3	8675	3.0
C512	12.43	0.3	9550	3.3

Table A 31: **BOS slurry solid contents – heat 32504**

Sample ID	Sample time	Solids Content (mass %)	Liquid volume (ml) @ 20°C	Solids content (g/litre)
C513	12.53	0.2	7786	2.3
C514	12.56	0.2	9576	2.2
C515	12.59	0.2	8630	2.1
C516	13.05	0.2	8370	1.8
C517	13.07	0.1	9210	0.8
C518	13.09	2.3	9067	23.7
C519	13.10	3.3	8710	33.8
C520	13.11	2.4	9352	24.5
C521	13.12	2.9	9383	29.8
C522	13.13	2.2	9242	22.0
C523	13.14	3.9	8771	40.1
C524	13.15	1.7	8809	17.3
C525	13.16	4.3	9326	45.3
C526	13.17	2.7	8844	27.8
C527	13.18	2.4	9401	24.8
C528	13.19	3.3	8456	33.9
C529	13.20	3.3	9408	34.1
C530	13.21	3.3	8883	33.7
C531	13.22	4.1	8195	42.5
C532	13.24	1.9	8467	19.8
C533	13.26	4.8	8426	50.0
C534	13.28	5.7	8686	60.3
C535	13.30	1.2	9947	11.6
C536	13.32	9.6	8456	105.9
C537	13.34	9.7	9126	107.2
C538	13.36	8.5	7948	92.6
C539	13.38	8.1	7839	88.3
C540	13.40	2.1	8782	21.8
C541	13.42	6.1	7852	65.5
C542	13.44	2.2	9025	22.6
C543	13.46	0.7	7660	7.3

Table A 32: **BOS slurry solid contents – heat 32504**

Sample ID	Sample time	Solids Content (mass %)	Liquid volume (ml) @ 20oC	Solids content (g/litre)
C544	13.48	0.5	8399	4.8
C545	13.53	0.6	7959	5.7
C546	13.58	1.8	9043	18.5
C547	13.59	6.7	8331	71.5
C548	14.00	3.6	7969	37.3
C549	14.01	2.7	8513	27.5
C550	14.02	1.5	8626	14.8
C551	14.03	0.1	87730	1.0
C552	14.04	0.5	9034	5.4
C553	14.05	1.2	8937	12.1
C554	14.06	0.1	7780	1.0
C555	14.07	0.9	8136	8.6
C556	14.08	1.7	7946	16.9
C557	14.09	1.9	8916	18.9
C558	14.10	4.4	9432	46.5
C559	14.11	2.8	9169	28.4
C560	14.12	2.3	9477	23.0
C561	14.13	2.0	9313	20.1
C562	14.14	2.7	9381	27.6
C563	14.15	1.7	8703	17.7
C564	14.16	1.8	8098	18.6
C565	14.17	1.0	8217	10.2
C566	14.19	1.3	8253	12.8
C567	14.21	3.3	9150	33.7
C568	14.23	2.5	8831	25.9
C569	14.25	2.4	9630	24.7
C570	14.27	1.2	8740	12.6
C571	14.29	0.5	7265	4.6
C572	14.31	1.5	8389	15.1
C573	14.35	3.5	8371	36.6

Table A 33: **ICP data for heat 32502**

Time relative to blow start (mins)	Zn (%)	Fe (%)	Ca (%)
-16.0	0.0	79.5	1.4
-15.0	0.0	83.8	0.8
-13.0	0.0	84.3	0.8
-11.0	0.1	71.8	3.8
-9.0	0.3	62.5	6.1
-7.0	0.2	67.7	4.8
-5.0	0.2	65.2	5.8
-3.0	0.2	70.6	4.7
-1.0	0.3	59.8	6.3
0.0	1.1	55.9	7.7
1.0	0.9	67.8	0.5
2.0	0.4	32.2	26.7
3.0	0.5	48.7	14.5
4.0	0.4	73.6	5.7
5.0	0.5	77.1	3.4
6.0	0.2	82.1	3.0
7.0	0.2	78.1	4.8
8.0	0.2	72.9	6.4
9.0	0.2	68.7	7.2
10.0	0.1	80.9	10.9
11.0	0.1	87.6	4.0
13.0	0.1	86.4	4.7
15.0	0.1	77.3	3.1
17.0	0.2	84.7	4.9
19.0	0.1	92.0	4.1
23.0	0.0	96.0	3.2
25.0	0.1	99.1	1.8
27.0	0.1	96.0	2.5
29.0	0.2	86.6	5.4
31.0	0.1	88.4	4.7

Table A 34: **ICP data for heat 32504**

Time relative to blow start (mins)	Zn (%)	Fe (%)	Ca (%)
-14.0	0.1	81.1	2.9
-11.0	0.1	76.2	3.1
-8.0	0.1	82.4	2.4
-2.0	0.2	70.4	3.8
0.0	0.3	68.4	4.1
2.0	0.5	72.7	0.9
3.0	0.6	47.3	14.4
4.0	0.5	65.3	6.2
5.0	0.5	73.0	3.9
6.0	0.5	68.7	4.1
7.0	0.2	74.9	4.9
8.0	0.4	64.4	9.7
9.0	0.2	66.9	6.3
10.0	0.1	73.2	5.4
11.0	0.1	75.1	5.1
12.0	0.1	80.7	3.9
13.0	0.1	83.5	3.0
14.0	0.0	83.6	2.6
15.0	0.0	83.6	2.4
17.0	0.1	81.8	3.7
19.0	0.1	82.0	4.4
21.0	0.0	88.3	2.7
23.0	0.1	79.3	3.1
27.0	0.0	96.0	0.9
29.0	0.0	88.2	1.0
31.0	0.0	92.2	1.3
33.0	0.0	84.6	1.8
35.0	0.0	93.9	0.9
37.0	0.0	93.7	1.0

Table A 35: **ICP data for heat 32505**

Time relative to blow start (mins)	Zn (%)	Fe (%)	Ca (%)
-8.0	0.1	86.8	1.8
-3.0	0.1	89.1	1.5
2.0	0.4	78.1	0.7
3.0	0.1	47.3	17.1
4.0	0.3	34.5	27.2
5.0	0.5	54.2	16.9
6.0	0.6	67.1	11.0
7.0	0.7	69.8	11.2
8.0	0.6	65.0	12.1
9.0	0.2	74.0	7.5
10.0	0.7	47.2	15.2
11.0	0.2	71.8	10.5
12.0	0.5	69.7	4.2
13.0	0.5	75.7	2.0
14.0	0.3	82.7	2.9
15.0	0.2	79.6	3.8
16.0	0.2	70.0	6.2
17.0	0.2	63.7	8.4
18.0	0.2	79.1	4.8
19.0	0.2	77.2	4.1
20.0	0.2	74.8	6.5
21.0	0.2	71.2	4.9
23.0	0.2	69.6	6.4
25.0	0.1	72.2	8.3
29.0	0.1	80.1	7.5
31.0	0.1	83.9	5.4
33.0	0.1	68.3	9.2
35.0	0.0	90.0	3.8
39.0	0.0	98.3	1.6