# THE DEVELOPMENT OF AN 'EMISSION INVENTORY TOOL' FOR BRICKMAKING CLAMP KILNS

BY

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# THE DEVELOPMENT OF AN 'EMISSION INVENTORY TOOL' FOR BRICKMAKING CLAMP KILNS

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# THE DEVELOPMENT OF AN 'EMISSION INVENTORY TOOL' FOR BRICKMAKING CLAMP KILNS

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## SYNOPSIS

An emission inventory tool for estimating $SO_2$, $NO_2$, and $PM_{10}$ emissions from brick clamp kiln sites was developed from investigations performed on three representative South African clamp kiln sites in order to facilitate application for Atmospheric Emission Licenses (AELs) from these sources. The tool utilizes readily available site-specific parameters to generate emission factors for significant activities that emit the aforementioned pollutants. $PM_{10}$ emission factors for significant processes were developed using empirical expressions from the Compilation of Air Pollutant Emission Factors (AP-42) documents.

$SO_2$ emission factor for clamp kiln firing was obtained from "reverse-modelling", a technique that integrates ambient monitoring and dispersion modelling (using Atmospheric Dispersion Modelling System software) to "standardize" actual emission rate from an assumed rate of 1 g/s. The use of multiple point sources proved to improve the simulation of the buoyancy-induced plume rise; therefore, a "bi-point" source configuration was adopted for the kiln. The "reverse-modelling" technique and "bi-point" source configuration produced $SO_2$ emission rates differing from -9 % to +22 % from mass balance results, indicating that the "reverse-modelling" calculations provide reliable emission estimates for $SO_2$.

An $NO_2$ emission factor could not be obtained from the "reverse-modelling" technique due to experimental errors and the significant effect of $NO_2$ emissions from other onsite air emission sources such as internal combustion engines. The $NO_2$ emission factor was obtained from previous comprehensive study on a similar clamp kiln site.

The emission factors obtained from this study were utilized in developing an "emission inventory tool" which is utilized by clay brick manufacturers in quantifying air emissions from their sites. Emissions quantification is a requirement for brick manufacturers to obtain an AEL which is regulated under South African environmental laws.

It is suggested that the technique used here for $SO_2$ emission confirmation could be used to estimate emissions from a volume or area source where combustion occurs and where knowledge of the source parameters is limited.

**KEYWORDS**: clamp kiln, atmospheric dispersion modelling, emission inventory, emission factor, reverse modelling, bi-point source, $PM_{10}$, $SO_2$, $NO_2$.

# DEDICATION

"All I am, and ever hope to be, I owe to God, to my parents, and to mentors".

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| | |
|---|---|
| ADMS | Atmospheric Dispersion Modelling System |
| AEL | Atmospheric Emission License |
| AP | Air pollution |
| BCME | British Columbia Ministry of Environment, Canada |
| BIA | Bricks Industry Association, Virginia USA |
| BTEX | Benzene, Toluene, Ethylbenzene, and Xylene |
| CBA | Clay Brick Association, South Africa |
| CERC | Cambridge Environmental Research Consultants, Cambridge UK |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| $CO_x$ | Oxides of Carbon |
| CTTB | Centre Techiques des tuiles et briques, France |
| DEA | Department of Environmental Affairs, South Africa |
| DEAT | Department of Environmental Affairs and Tourism, South Africa |
| EEA | European Economic Area |
| EMEP | European Monitoring and Evaluation Programme |
| FCBTK | Fixed Chimney Bull's Trench Kiln |
| FTHETA0 | Sensible Surface Heat Flux |
| GATE | German Appropriate Technology Exchange |
| $H_2S$ | Hydrogen Sulfide |
| HAP | Hazardous Air Pollutants |
| HCB | Hexachlorobenzene |
| HF | Hydrogen Fluoride |
| ISC3 | Industrial Source Complex 3 |
| JRC | Joint Research Commission |
| NEM-AQA | National Environmental Management: Air Quality Act, South Africa |
| NFP | Non-facing plaster |
| NGDC | National Geophysical Data Center, USA |
| NO2 | Nitrogen dioxide |
| NOAA | National Oceanic and Atmospheric Administration, USA |
| NOx | Oxides of Nitrogen |

| | |
|---|---|
| NPI | National pollutant Inventory, Australia |
| NWFP | North-West Frontier Province, India |
| O3 | Ozone |
| PCB | Polychlorinated biphenyl |
| PCDD/F | Polychlorierte Dibenzo-p-dioxine and Dibenzofurane |
| PHI | Wind direction (degrees) |
| PM | Particulate Matter |
| PM10 | Particulate Matter less than or equal to 10 microns in aerodynamic diameter |
| PM2.5 | Particulate Matter less than or equal to 2.5 microns in aerodynamic diameter |
| POPs | Persistent Organic Pollutants |
| SO2 | Sulphur dioxide |
| SO3 | Sulphur trioxide |
| T0C | Temperature (degree Celcius) |
| TOC | Total Organic Compounds |
| TVA | Transverse Arch Kiln |
| U | Wind speed (m/s) |
| USEPA | United States Environmental Protection Agency |
| VOC | Volatile Organic Compounds |
| VKT | Vehicle Kilometres travelled |

# 1 INTRODUCTION

## 1.1 BACKGROUND AND PROBLEM STATEMENT

This thesis reports the outcome of a research work on the development of a tool that can be used to calculate sulphur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), and “particulate matter less than or equal to 10 microns in aerodynamic diameter” ($PM_{10}$) emissions from brick clamp kilns based on easily measured operational parameters. These parameters are enumerated in Section 1.2.

Clamp kiln firing is associated with the emission of pollutants such as $SO_2$, $NO_2$, and $PM_{10}$ into the environment and thereby increasing their ambient concentration near the source (USEPA, 1997; DEA, 2012). The localised effect on the immediate environment is as a result of a relatively cool plume released into a “stable surface layer” where dispersion or mixing is limited, especially at night and in winter (DEA, 2012; Irm, 2011). As a result, “clamp kiln for brick production” in South Africa was listed as one of the activities (listed activity no. 5.3) that pose negative environmental effects as well as adverse health, social, economic and ecological impact, and therefore require regulation of their emissions (DEAT, 2008; Airshed Planning Professionals, 2002).

DEAT (2008) identifies sulphur dioxide ($SO_2$) and dust fall ($PM_{10}$) as emissions to be controlled by clamp kiln emitters and stipulates minimum standards and methods by which emissions monitoring must be carried out.

This directive poses a problem for clamp kiln operators due to the following:

- Unavailability of emission rate and pollutants emission factors for clamp kilns (Umlauf *et al,* 2011);
- Inadequate scientific techniques for estimating emission factors from clamp kilns using atmospheric dispersion models (Cardenas *et al,* 2009);
- Unavailability of data required for calculating emissions factors such as emission rate, emission velocity etc. (Cardenas *et al,* 2009; Umlauf *et al,* 2011);

- High cost of site monitoring and the cumbersome nature of data collection required to estimate emissions (Umlauf *et al,* 2011); and
- Lack of emission control on clamp kilns, for all pollutant emissions (DEA, 2012).

## 1.2 OBJECTIVE, METHOD AND SCOPE OF STUDY

The primary objective of the study is to provide an acceptable tool for estimating $SO_2$, $NO_2$ and $PM_{10}$ emissions from clamp kiln sites without the need for a comprehensive monitoring on individual sites. This is made possible by the provision of emission factors for all activities on a clamp kiln site that generate $SO_2$, $NO_2$ and $PM_{10}$ emissions.

This tool utilizes easily measured operational parameters such as size and capacity of kiln, properties of fuel used (sulphur content, moisture content and specific energy), moisture content of clay, particle size of road dust, site meteorology, as well as site related activities and processes involving movement and processing of materials.

Furthermore, the study was carried out to test a novel technique for estimating emission factors and emission rates from clamp kilns. The new technique utilises ambient monitoring and atmospheric dispersion modelling of results to calibrate emission factors for clamp kilns. The emission factors from the new technique will be compared with a standard material balance method for validation and then incorporated into the emissions inventory tool.

The study further aims to enable clamp kiln operators to:

- Use readily available site data to estimate their sites' daily, monthly and annual $SO_2$, $NO_2$ and $PM_{10}$ emissions;
- Apply or re-apply for an Atmospheric Emission License (AEL) as required under section 22 of the National Environmental Management: Air Quality Act (NEM: AQA) No 39 of 2004 of South Africa; and
- Compare their emissions with an industry baseline.

In addition, a comprehensive emissions inventory for the clamp kiln sector of brick manufacturing can be facilitated by this tool. This will provide a clearer perspective and better understanding of the appropriate control mechanisms and preventive measures required for clamp kiln production. Consequently, clay brick production can be made more efficient in terms of energy use and air pollution mitigation.

## 1.3 LIMITATIONS AND ASSUMPTIONS

It is important to note the following limitations and assumptions on which the study was based:

- Information on source specific characteristics (e.g. moisture content) was not available for all the sources. Use was made of data published by the US EPA emission estimation documents.
- Emission factors were used to estimate all fugitive and process emissions resulting from plant, transport and firing activities. These emission factors generally assume average operating conditions.
- Errors cannot be absolutely eliminated in a geophysical model. A model represents the most likely outcome of a collection of experimental results. Uncertainties may be due to errors in the data set, errors in the model physics or errors due to stochastic processes (atmospheric turbulence).
- It is assumed that all the energy in the coal is used up in firing the kiln. This might not always be the case because brick firing is not a fully controlled process.
- In the configuration of the brick kiln as a “bi-point” source, it is assumed that the kiln emits flue gas only from the surface. Emission from the sides of the kiln was accounted for, by configuring the surface of the “bi-point” source to be equivalent to the dimensions of the base of the kiln. However, the “bi-point” source is assumed to be situated at the top level of the actual kiln.

## 1.4 STRUCTURE OF THESIS

The following chapters are presented in this thesis:

- **Chapter 1 – Introduction:** This chapter provides background information to the study and gives the problem statement, purpose, method and scope of the study.

- **Chapter 2 – Literature:** This chapter provides a detailed historical background of clay bricks, a review of clamp kiln firing, processes involved and their associated emissions.

- **Chapter 3 – Methodology:** This chapter describes the experimental procedure and apparatus utilized in ambient and meteorological monitoring.

- **Chapter 4 - Atmospheric Dispersion Modelling:** This chapter describes the concept of atmospheric dispersion modelling utilized in this study, the technique of “reverse-modelling” as well as configuration of a clamp kiln source as two point sources.

- **Chapter 5 - Results and Discussion:** This chapter provides the results for monitoring, analysis, modelling and the “reverse-modelling” technique involved in the research. Discussion is presented with each result for clarity purpose.

- **Chapter 6 - Conclusions and Recommendations:** In this chapter, findings are inferred from the results and the discussions provided in the previous chapter. Recommendations are offered for further research on clamp kiln firing.

# 2 LITERATURE

## 2.1 HISTORICAL OVERVIEW OF CLAY BRICKS PRODUCTION

Brick is one of the earliest and simplest forms of building materials known to man and has gained popularity over the years (CBA, 2002; 2005). The mud brick was reportedly used as far back as 10000 BC, the moulded brick evolved in Mesopotamia at about 5000 BC while the fired brick was invented around 3500 BC (Campbell *et al,* 2003; Weaver, 1997; Handisyde *et al,* 1976 and CBA, 2005).

Brick making started as a simple method of mixing sub-soil materials with water and additives (straws, sticks or manure) followed by sun drying (El-Gohary *et al,* 2003; Kornmann *et al,* 2007). This product, otherwise known as adobe, houses a significant portion of the world population according to Sumanov (1990) and Kornmann *et al,* (2007).

The popularity of the clay brick is occasioned by its versatility or ability to be readily sculpted into various shapes and sizes; its flexibility in construction and design, as well as its cost effectiveness (Warren, 1999; CBA, 2002 and 2005). According to Kornmann *et al,* (2007) and Handisyde *et al,* (1976), these characteristics enable clay bricks to be efficiently utilised for facings, partitions and structural walls, roof tiles, pavements, chimneys, rustic floor tiles and decorative elements, etc.

NWFP Environmental Protection Agency (2004) describes primitive brick making as an energy intensive process that depends mainly on manual labour for most of its activities. Obeng *et al,* (2001); Schilderman (1999) and Hammond (1990) identified saw dust, firewood, boiler waste, briquette, palm kernel shell, residual oil, electricity, coal, fly ash etc. as fuels that have been used in the brick firing process. Majzoub (1999) also investigated the utilization of cow dung in brick making as body or internal fuel and concluded that cow dung, when compared to other common organic supplements, alters brick quality, improves plasticity, decreases cracking or breakage and increases the water absorption potential of the bricks.

Technological advancement motivated ancient Romans to begin utilization of fired bricks in building their greatest structures due to a discovery of the bricks' resilience as well as the afore-mentioned qualities (Campbell *et al,* 2003; Weaver, 1997).

Clay brick firing and manufacturing became effectively mechanized in the twentieth century with the evolution of computers, robots and machinery for winning, crushing, shaping, extruding and handling of clay, as well as significant advances in automation and kiln technology for brick firing (CBA, 2002; 2005; Kornmann *et al,* 2007 and El-Gohary *et al,* 2009).

CBA (2005) reports the introduction of fired bricks in South Africa in the Cape with the arrival of the Dutch in 1652. Hartdegen (1988) narrates that brick making experiments were carried out by digging up clay soil and watering it to form paste. The paste is made even by driving a team of horses over it. The even paste is moulded by hand into rough bricks and then sun dried in readiness for firing.

Hartdegen (1988) further relates that the first set of clay bricks in South Africa, (about 60 000 bricks), was fired on the 12th of May 1654. Mass production of fired bricks was underway by 1655 with about 650,000 bricks fired in the Cape in two ovens. The technique for production at this stage was subject to trial and error and was met with difficulties as enumerated by Hartdegen (1988), viz., inadequate sources of fuel (timber wood), high porosity and brittleness of the fired bricks.

According to the CBA (2005), the proliferation of fired bricks for building and construction activities in South Africa occurred in the 18th and 19th century. This widespread acceptance brought about its use in monumental buildings in Cape Town, Stellenbosch and other parts of the country.

In recent times, clay brick manufacturing has become highly mechanized and regulated with a high rate of processing and production (CBA, 2002; 2005). In South Africa, extrusion rates of bricks may be as high as 25,000 bricks per hour per machine. The bricks weigh between 3,0 kg and 3,5 kg with a conventional size of 222 x 106 x 73 mm (CBA, 2002; Williams, 2008).

Williams (2008) further claimed that more bricks were made and laid in the twentieth century than in all previous centuries combined. Campbell *et al,* (2003) and Williams (2008) also maintained that the clay bricks remain one of the most important construction materials in the world today, even though the advent of modern day construction materials like steel, glass and concrete may have instigated a general perception of its reduced application and acceptance.

This claim is supported by CBA (2005) with an assertion that "South Africa is essentially built on bricks", as well as a projection of annual clay brick production of 3,5 billion in South Africa. In similar fashion, the United States Census Bureau (2013) allocates about 60% (3,3 billion bricks) of the total bricks produced in the United States in 2008 to clay bricks. Kornmann *et al,* (2007) also estimates the total global production of clay bricks at 3 billion tonnes, nearly double the global cement production of 1.7 billion tonnes. These facts accentuate the significance of the clay brick in building and construction in modern times.

## 2.2 METEOROLOGY AND AIR POLLUTION

Meteorology studies and predicts weather changes that occur from large-scale atmospheric circulation (Cooper *et al,* 2002). The study of changes in atmospheric properties assists in the understanding of how air pollutants are dispersed and transported.

The basic properties of the atmosphere – wind, pressure, moisture and energy content – determine the weather or climatic conditions over a period of time (Peavy *et al,* 1985). The interaction of these four elements causes variation in seasons as well as diurnal and spatial changes which can be observed on different levels or "scales of motion" (Peavy *et al,* 1985; Burger *et al,* 2008). Scales of motion are related to the mass movement of air in the atmosphere having a global, regional or local span of influence (Peavy *et al,* 1985).

Therefore, the study of atmospheric motion and dynamic system at the macroscale, mesoscale and microscale levels assists in the understanding of how pollutants are dispersed, transformed and consequently eliminated from the atmosphere (Peavy *et al,* 1985; Tiwary *et al,* 2010 and Burger *et al,* 2008).

Air pollutants emitted by pollutant sources are distributed in a plume in the atmosphere and are removed by meteorological mechanisms that disperse and transform them due to mechanical and thermal turbulence within the earth's boundary layer (Burger *et al,* 2008; Tiwary *et al,* 2010 and Cooper *et al,* 2002).

Tiwary *et al,* (2010) and Cooper *et al,* (2002) identify three local meteorological conditions as major factors that affect dispersion of air pollutants:

- Wind direction;
- Wind speed; and
- Atmospheric turbulence (closely associated with the concept of stability).

Wind direction is conventionally referred to as the direction from which the wind is blowing and is expressed in degrees (Tiwary *et al,* 2010).

The wind speed is measured in m $s^{-1}$. It is the source of mechanical turbulence and it affects the dilution of pollution in proportion to the speed and surface roughness of the environment (Tiwary *et al,* 2010; Burger *et al,* 2008 and Cooper *et al,* 2002). The wind speed also determines the final height to which a buoyant plume will rise. A high wind speed, for instance, will induce a lateral dispersion closer to the source height than a lower wind speed (Tiwary *et al,* 2010; Peavy *et al,* 1985).

Atmospheric turbulence is a function of the energy content of an air "parcel" (Tiwary *et al,* 2010; Harrison, 2001). The energy content varies with the atmospheric pressure and the vertical temperature profile of the air parcel. Air parcels in lower layers of the atmosphere receive energy from solar radiation heating the earth surface and rise continuously by buoyant forces (Harrison, 2001; Tiwary *et al,* 2010). Consequently, air pollutants can be dispersed in the atmosphere based on the motion of the air parcel into which it is "captured".

Cooper *et al,* (2002); Harrison (2001) and Tiwary *et al,* (2010) further explain the calm or night condition where the earth surface cools off and causes the adjacent air to cool down rapidly. The air temperature therefore increases with height under these conditions. As a consequence, dispersion of air pollutants is minimal due to low buoyant forces that are available to drive the vertical motion of air parcels. Hence, during a calm or night condition, dispersion of air pollutants is localised and the concentration of pollutants is increased locally (Irm, 2011).

## 2.3 AIR POLLUTION FROM BRICK INDUSTRY

### 2.3.1 OVERVIEW

Air pollution from clamp kiln sites arise from various brick making activities such as mining, crushing, blending, firing etc. The various activities involved in brick making are reviewed in this section, with respect to their emissions. Reference is made to South African and international texts in order to accentuate the similarities as well as the differences in the processes involved.

### 2.3.2 BRICK MAKING PROCESSES AND ASSOCIATED EMISSIONS

#### *2.3.2.1 MINING*

Raw materials used for brick making are obtained from sub-soil materials such as clay, shale, soft shale, calcium silicate etc. (Punmia *et al,* 2003). These sub-soil materials are mined in open pits with moisture content ranging from a minimum of 3 % at one site to a peak of about 15 % at another site (USEPA, 1995b). This requires heavy earth-moving machinery such as bulldozers, mechanical shovels, scrapers, loaders and trucks for moving materials (CBA, 2002). Clay materials are stored in heaps after extraction for a period of time to allow weathering and for moisture to permeate the body (USEPA, 1995b; CBA, 2005).

According to EMEP/EEA (2009) and USEPA (1997b), significant emissions from the mining and storage of clay materials include “particulate matter (PM), PM less than or equal to 10 microns in aerodynamic diameter ($PM_{10}$) and PM less than or equal to 2.5 microns in aerodynamic diameter ($PM_{2.5}$)."

### *2.3.2.2 CRUSHING AND BLENDING*

The weathered clay materials are transported by truck or conveyor and are crushed or broken down into workable lumps in order to ease blending (CBA, 2002; 2005). The clay materials are fed into the plant by conveyor or hopper for initial or **primary crushing**. In South Africa, hammer mills are used and the clay materials are broken down to about 3-5 mm (CBA, 2002).

CBA (2005) and Kornmann *et al,* (2007) report that a typical plant operates by means of box-feeders, which release a pre-determined quantity of clay and other additives for proper blending.

USEPA (1997b) and EMEP/EEA (2009) identify significant emissions from crushing of clay materials as "particulate matter (PM), PM less than or equal to 10 microns in aerodynamic diameter ($PM_{10}$) and PM less than or equal to 2.5 microns in aerodynamic diameter ($PM_{2.5}$)."

### *2.3.2.3 GRINDING AND SCREENING*

In the grinding or **secondary crushing** stage, the clay material is further crushed down by means of refining rolls or grinding mills such as dry pan grinders, roller mills, and hammer mills (USEPA, 1997b). According to NPI (1998), the four principal processes for preparation of bricks prior to firing are extrusion, stiff mud, soft mud, and dry press methods.

These methods are described by USEPA (1997b); CBA (2002); BIA, (2006); CBA (2005); and NPI (1998), and are briefly discussed below.

- **The stiff mud process**: In this method, water is added to the clay material and then blended to give the material plasticity before it is forced through a ceramic or steel die.

- **The soft mud process:** This process is often used when the extrusion method cannot be applied to very wet clay material (USEPA, 2003a; BIA, 2006). The wet clay is blended with the addition of water in a mill, with moisture content rising to about 15 – 28 %. The clay material is then shaped into moulds and dried. This method is rarely used in South Africa on an industrial scale (CBA, 2002).

- **The dry press method:** In this process, the clay is blended using a small amount of water and a pressure of about 500 to 1,500 pounds per square inch (3,43 to 10,28 MPa) is applied to shape the clay in steel moulds (USEPA, 1997b; 2003a).

- **The Extrusion process:** This process is said to be the common method in South Africa and the dominant process in the industry (CBA, 2002; NPI, 1998). The process involves adding water to the clay material to increase moisture content to about 18 – 25% (CBA, 2002) or 14 – 18% (USEPA, 1997b) and blending the mixture in a mill to form a plastic mass. The plastic mass is discharged into a vacuum chamber where vacuum pumps extract air from the clay in order to strengthen the clay. USEPA (1997b) and (2003a) reveal that some facilities may add additives such as barium carbonate. The additive prevents sulfates from rising to the surface of the brick with the clay material before the clay is extruded. The resulting mixture is extruded or shaped by forcing it through a die.

  According to USEPA (1997b), the extrusion process can be lubricated with lubricants such as oil, while the clay can be given surface treatment by the addition of manganese dioxide, iron oxide, and iron chromite in order to change the colour or texture of the brick product.

  The extruded plastic mass is cut into individual bricks by a means of a wire-cutting machine and can be mechanically textured or patterned. The machine may give each brick between 3 – 12 perforations which increase the brick's surface area and consequently reduce cooling, firing and drying times. It also relieves the bricks of internal stress and reduces deformation during firing (CBA, 2002; 2005).

USEPA (1997b) and EMEP/EEA (2009) identify significant emissions from secondary crushing and grinding of clay materials as including "particulate matter (PM), PM less than or equal to 10 microns in aerodynamic diameter ($PM_{10}$) and PM less than or equal to 2.5 microns in aerodynamic diameter ($PM_{2.5}$)."

#### 2.3.2.3.1 AGEING OR SOURING

Kornmann *et al,* (2007) describes ageing as a process of storing clay after preparation in order to harmonize the moisture, improve the uniformity of the composition and aerate the total mass. It also serves to create buffer stock for regularity in production and increases the plasticity of the clay (Hamer *et al,* 2004; Whyman, 1994). This process emits particulate matter including $PM_{10}$ as a result of wind erosion.

### *2.3.2.4 DRYING*

USEPA (1997b) suggests that an optional **pre-drying** period may precede the drying process. Drying is required to reduce the moisture content of the bricks to about 8% volume in order to ensure proper firing (CBA, 2002).

CBA (2002) and (2005) identify three methods for drying the moulded bricks, namely, sun-drying, chamber drying and tunnel drying. Habla (2012) also suggests hot floor drying as another means of drying bricks.

- **Sun drying:** The bricks are stacked on an open hack-line to utilize the free source of energy from the sun, a common method among brick makers in South Africa due to relative abundance of sun light (CBA, 2002). This cheap method of drying takes about 14 to 21 days (CBA, 2002) or 4 to 6 weeks (CBA, 2005) to complete, especially during rainy season.

- **Chamber drying:** In chamber drying, bricks are packed on pallets in large rooms (CBA, 2005) or chambers having capacity of about 50,000 to 60,000 bricks (CBA 2002). Hot air is pumped into the chamber and bricks are dried in about 30 to 45 hours (CBA, 2002).

- **Tunnel drying:** CBA (2002) and (2005) describes the tunnel drying as consisting of a "kiln car" or "flat rail trolleys" that is packed with bricks. The car is pushed through a tunnel set at optimal temperature to ensure that the bricks dry evenly in a period of about 40 to 50 hours.

USEPA (1997c) and EMEP/EEA (2009) identify emissions from the drying stage to include "particulate matter (PM), PM less than or equal to 10 microns in aerodynamic diameter ($PM_{10}$) and PM less than or equal to 2.5 microns in aerodynamic diameter ($PM_{2.5}$)," as well as organic pollutant emissions from exhaust stream in chamber or tunnel drying.

#### *2.3.2.5 FIRING*

Brick kilns can be classified based on the type of firing system (or structure) and on the direction in which the emissions flow from the kiln (Merschmeyer, 2000a). Bricks can be fired in a continuous or intermittent process depending on the firing system adopted (Habla 2012; EMEP/EEA 2009; Merschmeyer, 2000a; BIA, 2006 and USEPA, 1997b).

In the intermittent process, kilns are enclosed and the temperature inside the enclosure or stable structure is regulated based on a time frame until the firing process is completed (Habla, 2012). External fuels are fed into the kiln via fire-holes (USEPA, 1997b). The kiln is allowed to cool completely before the bricks are de-hacked and sorted out for despatch or storage.

The continuous kiln system is a long structure in which bricks are fired midway. It works either by moving the bricks through a stagnant fire or by passing the fire around the stationery bricks using a suction fan or chimney (Habla, 2012).

Figure 2-1 illustrates the classification of kilns by Merschmeyer (2000a) and EMEP/EEA (2009). They classified kilns into three categories according to the direction in which the emissions flow, viz.:

- Up-draught firing;
- Down-draught firing;

- Horizontal or cross-draught firing

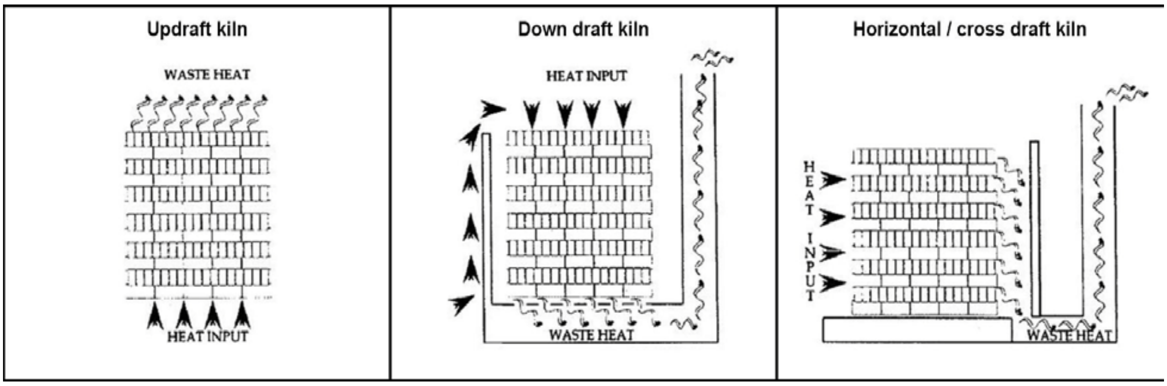


**Figure 2-1: Classification of clamp kilns based on flow of emissions (Potgieter *et al,* 2010)**

Table 2-1 shows the categorization of common kilns around the world based on the firing systems as well as the three sub-classes listed above.

**Table 2-1: Brick kiln firing systems and sub-classes (Merschmeyer, 2000a)**

| | |
|---|---|
| **Periodic or intermittent kiln**<br>(up-draught, no chimney) | • Clamp<br>• Vertical shaft brick kiln (VSBK) |
| **Periodic or intermittent kiln**<br>(down-drought, operated with chimney) | • Scotch kiln<br>• Round kiln<br>• Annular kiln<br>• Zigzag kiln (archless) |
| **Continuous kiln**<br>(horizontal draught, operated with chimney) | • Hoffmann kiln<br>• Tunnel kiln |

Bricks are fired at a temperature range of 900°C to 1200°C depending on the properties of the clay material used (Kornmann *et al,* 2007; CBA, 2002 and 2005). CBA (2005) and Kornmann *et al,* (2007) emphasize the need for proper temperature regulation during firing so as to prevent deterioration of the moulded clay. A steady increase in temperature to sintering point is also prescribed by Kornmann *et al,* (2007).

BIA (2006) and USEPA (1997c) identified 6 stages of the clay brick firing process as follows: evaporation of free water, dehydration, oxidation, vitrification, flashing, and cooling. Table 2-2 provides the temperature range for the six stages according to BIA (2006).

**Table 2-2: Temperature range for various stages of brick firing (BIA 2006; USEPA; 1997b; Merschmeyer, 2000a)**

| Stage | Average Temperature range $^{o}C$ |
|---|---|
| Evaporation of free water (final drying) | 100 – 150 |
| Dehydration | 149C – 982 |
| Oxidation | 538 - 982 |
| Vitrification | 871 – 1316 |
| Flashing | Holding the peak temperature for a period |
| Cooling | Decrease from peak to ambient temperature. |

The temperature range for firing at each stage is crucial to the quality of bricks produced, while the temperature required is dependent on the clay material as well as the size and “coring” of the fired bricks (Merschmeyer, 2000a; Kornmann *et al,* 2007 and BIA, 2006).

USEPA (1997c) and (2003a) describe flashing as a reduction process that takes place in a “flashing zone” and is used to impact colour to bricks by the addition of “un-combusted fuel” to the kiln.

#### 2.3.2.5.1 EMISSIONS FROM BRICK KILN FIRING

USEPA (1997c) identifies emissions from firing activities as including “particulate matter (PM), PM less than or equal to 10 microns in aerodynamic diameter ($PM_{10}$), PM less than or equal to 2.5 microns in aerodynamic diameter ($PM_{2.5}$), sulfur dioxide (SO2), sulfur trioxide ($SO_3$), nitrogen oxides (NOx), carbon monoxide (CO), carbon dioxide ($CO_2$), metals, total organic compounds (TOC) (including methane, ethane, volatile organic compounds [VOC], and some hazardous air pollutants (HAP), and fluorides.”

## 2.3.3 TYPES OF BRICK FIRING KILNS

### *2.3.3.1 CLAMP KILNS*

Clamps are traditional kilns, invented by Egyptians at about 4000 BC and are the most commonly used kiln type in developing countries, including South Africa (Habla, 2012; CBA, 2005; Guttikunda *et al*, 2012). The bricks are packed in a pyramid-shaped formation with a layer of combustible material such as coke, cinder or coal at the bottom of the kiln and after each layer of brick. Three layers of fired bricks (skinkles) are arranged to serve as funnel to accommodate the base combustible material (CBA, 2002; 2005 and Rajasthan State Control Board, 2011).

According to Habla (2012), clamp kilns are often “operated in clusters” and are “inefficient in fuel, labour intensive and highly polluting.” Obeng *et al,* (2001) describes the clamp kiln as simple to build, affording operators the ease of building close to a source of clay and raw materials in order to minimize transportation costs.

When the base layer of coal is ignited, it sets the bricks on fire layer by layer until the whole kiln is ablaze. The kiln temperature rises gradually, igniting the fuel in the clay at about 800 °C and peaking at an average of 1200 °C or 1400 °C at the centre of the kiln (Habla, 2012; CBA, 2002; 2005 and Rajasthan State Control Board, 2011). Figure 2-2 illustrates a typical temperature distribution within a kiln in a 14 day firing cycle.

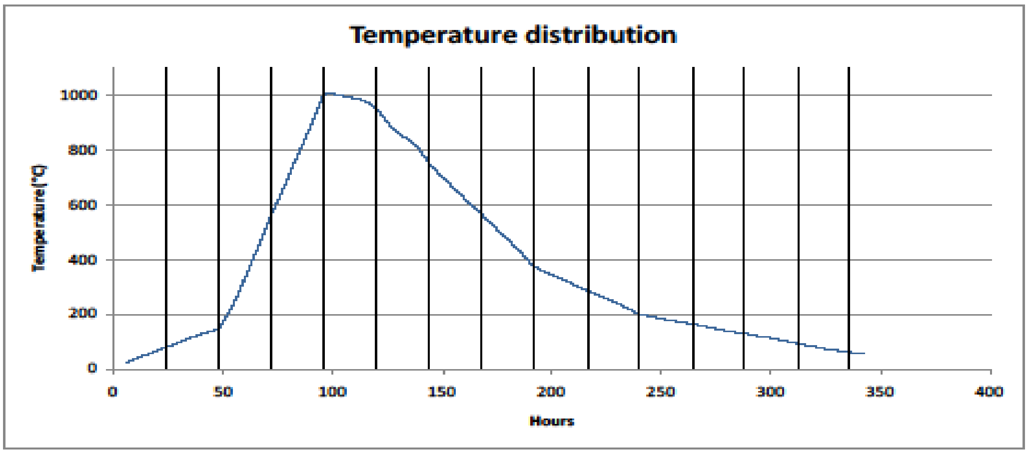


**Figure 2-2: Typical temperature distribution within a kiln during a 14 day firing cycle (Potgieter *et al*, 2010)**

In South Africa, "duff" coal or carbon-containing fly ash is added to the clay material before processing to serve as internal or body fuel (CBA, 2002; 2005). Lordan, 2011 and Burger *et al,* 2008 estimate the ratio of coal (body fuel) to clay as about 1:10. The internal fuel ensures that the bricks are evenly fired and that the temperature change in the kiln is evenly distributed (CBA, 2002; 2005). "Small nuts" coal is used as external fuel in the skinkles (CBA, 2005; Lordan, 2011). A large-capacity clamp kiln in its latter period of firing is depicted in Figure 2-3.

CBA (2002) and (2005) put the average time to complete clamp firing at 2-3 weeks. This is basically when the fire in the kiln burns out completely. Bricks produced by clamp kiln firing are used mostly as "non-facing plaster (NFP) bricks" or "NFP for plastered walls" and foundation bricks (CBA, 2005).

**Figure 2-3: Red brick kiln at Bert's Bricks, Potchefstroom firing over seven million bricks in less than 3 weeks**

### *2.3.3.2 TUNNEL KILNS*

USEPA (1997b); Kornmann *et al,* (2007) and Habla (2012) describe tunnel kilns as the most commonly used kiln type for firing bricks in the developed world and estimates its invention at around 1877 in Germany. In tunnel kilns, green bricks are set on "kiln cars" and are driven continuously through a long stationary fire in the tunnel where the bricks are fired and the temperature is regulated at 900 – 1200 °C (CBA, 2005; Kornmann *et al,* 2007).

Tunnel kilns are low in labour demand but require high electricity and capital costs (Habla, 2012). They require 3-5 days for drying and firing; and they produce bricks that meet specific demands in terms of size, shapes and colour (CBA, 2005). Kornmann *et al,* (2007) identifies modifications to the Tunnel kiln as the Roller kiln which can fire bricks at duration as short as 3-8 hours.

#### *2.3.3.3 VERTICAL SHAFT BRICK KILNS (VSBK)*

This was invented in China in 1958 and consists of a tall, rectangular, vertical shaft through which the green bricks and crushed coal or fuel are lowered from top to bottom in a batch (Habla, 2012). The brick passes through all stages of firing before reaching the exit of the shaft where they are removed (Subroto, 2012). VSBK is said to have high energy efficiency, low operating costs, and it is suitable for firing bricks of high qualities and specifications (Subroto, 2012).

#### *2.3.3.4 HOFFMAN KILNS*

The Hoffman kiln is analogous to the Tranverse Arch kiln (TVA) and was invented by F. Hoffman at Germany in 1858 (Habla, 2012; Neaverson, 1994). The Hoffmann or barrel arch kiln has a number of open-wall chambers through which bricks and fuel are stacked for firing in a continuous process (Thring, 1962; Ubaque *et al,* 2010).

The fired bricks are removed from a chamber when the firing process is complete. Another load of bricks is fed to the fire chamber as soon as the fired bricks have been packed (CBA, 2002; Thring 1962, Ubaque *et al,* 2010 and Neaverson, 1994). According to Habla (2012) and Neaverson (1994), these kilns are seldom operated since the early 20th century and have been replaced by the large, wall chambered TVAs and the Tunnel kilns.

#### *2.3.3.5 OTHERS*

Other types of brick firing kiln include the **Bull's trench kiln**, which is an arch-less form of the Hoffmann Kiln, designed by a British engineer, W. Bull in the late 19th century (NWFP Environmental Protection Agency, 2004; Kornmann *et al,* 2007). Another type of kiln is the **Down draught kiln,** which according to CBA (2002), is a "rectangular space with a barrel-vaulted roof and a slotted or perforated floor open to flues below".

Less common kiln types include the **Habla Zigzag kiln**, which is an energy efficient kiln invented in Germany (Habla, 2012); the **Igloo** or **Beehive kiln**, common in Zimbabwe for firing various materials including bricks (Tawodzera, 1997). A typical brick making process in South Africa is depicted in Figure 2-4.

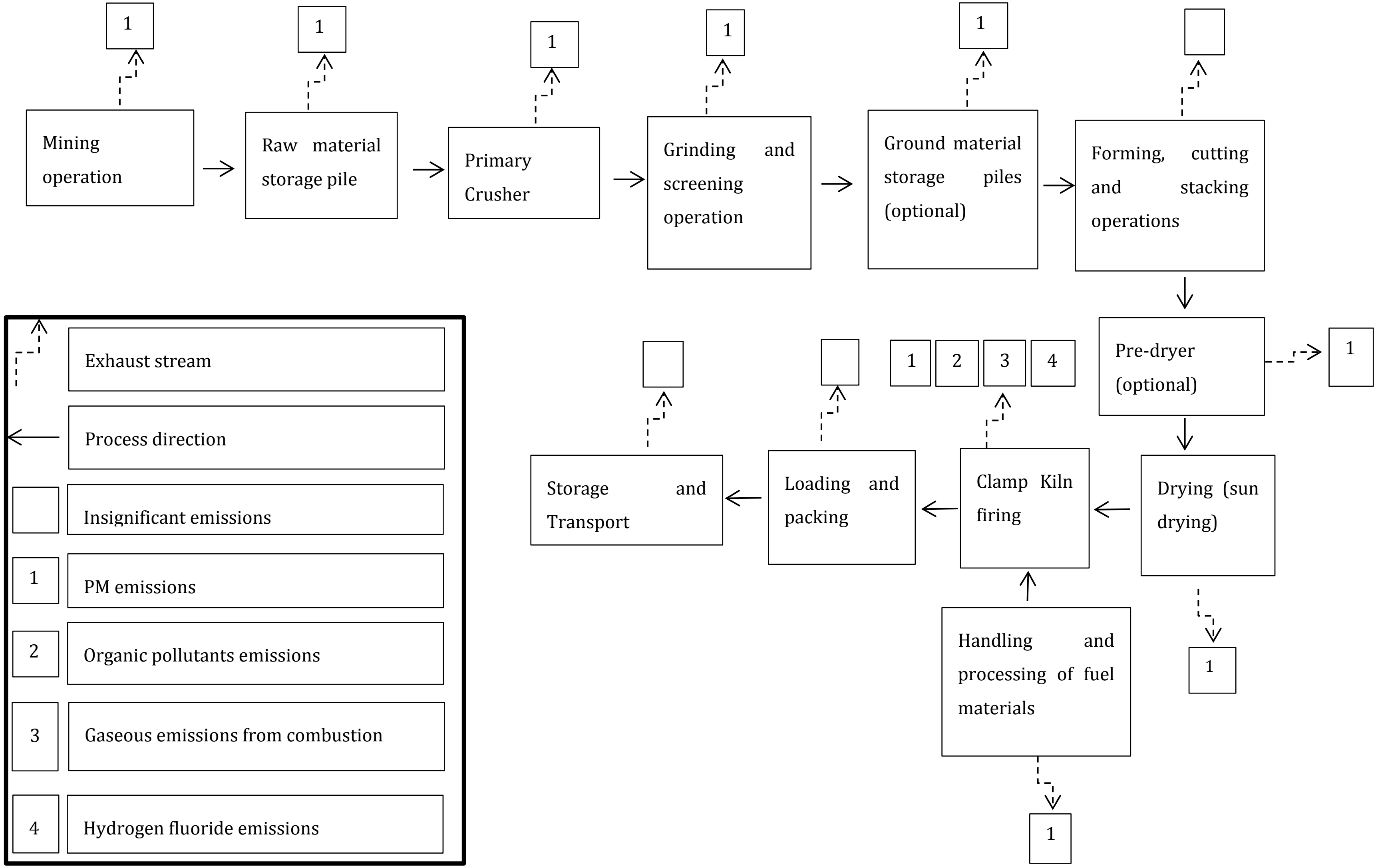


Figure 2-4: A typical brick manufacturing process in South Africa (adapted from USEPA 1997b)

## 2.4 EMISSIONS FROM CLAMP KILN AND SOUTH AFRICAN REGULATIONS

"Clamp kiln for brick production" in South Africa was identified by the Department of Environment Affairs as one of the activities (Listed Activity no. 5.3) that will require application for an Atmospheric Emissions License (AEL) by operators. This requires ambient monitoring and reporting of dust fall and $SO_2$ concentration at the boundary of the clamp kiln site (DEAT, 2008; DEA, 2013).

DEAT (2008) opines that brick firing using clamp kiln poses "negative environmental effects by impacting negatively on health, social, economic and ecological conditions".

DEA (2013) summarizes the challenge involved with emissions from clamp kiln firing as inadequate abatement technology for reducing oxides of carbon ($CO_x$), $SO_2$ and $PM_{10}$ emissions from the kilns. DEA (2013) further describes the challenges as follows:

> *"Brickworks using clamp kiln technology emit* $S0_2$ *and particulates near ground level, and compared with industrial emissions, the plume is relatively cool. The pollutants are therefore released into the stable surface layer where dispersion is inhibited, particularly at night and in the winter. As a result of poor dispersion, the ambient concentrations are high at the source and the effect is generally limited to the surrounding area".*

Thus, the impact of emissions from clamp kilns is localised (Irm, 2011) and contributes significantly to the ambient concentrations of pollutants (DEA, 2012).

The Atmospheric Emissions Licence, regulated under the NEM-AQA, stipulates emission limits for each listed activity as well as requirements for measurement. However, ambient air quality measurements are set for the clamp kiln firing process rather than emission standards due to the nature of the source and the absence of obvious mitigation measures (DEA, 2013). This is depicted in Table 2-3 below.

**Table 2-3: Ambient standards for brick plants using clamp Kiln firing technology (reproduced from DEA, 2013)**

<table>
<tr><td>Description</td><td colspan="3">The production of bricks using clamp kilns</td></tr>
<tr><td>Application</td><td colspan="3">All installations producing more than 10 000 bricks per month.</td></tr>
<tr><td colspan="2">Substance or mixture of substance</td><td rowspan="2">Plant status</td><td rowspan="2">mg/Nm$^3$ under normal conditions of 273 Kelvin and 101,3 kPa.</td></tr>
<tr><td>Common name</td><td>Chemical symbol</td></tr>
<tr><td rowspan="2">Dust fall</td><td rowspan="2">N/A</td><td>New</td><td>A</td></tr>
<tr><td>Existing</td><td>A</td></tr>
<tr><td rowspan="2">Sulphur dioxide</td><td rowspan="2">$SO_2$</td><td>New</td><td>B</td></tr>
<tr><td>Existing</td><td>B</td></tr>
<tr><td colspan="4">[a] three months running average not to exceed limit value for adjacent land use according to dust control regulations promulgated in terms of section 32 of the NEM: AQA, 2004 (Act No. 39 of 2004), in eight principal wind directions.</td></tr>
<tr><td colspan="4">[b] Twelve months running average not to exceed limit value as per GN 1210 of 24 December 2009. Passive diffusive measurement approved by the licensing authority carried out monthly.</td></tr>
</table>

## 2.5 PREVIOUS STUDIES ON CLAMP KILN EMISSIONS

Potgieter *et al,* (2010) and Burger *et al,* (2008) carried out onsite investigations in quantifying emissions from brick making clamp kilns sites. Guttikunda *et al*, (2012) also investigated the pollution caused by particulates from brick kiln clusters in Greater Dhaka region, Bangladesh.

The study conducted by Potgieter *et al,* (2010) involves the review of operations and emissions from three operational sites in South Africa; quantification of the emissions from the sites' clamp kiln brick operations; and general prediction of potential impacts on ambient air quality.

Potgieter *et al,* (2010) utilized site measurements as well as estimations and assumptions in the review of operations and quantification of emissions. Relevant conclusion on emission estimation from the study reveals that approximately 13.4% of the expected ash content of the fuel is emitted from the clamp kiln operation.

The study conducted by Burger *et al,* (2008) involves the review of operations and emissions from one operational clamp kiln site (Apollo Bricks, Atlantis); quantification of the emissions from onsite operations; and prediction of potential impacts on ambient air quality.

Burger *et al,* (2008) utilized short-term onsite measurements as well as assumptions in the review of site operations and quantification of emissions. Emissions quantification was carried out on a clamp kiln (production capacity of 880,000 bricks) and fitted to predicted concentrations at the sampling points using an assumed emission rate. The actual emission rate was "back-calculated" from the assumed rate to give **3,21 g/s** for $PM_{10}$, **0.47 g/s** for $SO_2$ and **0.15 g/s** for $NO_2$**.**

The study undertaken by Guttikunda *et al*, (2012) estimated emissions from brick kiln clusters in the Greater Dhaka region, Bangladesh. However, the major technology utilized in bricks firing in the region is the Fixed Chimney Bull's Trench Kiln (FCBTK) technology**.** The proportion of clamp kilns included in the study could not be verified.

### 2.5.1 LIMITATIONS ON PREVIOUS STUDIES

The following has been identified as limitations in quantifying clamp kiln emissions from studies conducted by Potgieter *et al,* (2010) and Burger *et al,* (2008):

- In simulation of impacts due to emissions from clamp kilns, these studies did not account for plume rise due to buoyancy of the emissions. A significant disparity between ambient temperature and flue gas temperature will generate substantial rise in the plume due to buoyancy, which will ensure that ground level concentrations are impacted further downwind from the kiln;
- Particulates monitoring utilized in these studies were conducted on a short term basis. Consideration was not given to the variation in emission rates from different stages of the firing cycle and its effect on downwind simulated concentrations;
- The technique used in measuring emissions in these studies requires that the kiln be isolated from emissions from other activities such as vehicle traffic and

firing from another clamp kiln. This is to avoid duplicate measurements or interference with ambient monitoring. These studies did not consider the need for absolute isolation of the kiln;

- These studies did not extensively review or account for other emission generating activities on a clamp kiln site; and
- The significant effect of $NO_2$ emissions from other onsite air emission sources such as internal combustion engines was not accounted for in these studies.

In summary, studies conducted by Potgieter *et al,* (2010) and Burger *et al,* (2008) provide a background for estimation techniques required for quantifying emissions from clamp kiln sites. These studies underlie the need for a more appropriate site monitoring and data collection technique. They also accentuate the need for a more appropriate technique for simulating ground level concentration downwind of the kiln.

# 3 METHODOLOGY

## 3.1 EXPERIMENTAL PROCEDURE

The emission inventory tool was developed from the investigation of three clamp kiln sites in South Africa. The tool was developed using the Microsoft Excel (2010) spreadsheet application. The emission inventory tool workbook is made up of one information sheet, six sheets representing various process calculations, a final emissions summary sheet and an appendix sheet.

Figure 3-1 illustrates a four-stage conceptual plan employed in developing the emission inventory tool. Stage 1, the data collection and input stage, involves activities such as site selection and visit, preparation of the emission inventory tool, collection and preparation of meteorological data, collection of site data and ambient monitoring. Stage 2, the data processing stage, involves dispersion modelling and laboratory analysis of samples. Stage 3 is the data analysis stage where emission factors are generated, for all significant processes, using the 'reverse modelling' technique described in Section 4 and 5. Stage four, the output stage, involves the validation of results and their integration into the into the emission inventory tool.

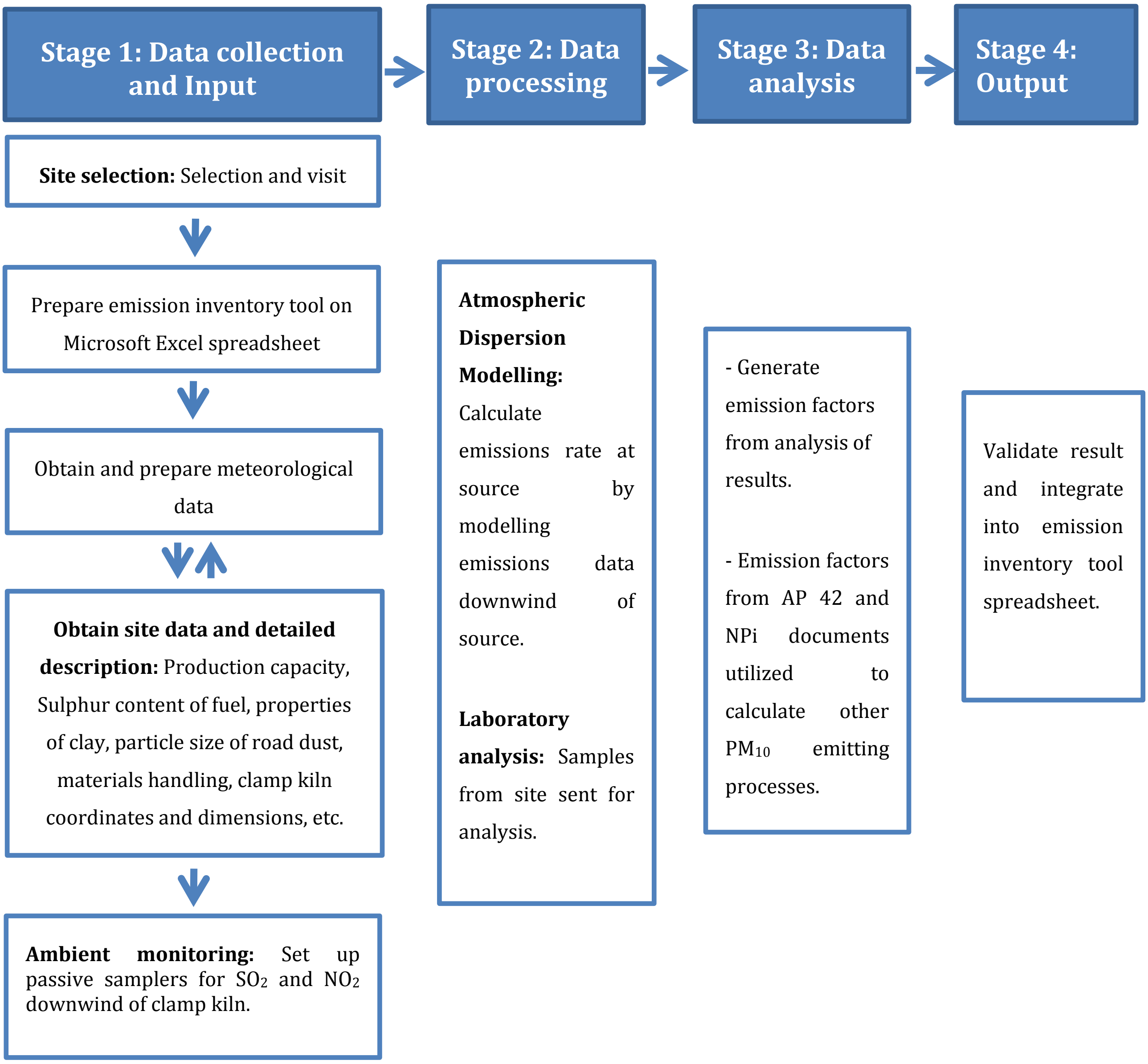


Figure 3-1: Conceptual plan for development of emission inventory tool for clamp kilns

### 3.1.1 PREPARATION OF THE EMISSION INVENTORY TOOL

The emission inventory tool was prepared after a series of consultations with the CBA and brick makers. It was concluded that the tool has to be easy to operate, in order for it to be effectively utilized.

The tool automatically calculates emission factors and generates the final emissions for a particular site when the relevant data are entered. It is built on a Microsoft Excel

(2010) spreadsheet application and is divided into nine spreadsheets to accommodate all applicable site activities as well as other relevant information.

USEPA (1995a) provides the general equation for emission estimation:

$$E = A \mathrm{~x~} EF \mathrm{~x~} \frac{(1-ER)}{100} \qquad \text{(Equation 3-1)}$$

Where: E = emission rate,
A = Activity rate,
EF = emission factor, and
ER = overall emission reduction efficiency, %.

The cells in the tools are filled with different colours to indicate various actions required for usage, as shown in Table 3-1. The pages of the tool are presented in appendix A. The draft tool was disseminated to clamp kiln operators in South Africa via the CBA, in order to gather relevant site information. As at the time of writing this report, 29 clamp kiln operators have prepared and returned their draft emission inventory tool.

**Table 3-1: Cells description in the emission inventory tool**

| Colour | Description |
|---|---|
| 🟨 | Input cell for user |
| 🟦 | Output - Automated cells |
| 🟩 | Data to be sourced/entered by user (site specific) |
| 🟧 | Constants (not subject to change) |
| 🟫 | Data input required for further research |
| 🟪 | Data to be entered if available (site specific) |

### *3.1.1.1 INFORMATION PAGE (SHEET ONE)*

This sheet collects information about the site and the contact person on site. It also provides guidance notes for usage as well as the contact details of the tool developers.

### *3.1.1.2 VEHICLE DATA – PAVED ROAD (SHEET TWO)*

This sheet collects all data on paved roads that are relevant to particulate matter emissions. It calculates emission factors and total emissions of $PM_{10}$ on all paved roads on site.

#### 3.1.1.2.1 EMISSION FACTOR

The USEPA AP 42 document 4th Edition (USEPA 1985) provides the empirical expression for calculating emission factors on paved roads as follows:

$$E = 0,022I \left(\frac{4}{n}\right)\left(\frac{s}{10}\right)\left(\frac{L}{280}\right)\left(\frac{W}{2,7}\right)^{0,7} \qquad \text{(Equation 3-2)}$$

Where: E = emission factor (kg/VKT)
I = industrial augmentation factor (dimensionless)
n = number of traffic lanes
s = surface material silt content (%)
L = surface dust loading (Kg/km)
W = average vehicle weight, (ton)

This formula was preferred to the one provided in the newer version of the AP 42 document (5th edition) because it makes provisions for more site-related parameters and thereby provides better representation of a clamp kiln site. The Industrial augmentation factor I was taken as 7.0 (USEPA 1985). Averages for the surface material silt content (%) and the surface dust loading (kg/km) were estimated by taking road samples from two clamp sites and is depicted in Table 3-2. Only two sites were sampled because most clamp kiln sites in South Africa do not have paved roads, hence, a low number of sites are available to sample.

USEPA (1993a) provides procedures for sampling road dust particles while USEPA (1993b) provides procedures for laboratory analysis of the samples collected.

The site operators are required to supply all other input data such as weight of empty and loaded truck; total trips per vehicle type in a month; number of traffic lanes; kilometres travelled per trip; and number of water sprayers applied per day.

**Table 3-2: Surface and bulk dust loading averages for paved roads**

| Site | Silt loading (%) | Average silt loading (%) | Average bulk loading (kg/km) |
|---|---|---|---|
| Sterkfontein Bricks | 14,91 | 14,13 | 30,20 |
| Apollo Bricks (weighbridge) | 13,35 | | |

#### 3.1.1.2.2 EMISSION MITIGATION

Provision was made for mitigation of dust emissions from paved roads in the emissions inventory tool. Operators reported the use of water spraying tankers to mitigate dust emissions. The percentage for control efficiency was obtained from USEPA (2003c) and NPI (1998).

It should be noted that visit to two sites (Apollo and Sterkfontein Bricks) confirmed the site operators' claim of using water sprayers to mitigate dust emissions from paved roads.

### *3.1.1.3 VEHICLE DATA – UNPAVED ROAD (SHEET THREE)*

Unpaved roads constitute a large percentage of the roads on clamp kiln sites. Table 3-3 shows the distribution of paved and unpaved roads for the 29 sites reported.

**Table 3-3: Paved and unpaved road distribution for 29 clamp kiln sites**

| Road type | Number of sites |
|---|---|
| Paved roads | 5 |
| Unpaved roads | 29 |

#### 3.1.1.3.1 EMISSION FACTOR

The empirical expression for emission factor calculation for unpaved roads was derived from USEPA (1995b) as follows:

$$E = k(1,7)\left(\frac{s}{12}\right)\left(\frac{S}{48}\right)\left(\frac{W}{2,7}\right)^{0,7}\left(\frac{w}{4}\right)^{0,5}\left(\frac{(365-p)}{365}\right) \qquad \textbf{(Equation 3-3)}$$

Where:
E = emission factor (kg/VKT)
k = particle size multiplier (dimensionless)
s = silt content of road surface material (%)
S = mean vehicle speed (km/hr)
W = mean vehicle weight (tons)
w = mean number of wheels
p = number of days with at least 0,254 mm of precipitation per year

The particle size multiplier, k, was taken as 0,36 for $PM_{10}$ (USEPA 1995b). The silt content of road surface material on unpaved roads was obtained from analysis of 8 road samples taken from 4 clamp kiln sites as shown in Table 3-4.

The number of days with at least 0,254 mm of precipitation per year, p, is a site-specific parameter that depends on geographical location. This and other historical data for the monitoring station nearest to the site can be obtained at www.wunderground.com.

Site operators are required to supply all other input data such as weight of empty and loaded truck; total trips per vehicle type in a month; mean vehicle speed; mean number of wheels per type; kilometres travelled per trip; and number of water sprayers applied per day.

**Table 3-4: Surface dust loading for unpaved roads**

| Unpaved yard road | Silt loading (%) | Average silt loading (%) |
|---|---|---|
| Unicorn Bricks Entrance road | 18,69 | 16,81 |
| Unicorn Bricks Kiln road | 16,14 | |
| Sterkfontein Bricks workshop road | 14,49 | |
| Nova Bricks | 19,57 | |
| **Unpaved mine road** | | |
| Sterkfontein Bricks | 8,43 | |
| Apollo Bricks sample A | 28,33 | |
| Apollo Bricks sample B | 15,84 | |
| Nova Bricks | 12,98 | |

### 3.1.1.3.2 EMISSION MITIGATION

Unpaved roads generate more particulates emission than paved roads and therefore require more mitigation. Provision was made for mitigation of dust particles on unpaved roads in the emissions inventory tool through the use of water spraying tankers. The percentage control efficiency was derived from USEPA (2003c) and NPI (1998) as shown in Figure 3-2.

USEPA (2003c) and Cecala *et al,* (2012) recommends 80% efficiency when chemical surfactants are used for dust abatement (for application once every two weeks to one month).

It should be noted that visit to six sites (Apollo, Unicorn, Nova, Molopo, Bert's and Sterkfontein Bricks) confirmed the site operators' claim of using water sprayers to mitigate dust emissions on unpaved roads.

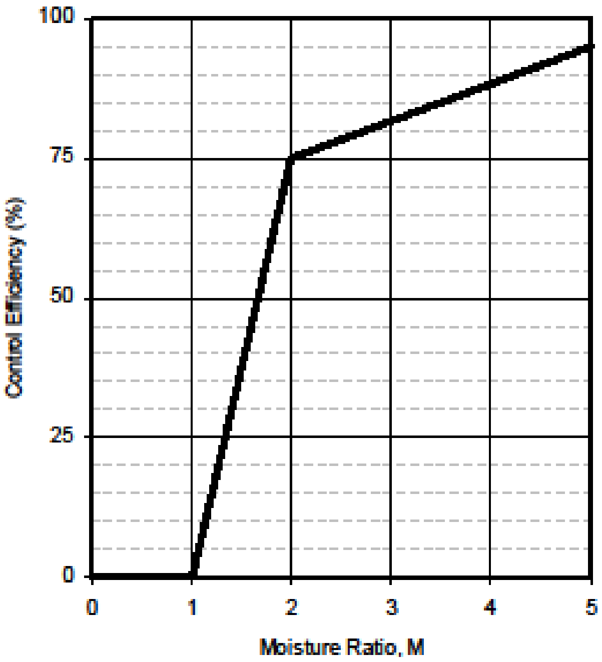


**Figure 3-2: Watering control effectiveness for unpaved road surfaces (USEPA 2003c)**

### *3.1.1.4 MATERIALS HANDLING – SHEET FOUR*

Emissions from handling of materials such as clay, coal and ash are calculated based on the number of times the material was handled. Handling steps includes loading, offloading, conveying etc. USEPA (1995c) gives the empirical expression for estimating particulates emission from material handling as:

$$E = k\,(0{,}0016)\left(\frac{\left(\frac{U}{2{,}2}\right)^{1{,}3}}{\left(\frac{M}{2}\right)^{1{,}4}}\right) \qquad \text{(Equation 3-4)}$$

Where: E = emission factor for each handling step (kg/Mg or kg/ton)
k = particle size multiplier (dimensionless)
U = mean wind speed, meters per second (m/s)
M = material moisture content (%)

The particle size multiplier, k, was taken as 0,35 for $PM_{10}$ (USEPA, 1995c). Input data such as number of times material handled; total weight of material handled; and moisture content of material handled; are to be supplied by operators. Wind data are based on geographical location and historical data estimates for nearby monitoring stations can be obtained from www.wunderground.com.

### 3.1.1.5 CRUSHING AND SCREENING – SHEET FIVE

$PM_{10}$ emission for each crushing and screening step was obtained from USEPA (1997c) as the uncontrolled grinding and screening expression:

$$E = 0{,}00115 \qquad \text{(Equation 3-5)}$$

Where:

E = emission factor for each crushing and screening step (kg/Mg or kg/ton)

The uncontrolled factor was utilised in order to prevent double representation of control in the final emission calculation.

All other data are required from the operators. These include the weight of the material handled; dust abatement used; the number of operational hours per week for the crushers and the screen.

Provision was made for mitigation of dust particles through the use of cyclones, atomising sprays, bag filter, and water addition to clay etc. The percentage for control efficiency was obtained from USEPA (2003c) and NPI (1998).

### 3.1.1.6 CLAMP FIRING 'A' AND 'B' – SHEET SIX AND SEVEN

Sheet six and seven calculate clamp kiln output, as well as $PM_{10}$, $SO_2$ and $NO_2$ emissions from clamp kiln. The two sheets calculate the same output in two different formats as requested by clamp kiln operators. Data to be entered by clamp kiln operators include the input and output quantity of clay and fired bricks; sulphur, fixed carbon and specific energy content of fuel used; and moisture content of clay.

The sheet consequently calculates $PM_{10}$, $SO_2$ and $NO_2$ emission from the clamp kiln using the emission factors derived from this study. The emission factors are discussed in details in subsequent sections.

#### *3.1.1.7 EMISSION SUMMARY – SHEET EIGHT*

This is a summary of all $PM_{10}$, $SO_2$ and $NO_2$ emission on the site. It gives the daily, monthly and annual estimates of the emissions in kg and tons. This is the final output sheet and does not require any input data from the user.

#### *3.1.1.8 APPENDIX – SHEET NINE*

The appendix provides information on site specific data such as wind speed and rainfall data. This data are required by users to input into the green cells of the emission inventory tool.

### 3.1.2 SITE SELECTION

Table 3-5 shows the three sites recommended by the CBA. Their selection criteria include:

- Production capacity;
- Proximity; and
- The need to have one clamp or two isolated clamps firing at a time. This is to avoid duplicate measurements or interference with ambient monitoring.

**Table 3-5: Three sites investigated and their relevant parameters**

| Site | Production Capacity (bricks per month) | Estimated production during study (bricks) | Location | Number of kiln(s) firing at a time |
|---|---|---|---|---|
| Unicorn Bricks | +/- 1 000 000 | 1 000 000 | Rural | 1 |
| Bert's Bricks | +/- 10 000 000 | 7 142 290 | Rural/semi-urban | 2 |
| Molopo Bricks | +/- 2 500 000 | 3 200 000 | Rural | 1 |

#### *3.1.2.1 UNICORN BRICKS, MAGALIESBURG*

Unicorn Bricks is located about 3 kilometres northeast of Magaliesburg, Gauteng, South Africa. It is located in a rural area, surrounded by farmlands and other agricultural activities that do not generate any significant amount of the pollutants under examination (Figure 3-3). Unicorn Bricks averages about one million bricks production per month and is selected as a prototype for small clamp kilns. Site monitoring and data collection was carried out from 2012-10-03 18:00:00 to 2012-10-24 10:00:00.

**Figure 3-3: Aerial view of Unicorn Bricks showing clamp kiln area and immediate surroundings (Coordinates: 25,984563°S 27,574089°E)**

### *3.1.2.2 BERT'S BRICKS, POTCHEFSTROOM*

Bert's Bricks is located about 10 kilometres southwest of Potchefstroom, North West, South Africa. It is located in a rural/semi-urban area surrounded by farmlands and the settlement of Ikageng to the Northwest. The site is within 1 kilometre of the N12 highway, which could be a source of $NO_2$ pollution from motor vehicles (Figure 3-4).

**Figure 3-4: Aerial view of Bert's Bricks showing clamp kiln areas and immediate surroundings (Coordinates: 26,750296°S 27,030942°E)**

Bert's Bricks produces about 10 million bricks per month and was selected as a prototype large clamp kiln site. Two kilns (kiln 1 and 2) are fired simultaneously at a significant distance away from one another and produce red and white bricks respectively.

Site monitoring and data collection was carried out from 2012-11-09 10:00:00 to 2012-12-12 09:00:00.

#### *3.1.2.3 MOLOPO BRICKS, MAHIKENG*

Molopo Bricks was selected as a model for medium capacity clamp kilns. It produces an average of 3 million bricks monthly and operates one kiln firing at a time. It is located about 15 kilometres southwest of Mahikeng, North West province, South Africa. It is located in a rural area surrounded by arable lands (Figure 3-5). The site is isolated from any known source of external air pollution. Site monitoring and data collection was carried out from 2013-02-11 11:00:00 to 2013-04-03 14:00:00.

**Figure 3-5: Aerial view of Molopo Bricks showing clamp kiln area and immediate surroundings (Coordinates: 25,907378°S 25,525984°E)**

### 3.1.3 METEOROLOGICAL DATA

Section 2.2 provides background information on the significance of meteorology on air pollution.

Wind speed and wind direction were measured on the three sites using the **Wilh. Lambrecht KG Gottingen®** cup anemometer (Model Number: 470279), shown in Figure 3-6. The manufacturer's instruction for the anemometer is included in appendix B.

The wind anemometer was set up between 300m to 500m upwind of the clamp kiln on the three sites. It was mounted on a 10m stand and set to due north using a magnetic compass and the published magnetic declination for each site.

#### *3.1.3.1 MAGNETIC DECLINATION*

Magnetic Declination is the angle between the magnetic north (compass north) and the true north or geographic north (Nebylov, 2013; NOAA/NGDC, 2012).

The magnetic declinations for the three sites were generated from NOAA/NGDC (2012) using each site's GPS coordinates and shown in Table 3-6. Appendix C provides illustrations of magnetic declination for the three sites.

**Table 3-6: Magnetic declination for the three sites investigated**

| Site | Coordinates | Magnetic Declination |
|---|---|---|
| Unicorn Bricks | 25,984563° S 27,574089° E | 17,70° W changing by 0,03° W p/a |
| Bert's Bricks | 26,750296° S 27,030942° E | 18,62° W changing by 0,04° W p/a |
| Molopo Bricks | 25,907378° S 25,525984° E | 17,00° W changing by 0,01° W p/a |

The Anemometer records data as a graph on a paper chart. The chart is processed and recorded manually as hourly data, a requirement for atmospheric dispersion models.

Wind speed and wind direction were measured on site in preference to sourcing from nearby monitoring stations in order to obtain readings that are better representative of the site conditions. This was however, not possible for monitoring temperature due to unavailability of the monitoring equipment.

Consequently, hourly temperature data for Magaliesburg and Potchefstroom were requested from the Agricultural Research Council, South Africa; while the South African Weather Services provided the temperature data for Mahikeng. These data were obtained from nearby monitoring stations in Tarlton, Potchefstroom and Mahikeng respectively.

**Figure 3-6: The Wilh. Lambrecht KG Gottingen® Cup Anemometer (Campbell Scientific, 2013)**

The meteorological input file (.MET) for required by atmospheric dispersion models consists of the following data:

- Year (e.g. 2012)
- Julian day (e.g. April 1 = 91 or 92 for regular and leap year respectively)
- Hour (0-23)
- Wind speed, U (e.g. 4,61 m/s)
- Wind direction, PHI (e.g. 280$^{o}$)
- Atmospheric temperature, T0C (e.g. 19,2 $^{o}$C)
- Sensible heat flux, FTHETA0 (e.g. -21,9512 W/m$^{2}$)

The sensible surface heat flux (FTHETA0) is the conductive or convective heat flux from the earth's surface to the atmosphere (Miglietta *et al,* 2009). It was generated from

METREADER, a computer program that calculates sensible heat flux from available meteorological data using the empirical expressions described in appendix D (Burger, 1986).

## 3.1.4 AMBIENT MONITORING AND DATA COLLECTION

### *3.1.4.1 OVERVIEW*

#### 3.1.4.1.1 $PM_{10}$

Monitoring and modelling of $PM_{10}$ emissions from clamp kiln was not carried out in this study due to unavailability of adequate monitoring equipment for measuring emissions from a volume source with the configuration of a clamp kiln.

The results published in Section 2.5 from previous study conducted by Burger *et al,* 2008 was utilized for $PM_{10}$ emissions. Section 5.4 also provides details of the results inferred from the report.

#### 3.1.4.1.2 $SO_2$ and $NO_2$

Passive or diffusive samplers use unaided molecular diffusion of gaseous substance such as benzene, toluene, ethylbenzene, and xylene (BTEX); hydrogen fluoride (HF); ozone ($O_3$); hydrogen sulfide ($H_2S$); $SO_2$ and $NO_2$, through a diffusive surface to be adsorbed on an internal surface (Sigma-Aldrich 2013a). Thermal or solvent desorption is used to desorb the “analytes” after the sampling period.

The Radiello® diffusive sampler is an axial sampler that was designed for a faster and higher rate of sampling than other conventional samplers (Sigma-Aldrich 2013b). Sigma-Aldrich (2013a and 2013b) further describes the samplers as simple to use, inexpensive, not requiring energy input or mechanical parts and able to sample long term periods without supervision. Therefore, they are suitable for the purpose of this investigation. Figure 3-7 and Figure 3-8 illustrate the adsorbing and diffusive surfaces of the sampler.

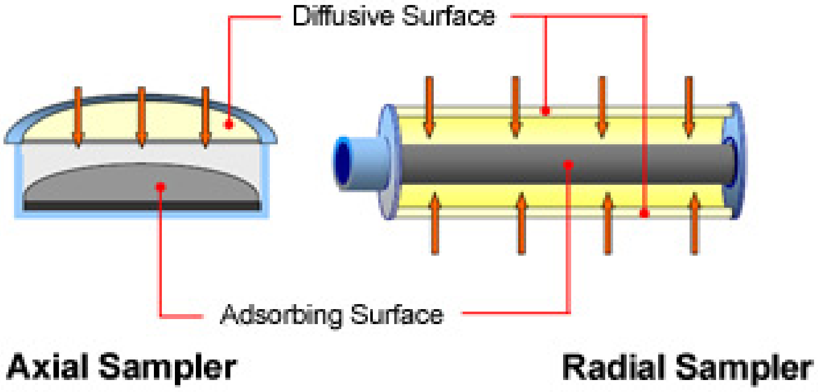


Figure 3-7: Graphic illustration of the axial and radial diffusive sampler (Sigma-Aldrich 2013a)

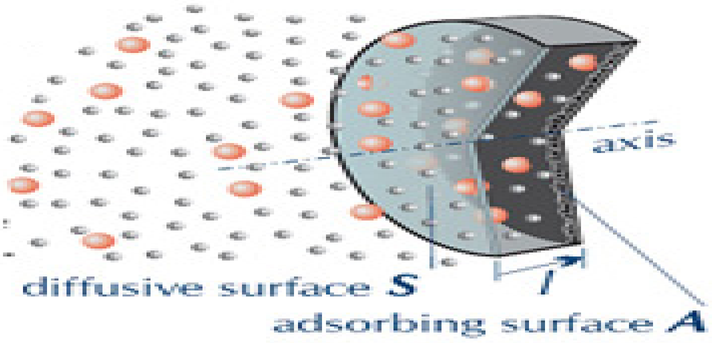


Figure 3-8: Diffusive and adsorbing surface of the sampler (Sigma-Aldrich 2013a)

### *3.1.4.2 SAMPLING LOCATION*

Sampling was performed at about 60m to 120m (where ambient concentration of pollutants is expected to be at maximum) downwind of the clamp kiln area and installed at heights ranging from 1m to 4m above ground level depending on the topography of each site (Figure 3-10, Figure 3-12 and Figure 3-14). Most of the samplers were positioned downwind of the clamp kiln where they are likely to be exposed to a high concentration of pollutants emitted from the kiln. At least one sampler per site was located upwind of the kiln to monitor the background concentration for the site, with little or no interference from pollutants emitted from the kiln. Samples were processed for $SO_2$ and $NO_2$ concentration at the Biograde CC Laboratories using the Radiello method F1 (Sigma-Aldrich 2013b).

Figure 3-9 to Figure 3-16 depict the wind rose for the monitoring period at each site and the installation of the passives around the clamp area.

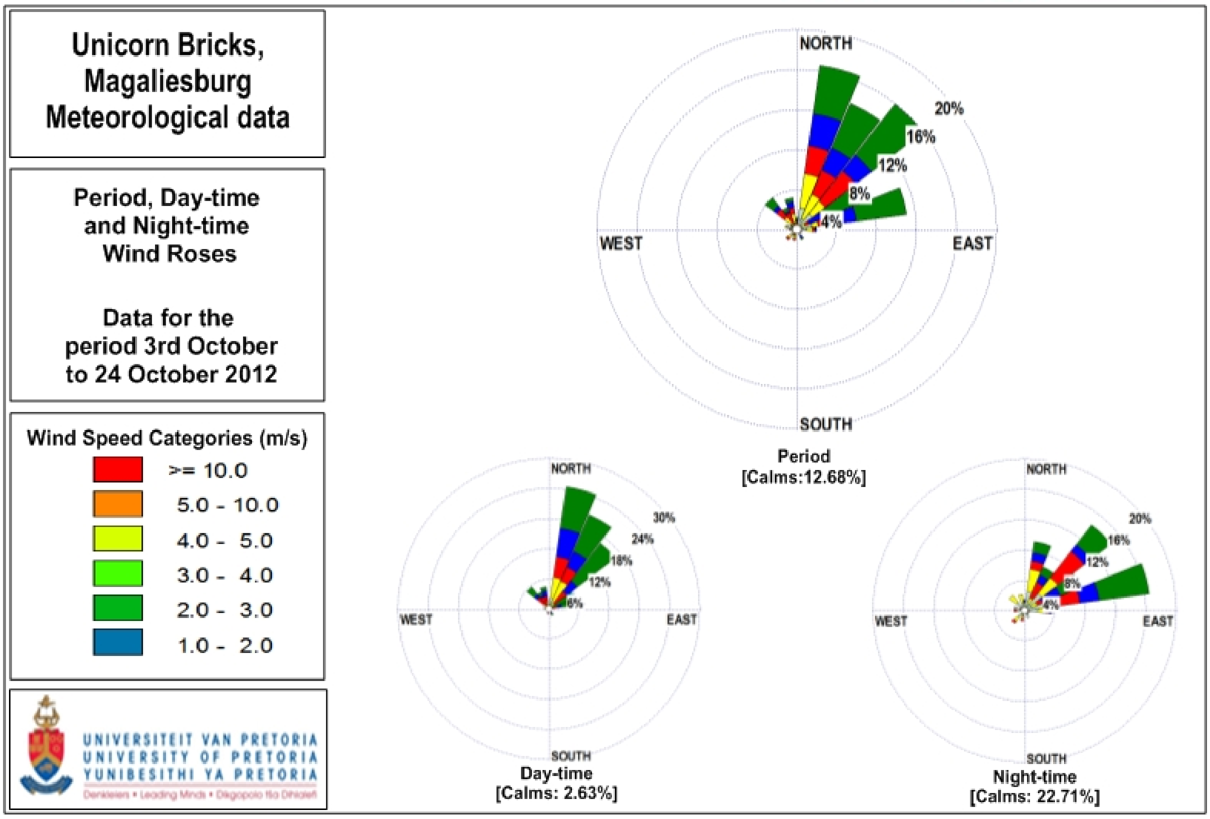


Figure 3-9: Wind rose for Unicorn Bricks, Magaliesburg

Figure 3-10: Location of samplers at Unicorn bricks, Magaliesburg

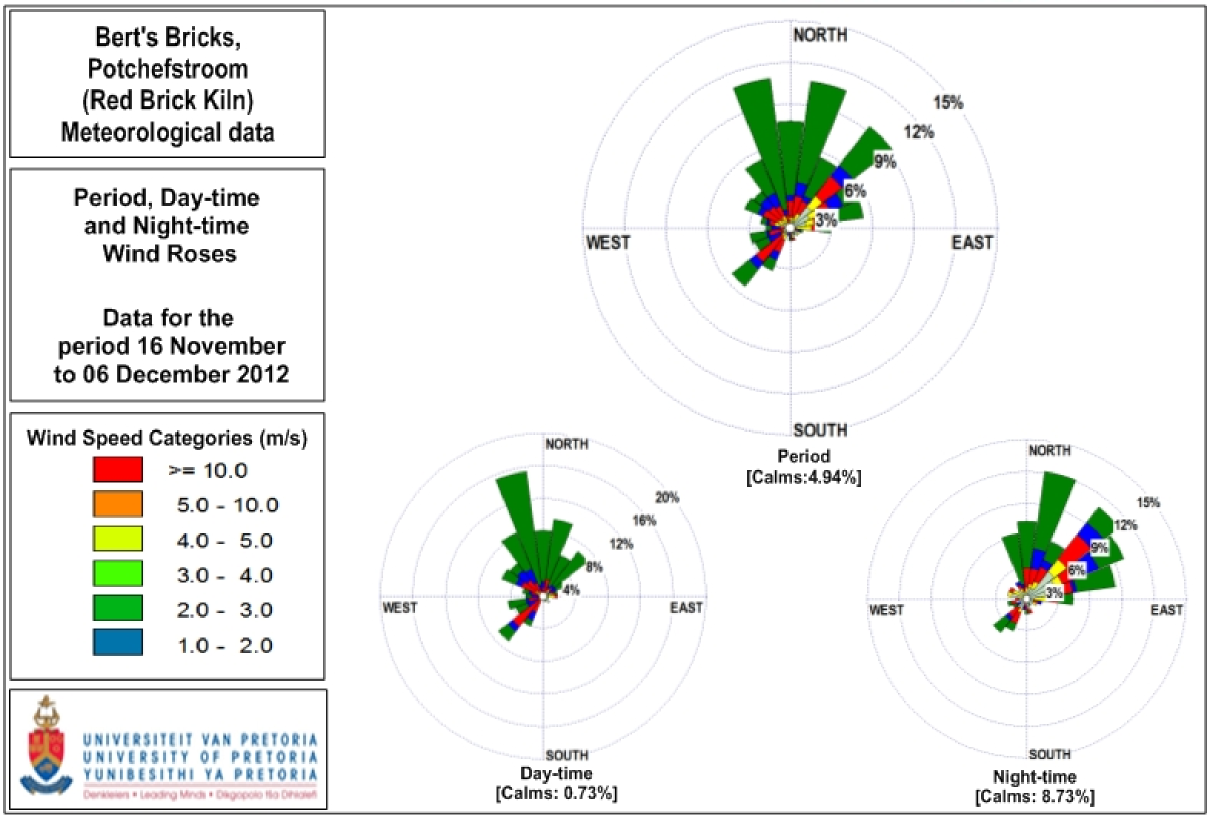


Figure 3-11: Wind rose for red brick kiln at Bert's Bricks, Potchefstroom

Figure 3-12: Location of samplers around red brick kiln at Bert's Bricks, Potchefstroom

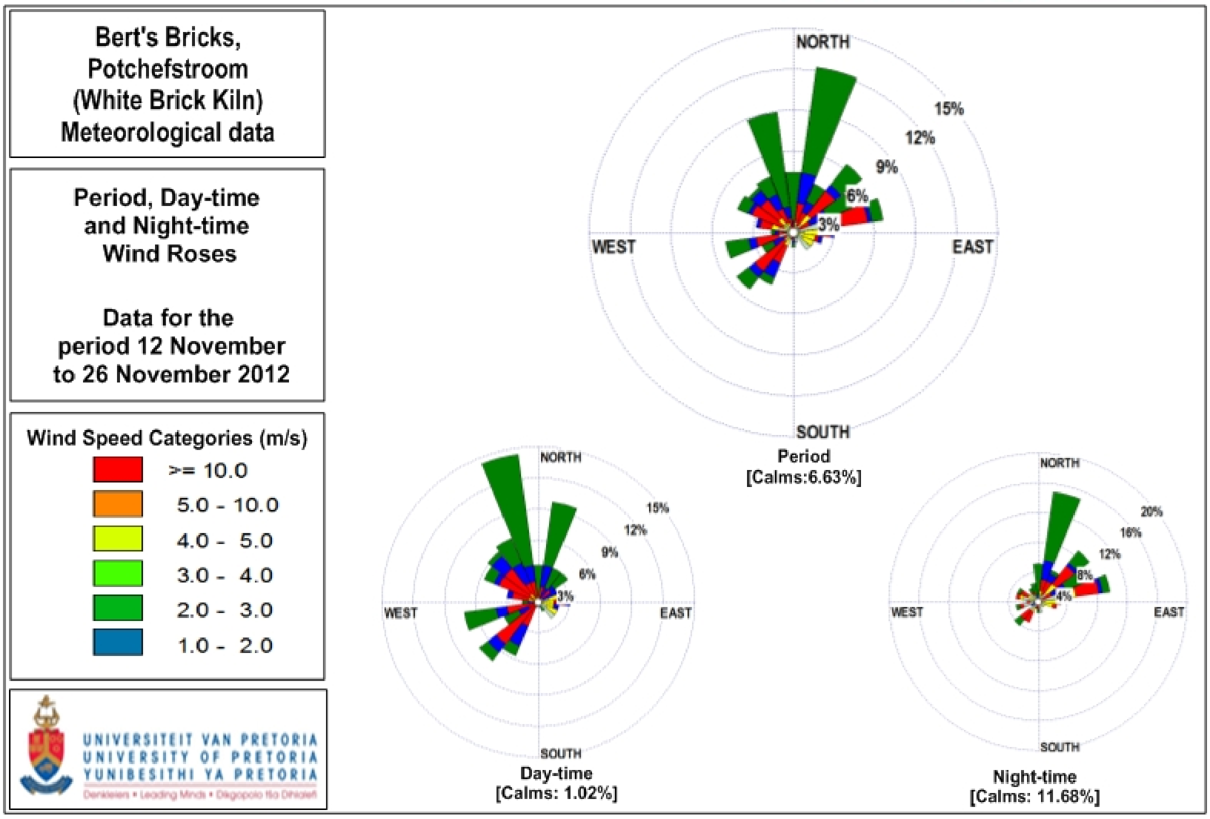


Figure 3-13: Wind rose for white brick kiln at Berts Bricks, Potchefstroom

Figure 3-14: Location of samplers around white brick kiln at Berts Bricks, Potchefstroom

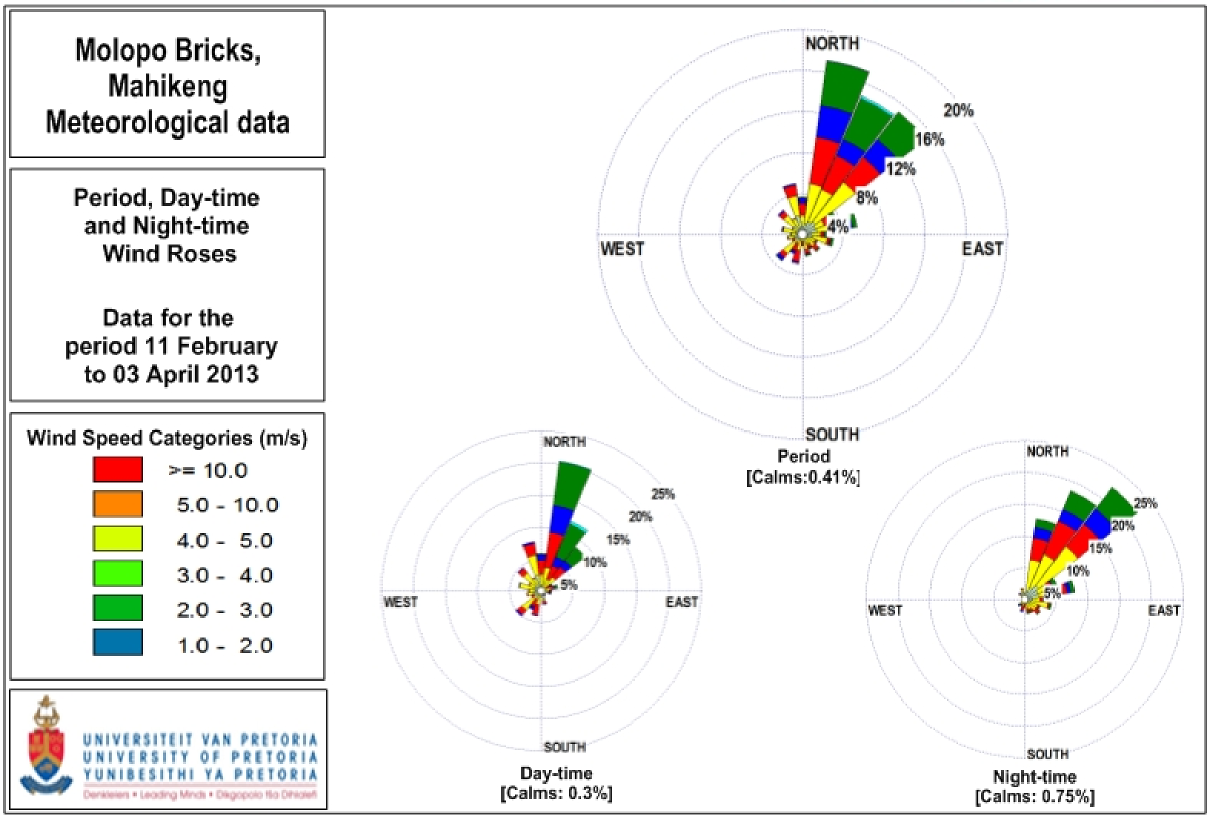


Figure 3-15: Wind rose for Molopo Bricks, Mahikeng

Figure 3-16: Location of samplers around kiln at Molopo Bricks, Mahikeng

Figure 3-17: Radiello passive sampler installed on a supporting triangle and a plastic shield

Ambient monitoring was performed for the firing period of each kiln at the three sites as shown in Table 3-7 below.

Table 3-7: Sampling period and dates for four clamp kilns

| Kiln | Sampling period (Hours) | Sampling/firing Date (YYYY:MM:DD) |
|---|---|---|
| Unicorn Bricks | 497 | 2012:10:03 - 2012:10:24 |
| Bert's Bricks red kiln | 486 | 2012:11:16 - 2012:12:06 |
| Bert's Bricks white kiln | 342 | 2012:11:12 - 2012:11:26 |
| Molopo Bricks | 1225 | 2013:02:11 - 2013:04:03 |

## 3.2 ENERGY INPUT

Clamp kiln energy input parameter varies from one site to another. The major source of energy for South African clamp kiln is coal - small nuts coal, duff coal or carbon-containing fly ash (Lordan, 2011; CBA, 2002 and 2005). The feedback of the draft emission inventory tool from 29 clamp kiln operators show that duff coal or carbon fly ash (CFA) are used as “body fuel” (that is, are mixed into the clay material during processing) while the small nuts or peas serves as the “external fuel” in the skinkle. This is also corroborated by Lordan, 2011 and is depicted in Table 3-8.

**Table 3-8: Energy input analysis for South African clamp kilns operation (Reproduced from Lordan, 2011)**

| Clay bricks produced annually in South Africa | Bricks burnt annually in clamp in South Africa | Non facing Plaster (NFP) bricks burnt annually in clamps (RSA) |
|---|---|---|
| 4 000 000 000 | 3 400 000 000 | 2 800 000 000 |
| | Tons of coal annually | Tons of coal annually |
| External fuel – small nuts/peas | 374 000 | 308 000 |
| | Tons of coal annually | Tons of coal annually |
| Internal fuel – duff/carbon fly ash | 863940 | 711 480 |
| Total carbon fuel annually | 1 237 940 | 1 019 480 |
| Total fuel per million bricks | 364,1 | 364,1 |
| Total fuel per 1000 bricks | 0,364 | 0,364 |

From Table 3-8, it can be deduced that:

- External fuel (small nuts or CFA) = 30,21 % of total energy consumption.
- Body fuel (duff coal) = 69,79 % of total energy consumption.

Table 3-9 and Table 3-10 show the estimated energy consumption and properties of the fuel used for firing bricks at the three sites investigated.

**Table 3-9: Estimated energy consumption for the three sites investigated**

| Kiln | Internal fuel (tons) | External fuel (tons) | CV (MJ/kg) |
|---|---|---|---|
| Unicorn Bricks | 380 | 100 | 28,09 |
| Bert's Bricks red kiln | 1625 | 468 | 22,93 |
| Bert's Bricks white kiln | 355 | 102 | 22,93 |
| Molopo Bricks | 346 | 243 | 22,93 |

**Table 3-10: $SO_2$ and fixed carbon content of coal used in firing bricks**

| Kiln | Total fuel consumed (tons) | Sulphur content of coal (%) | Fixed carbon content (%) |
|---|---|---|---|
| Unicorn Bricks | 480 | 0,75 | 54,30 |
| Bert's Bricks red kiln | 2093 | 0,62 | 49,60 |
| Bert's Bricks white kiln | 457 | 0,62 | 49,60 |
| Molopo Bricks | 589 | 0,62 | 49,60 |
| Average | - | 0,64 | 50,20 |

USEPA (1997b), (1997c) and Potgieter *et al,* (2010) identify a connection between the ash content of coal or fuel (for $PM_{10}$ and PM emissions) and sulphur content of coal or fuel (for $SO_2$ emissions). CBA (2005) reports a common industry practice of adding the ash from previous firing cycle into the clay to augment the body fuel. This was confirmed by 29 site operators in the draft emission inventory tool that was returned.

A relationship between energy input in a firing cycle and other parameters such as particulates emission and duration of firing cycle, has been identified by Burger *et al,* (2008) and Potgieter *et al,* (2010). Molopo Bricks utilizes lower energy input to bricks fired ratio, relative to the other two sites. The consequential outcome of this is discussed in Section 5.2.3.1.

# 4 ATMOSPHERIC DISPERSION MODELLING

## 4.1 BACKGROUND

Dispersion modelling is the mathematical simulation of the transport and diffusion of pollutants in the atmosphere as a function of source geometry, meteorological mechanisms and emission strength (Tiwary *et al,* 2010; Scorgie, 2012). The model utilizes atmospheric, physical and chemical processes within a plume to compute concentrations at desired location (Holmes *et al,* 2006; Tiwary *et al,* 2010 and Cooper *et al,* 2002). The basic stages of a dispersion model are illustrated in Figure 4-1.

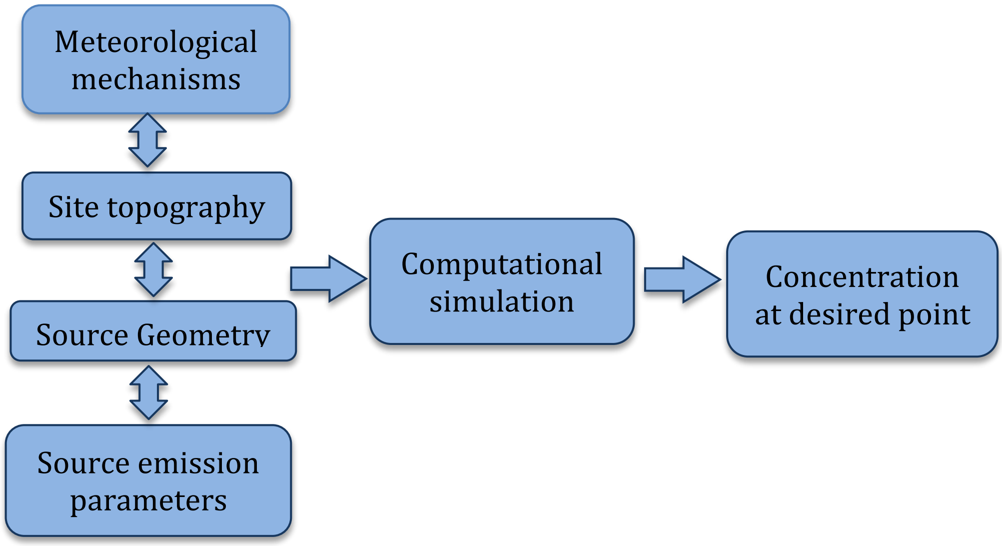


**Figure 4-1: Basic Input, process and output stage of an air dispersion model**

The meteorology and air pollution section of this report (Section 2.2) describes factors that affect pollutants transport and dispersal in the atmosphere.

Various types of mathematical simulation have been developed to process algorithms for modelling of air pollutants. Holmes *et al,* (2006); Reed (2005); Tiwary *et al,* (2010); Peavy *et al,* (1985) and Cooper *et al,* (2002) describe the significant types of mathematical algorithms, viz., Gaussian, Eulerian, Lagrangian and Box models. These models differ, among other features, in the parameters utilized in calculating pollutants dispersion in the atmosphere (Tiwary *et al,* (2010); Holmes *et al,* 2006 and Reed, 2005).

## 4.2 MODEL SELECTION

The Gaussian plume model, the most commonly used in atmospheric dispersion modelling, utilizes a “constant rate continuous” release of a pollutant from a point source. The model calculates the concentration at any location downwind, as a function of the expanded plume volume, air dilution, as well as small random movements generated by turbulence (Tiwary *et al,* 2010; Holmes *et al,* 2006 and Reed, 2005). This model, illustrated in Figure 4-2, utilizes the mathematical expression below:

$$x = \frac{Q}{2\pi u \sigma_y \sigma_z} exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left\{exp\left[-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right] + exp\left[-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right]\right\} \quad \textbf{(Equation 4-1)}$$

Where:

C = steady state concentration at a point (x, y, z), µg/m$^3$

Q = emissions rate, µg/s

$\sigma_y$, $\sigma_z$ = horizontal and vertical spread parameters, m (these are functions of distance, x, and atmospheric stability).

u = average wind speed at stack height, m/s

y = horizontal distance from plume centreline, m

H = effective stack height (*H* = *h* + *dh,* where *h* = physical stack height and *dh* = plume rise, m).

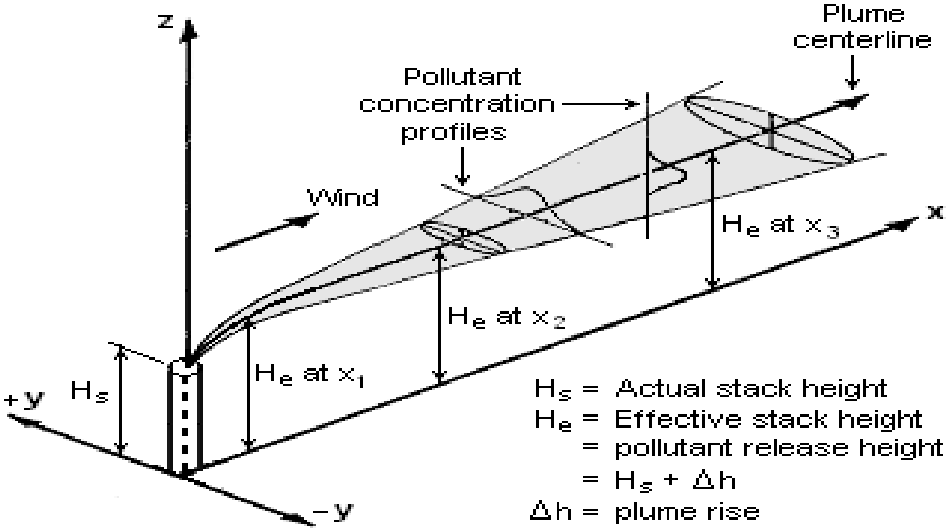


**Figure 4-2: Visualization of a buoyant Gaussian air pollution dispersion plume (Beychok, 2005)**

The Atmospheric Dispersion Modelling system (ADMS) software developed by the Cambridge Environmental Research Consultants Ltd. (CERC) is a new generation advanced modelling system that utilizes the Gaussian model (CERC, 2010; Kanevce *et al,* 2006 and Holmes *et al,* 2006).

CERC (2001) investigated the performance of ADMS against other conventional models, such as Industrial Source Complex (ISC3). Burger *et al,* 2008 proffers that ADMS offers conservative values under unstable meteorological conditions and computes higher near-source concentration relative to other models.

Neshuku (2012) also investigated the performance of ADMS and another frequently used model developed by USEPA viz. AERMOD. The study concluded that the performance of ADMS was superior to AERMOD for modelling of $PM_{10}$ emissions from open cast mining.

More so, AERMOD requires input data such as upper air meteorological data, albedo and Bowen ratio (USEPA, 2005; British Columbia Ministry of Environment, 2008). These data were not easily accessible for this investigation.

It was therefore decided that ADMS (version 4.2) was most appropriate for this study.

## 4.3 "REVERSE-MODELLING" AND ADMS INPUT DATA

In this study, ADMS 4.2 was used to model $SO_2$ and $NO_2$ concentration at the sampling points. An emission rate of 1 g/s was assumed for each source. The modelled and measured concentrations were compared and the ratio of the measured to the modelled was utilized in determining the emission rate to the use of a "**wind direction frequency multiplier**". This technique is termed **"reverse-modelling"** or **"reverse dispersion modelling"** and it is described step-wise in Section 5.

The "wind direction frequency multiplier" is a value representative of the number of hours for which the wind was prevalent in the direction of a particular sampling point from the source.

ADMS 4.2 requires users to input information stipulating the source release conditions, meteorological conditions and details of the output desired (CERC 2010).

Collection and preparation of meteorological data for the three sites has been described in Section 3.1.3 of this report. The required source and output data were prepared and employed as shown in Table 4-1.

Appendix E provides the report file of the ADMS 4.2 model run for the three sites.

It is assumed that all the energy in the coal is used up in firing the kiln.

**Table 4-1: ADMS input data for the three sites**

| Parameter | Unicorn Bricks | Bert's Bricks | Molopo Bricks |
|---|---|---|---|
| **Source** | | | |
| Source type | Point [a] | Point [a] | Point [a] |
| Number of points [b] | 2 | 2 | 2 |
| Emission rate[c] (g/s) | 1 | 1 | 1 |
| Efflux format | Fm, Fb | Fm, Fb | Fm, Fb |
| Height of source (m) | 4,40 | 4,20 | 4,20 |
| Diameter of each point source | 30,31 | 54,44 & 20,31[d] | 34,42 |
| Fm ($m^4/s^2$)[e] | 1 | 1 | 1 |
| Fb (MW)[e] | 3,77 | 13,72 & 4,26[d] | 3,06 |
| **Meteorology** | | | |
| Surface roughness | 0,50 | 0,80 | 0,50 |
| **Output** | | | |
| Output short/long term | Long term | Long term | Long term |
| Averaging time (Hr) | 1 | 1 | 1 |

**NOTES:**

- [a] Refer to section 4.4 for rationale behind point source modelling (rather than volume source).
- [b] Refer to section 4.4.
- [c] Emission rate from the kiln is not known. A unit rate of 1 g/s is assumed in order to generate concentrations from which actual emission rate can be "back-calculated" using measured results.
- [d] For red and white brick kiln respectively
- [e] Fm ($m^4/s^2$) and Fb (MW) is the momentum flux of emission and heat flux respectively. ADMS allows the input of these two parameters as alternatives to the velocity, volume flow rate or mass flux with temperature and density (CERC 2010).
- Fm was taken as a single unit since momentum is at a minimum. Fb was calculated from the energy input as follows:

$$Fb = \frac{q \text{ x CV}}{t} \qquad \text{(Equation 4-2)}$$

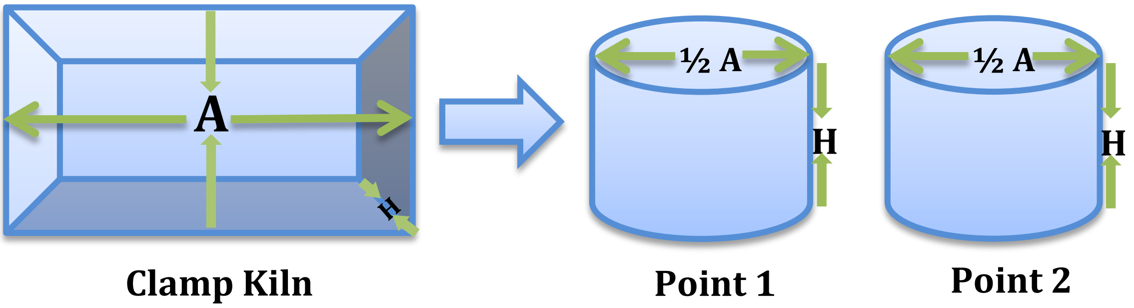
- Where: Fb = Heat flux, MW
- q = Quantity of coal used, kg
- CV = specific energy of coal used, MJ/kg
- t = time, seconds

- Surface roughness was determined from site vegetation features during monitoring, in consultation with Cowherd *et al,* (1988) and Burger *et al,* (2008).

## 4.4 "BI-POINT" SOURCE CONFIGURATION FOR A CLAMP KILN

The dimension of a clamp kiln makes the volume source the best selection for the modelling input. However, CERC (2010) describes the ADMS 4.2 volume source as an area source having vertical extent but lacking plume rise. This means that the volume source modelling does not account for plume rise due to buoyancy from the clamp firing. It regards the source as similar to a fugitive emission around a building. Recent studies (Burger *et al,* 2008; Potgieter *et al*, 2010) using volume source modelling for clamp kiln have returned very low emission rate when compared with results of mass balance analysis.

Therefore, in order to account for plume rise due to buoyancy, the clamp was modelled as two point sources as shown in Figure 4-3. ADMS 4.2 accepts the maximum diameter of a point source as 100m. Modelling the clamp kiln as two or more large-diameter point sources circumvents this limitation for clamp kilns that may have a diameter larger than 100m, and allows the use of buoyancy in the modelling.



**NOTE**: A = Area, H = Height. Diameter, $D = \sqrt{\left(\frac{4A}{\pi}\right)}$

Figure 4-3: Configuring a clamp kiln as two point sources

It is assumed in this design that the kiln emits flue gas only from the surface. Emission from the sides of the kiln was accounted for, by configuring the surface of the "bi-point" source to be equivalent to the dimensions of the base of the kiln. However, the "bi-point" source is assumed to be situated at the top level of the actual kiln.

This approach can be adapted to kilns of different shapes (e.g. a long rectangle) by utilizing more than two point sources in such a way that the point sources effectively cover the bottom footprint of the kiln.

In order to validate the use of this approach, Section 5.2.7 compares the results of volume, area and point source modelling for the clamp kilns investigated.

# 5 RESULTS AND EMISSION FACTOR CALIBRATION

## 5.1 INTRODUCTION

Emission rates for $SO_2$ and $NO_2$ were calibrated by 'reverse-modelling' technique as discussed in Section 4.

Results, discussions and calibration are reported one pollutant at a time. $SO_2$ mass balance analysis was used to validate the application of the technique. $NO_2$ is a common air pollutant from combustion engines such as motor vehicles and other internal combustion engines that operate on clamp kiln sites. However, there is no other known significant source of $SO_2$ emission on site except for the kiln (Tiwary *et al,* 2010; Schnelle *et al,* 2002).

## 5.2 SULPHUR DIOXIDE, $SO_2$

### 5.2.1 UNICORN BRICKS, MAGALIESBURG

$SO_2$ ambient and modelled results are given in Table 5-1 below. Results show that the measured ambient concentration is significantly higher than the modelled concentration at an assumed rate of 1 g/s. Consequently, an emission rate higher than 1 g/s is expected from the kiln.

**Table 5-1: Modelled and ambient $SO_2$ concentrations at Unicorn Bricks**

| Receptor | X(m) | Y(m) | Z(m) | Modelled ($\mu g/m^3$) | Measured ($\mu g/m^3$) |
|---|---|---|---|---|---|
| Point 1 | 557385 | 7125853 | 1 | 7,41 | 29,19 |
| Point 2 | 557358 | 7125816 | 1 | 9,17 | 56,52 |
| Point 3 | 557285 | 7125831 | 1 | 51,94 | 87,81 |
| Point 4 | 557235 | 7125861 | 1 | 43,21 | 40,59 |
| Point 5 | 557242 | 7125926 | 1 | 7,93 | Missing |
| Point 6 | 557291 | 7125952 | 1 | 2,81 | 3,38 |
| Point 7 | 557421 | 7125940 | 1 | 0,46 | 5,92 |

#### *5.2.1.1 $SO_2$ EMISSION RATE CALIBRATION*

Figure 5-1 illustrates the modelled average hourly downwind $SO_2$ concentration in $\mu g/m^3$. The contour indicates the modelled concentration at the various sampling points downwind of the kiln. Sampling points 6 and 7 are located away from significant plume dispersion from the kiln and were consequently taken as background.

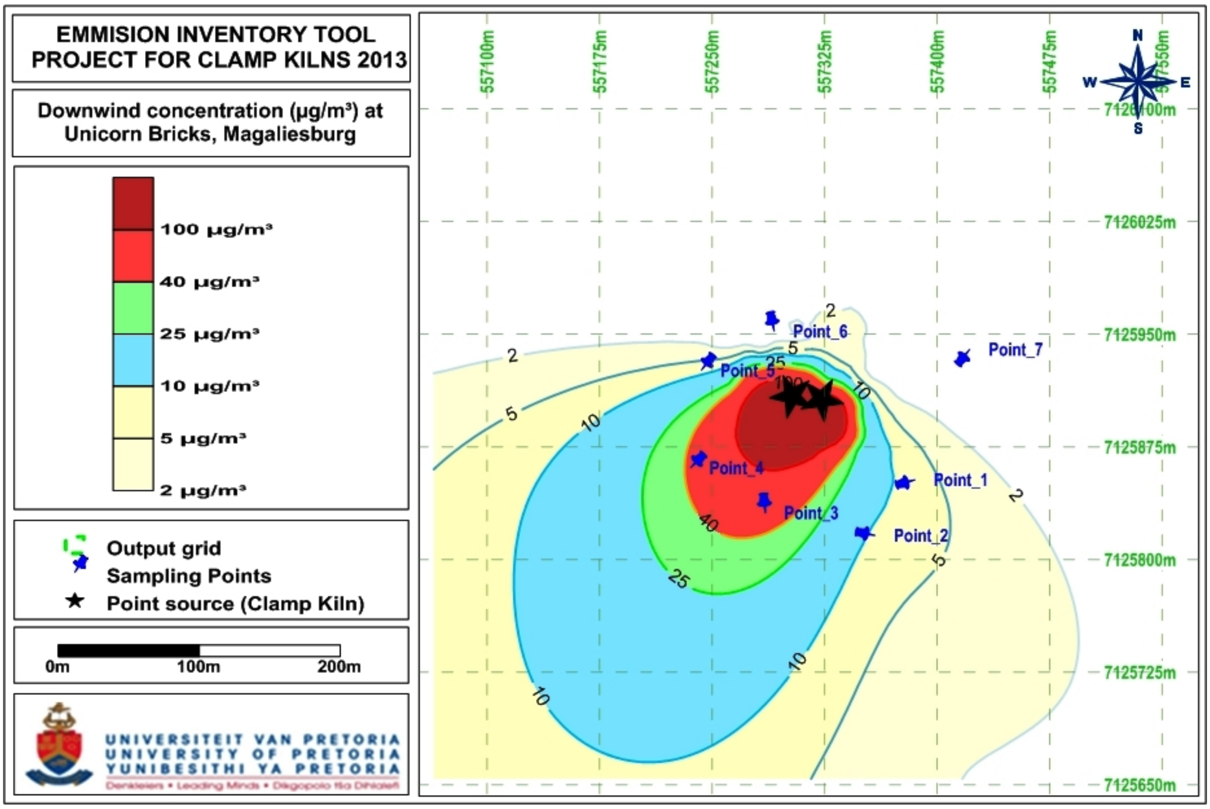


Figure 5-1: Modelled $SO_2$ hourly average concentration ($\mu g/m^3$) at Unicorn Bricks

#### 5.2.1.1.1 DESCRIPTION OF 'REVERSE-MODELLING'

Table 5-2 gives the emission rate calibration estimation as follows:

- Column B gives the values of the measured values of the ambient concentration.
- Column C deducts the ambient background concentration (4,65 $\mu g/m^3$) from the measured values.
- Column D gives the values of the modelled concentrations at an assumed emission rate of 1 g/s.
- Column E is the result of column C divided by column D, in order to generate the emission rate at the source from results at that measuring point.
- Column F gives the frequency multiplier of the wind. That is, the number of hours for which the wind was prevalent in the direction of a particular sampling point from the source. Figure 5-2, Table 5-3 and appendix F illustrate the method for estimating the frequency multiplier.

- Column G multiplies each wind multiplier factor (column F) by the implied emission rate (column E) and divides that by the total number of hours to give the average.
- Column H provides the final emission rate per brick (One million for Unicorn).

**Table 5-2: Emission rate calibration for $SO_2$**

| Point | Measured ($\mu g/m^3$) | Measured - background ($\mu g/m^3$) | Modelled (as 1 g/s) ($\mu g/m^3$) | Implied emission rate | Frequency multiplier (wind ) | Emission rate calibrated (g/s) | Emission rate calibrated ($g\ s^{-1} brick^{-1}$) |
|---|---|---|---|---|---|---|---|
| **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** |
| Point 1 | 29,19 | 24,54 | 7,41 | 3,3137 | 8 | 1,8133 | $1,8133 \times 10^{-6}$ |
| Point 2 | 56,52 | 51,87 | 9,17 | 5,6584 | 12 | | |
| Point 3 | 87,81 | 83,16 | 51,94 | 1,6011 | 89 | | |
| Point 4 | 40,59 | 35,94 | 43,21 | 0,8318 | 40 | | |
| Point 6* | 3,38 | | | | | | |
| Point 7* | 5,92 | | | | | | |

*** Taken as Background = (3,38+5,92)/2 = 4,65 $\mu g/m^3$ (Figure 5-1)**

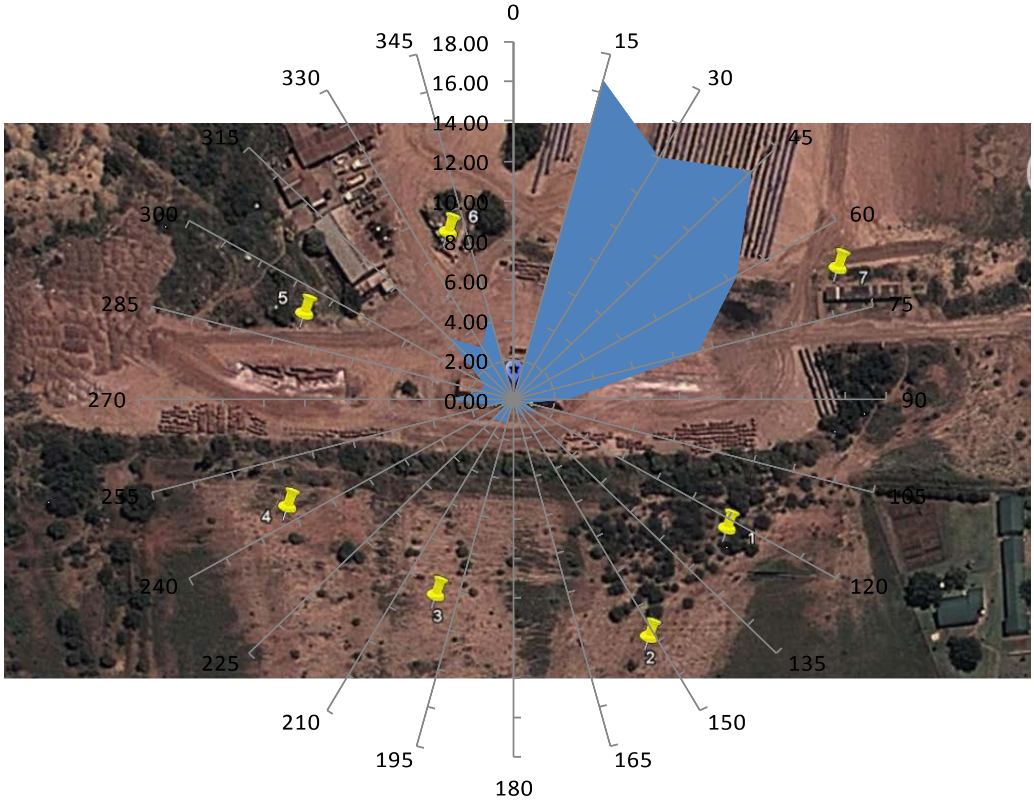


Figure 5-2: Wind rose for Unicorn Bricks indicating strength of wind direction multiplier

Table 5-3: Frequency multiplier for sampling points at Unicorn Bricks (Appendix F)

| Point | Angle ($^0$) | Frequency multiplier |
|---|---|---|
| Point 1 | 300 | 8 |
| Point 2 | 330 | 12 |
| Point 3 | 15 | 89 |
| Point 4 | 60 | 40 |
| Point 6 | 150 | 7 |
| Point 7 | 255 | 5 |

### 5.2.1.1.2 MASS BALANCE

In order to verify the accuracy of this technique, a mass balance analysis was conducted using the sulphur content in the body and external fuel of the bricks, as shown in Table 5-4. Appendix G gives the details of the complete mass balance analysis calculation.

**Table 5-4: $SO_2$ emission rate using mass balance**

| Site | Amount of bricks fired | Time (s) | Emission rate (g/s) | Emission rate (g $s^{-1}$brick$^{-1}$) |
|---|---|---|---|---|
| Unicorn Bricks | 1000000 | 1789200 | 1,4869 | 1,4869 x$10^{-6}$ |

### 5.2.2 BERT'S BRICKS, POTCHEFSTROOM

Table 5-5 gives hourly modelled and measured ambient $SO_2$ concentration from the red and white brick kiln at Bert's Bricks. Sampling was done with the two kilns operating simultaneously and it is therefore expected that varying contributions from each kiln are captured by the samplers.

The two kilns were modelled separately and the ambient concentrations were added to give a resultant concentration.

**Table 5-5: Modelled and ambient $SO_2$ concentrations at Bert's Bricks**

| Receptor | X(m) | Y(m) | Z(m) | Modelled (µg/m$^3$) | Measured (µg/m$^3$) |
|---|---|---|---|---|---|
| Point 1 | 502899 | 7040862 | 1,5 | 9,12 | 73,77 |
| Point 2 | 503071 | 7040843 | 1,8 | 2,76 | 6,06 |
| Point 3* | 503033 | 7040984 | 1,0 | 4,34 | 29,04 |
| Point 4 | 503010 | 7041124 | 1,2 | 5,55 | 9,86 |
| Point 5 | 502789 | 7040933 | 3,5 | 6,23 | 34,89 |
| Point 6 | 502914 | 7041168 | 1,0 | 2,78 | 20,79 |
| Point 7# | 502615 | 7041197 | 1,0 | 0,38 | 4,22 |
| Point 8 | 502720 | 7040434 | 1,5 | 6,80 | 21,58 |
| Point 9 | 502597 | 7040395 | 1,5 | 14,17 | 44,83 |
| Point 10* | 502757 | 7040598 | 1,2 | 6,31 | 42,96 |

# Background, * passives found on the ground

#### *5.2.2.1 $SO_2$ EMISSION RATE CALIBRATION*

Figure 5-3 and Figure 5-4 illustrate modelled average hourly downwind $SO_2$ concentration from both kilns by dispersion modelling. Emission rate was calibrated in similar fashion to that of Unicorn Bricks (Section 5.2.1.1) and is shown in Table 5-6. Emission rate for Bert's Bricks is published in Table 5-7.

The contour indicates the modelled concentration at the various sampling points downwind of the kiln. Sampling point 7 is positioned away from significant plume dispersion from both kilns and was consequently taken as background. Figure 5-5 and Figure 5-6 illustrate the wind frequency multiplier for the two kilns while Table 5-8 summarises the wind frequency data.

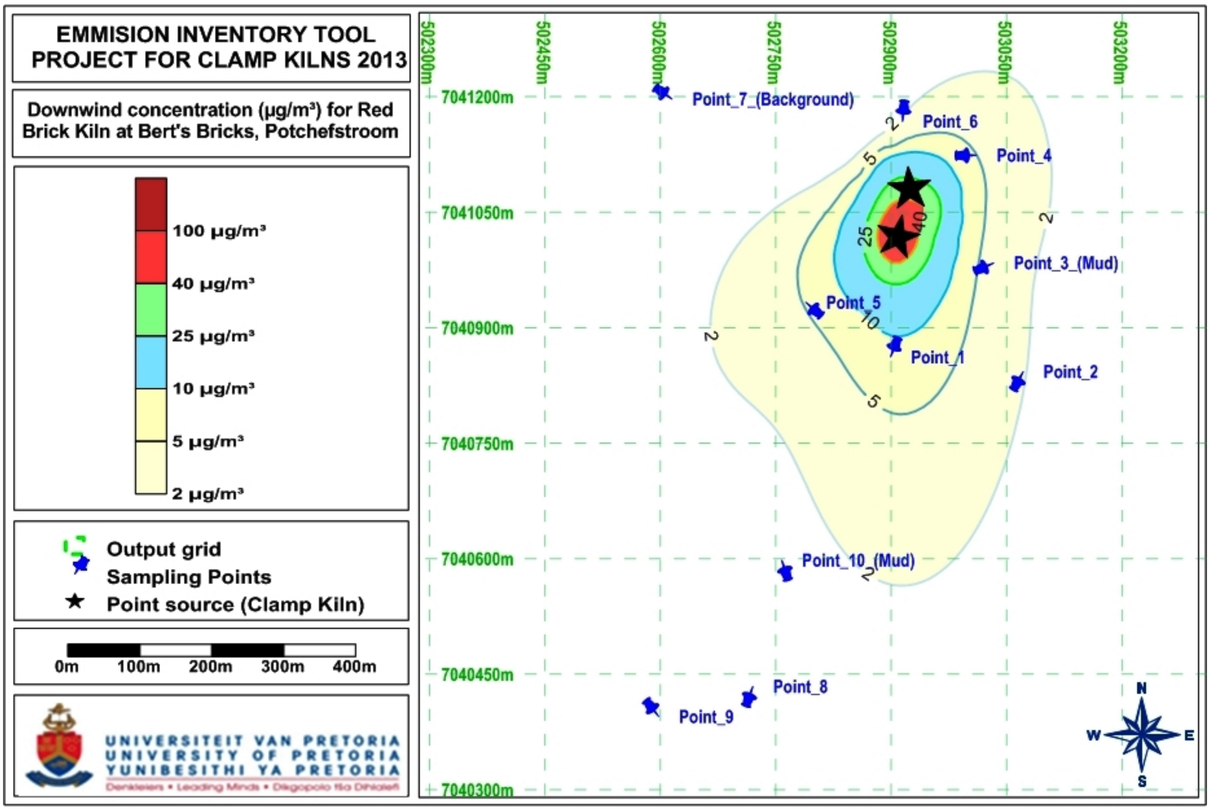


Figure 5-3: Average hourly $SO_2$ concentration for Bert's Bricks red kiln ($\mu g/m^3$)

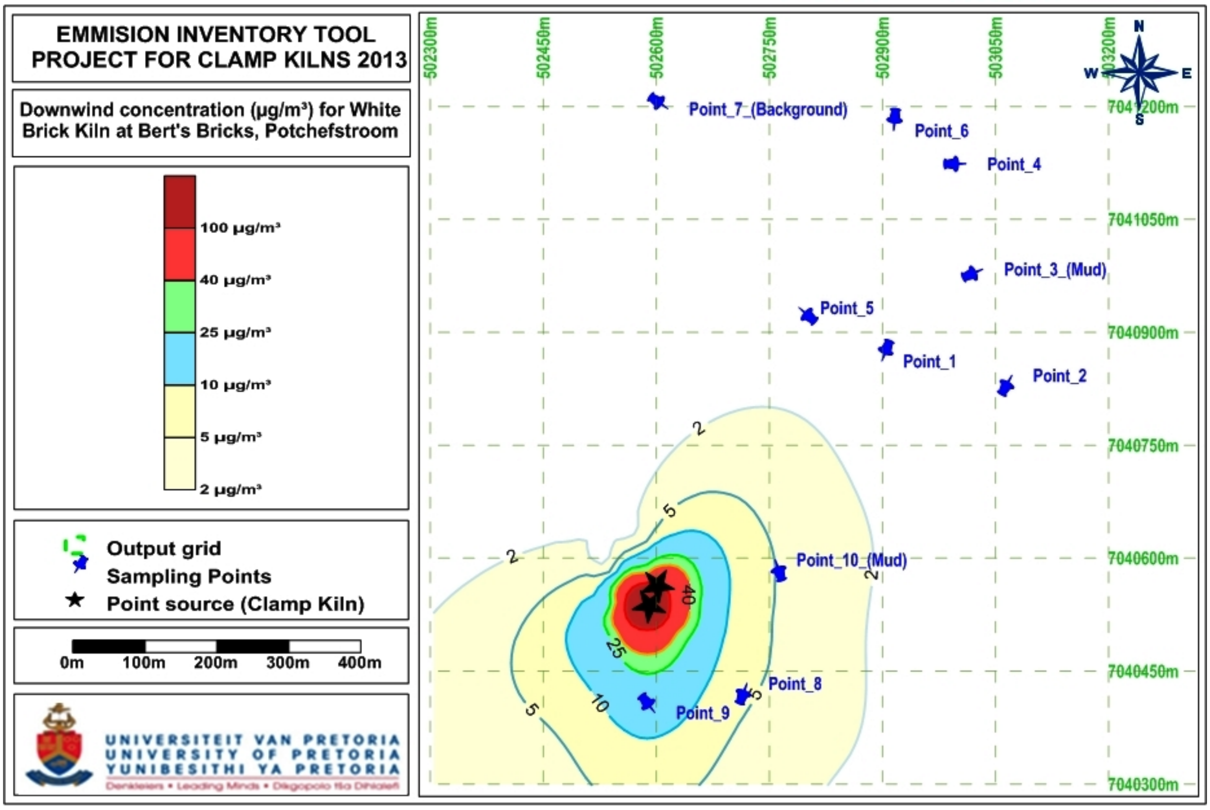


Figure 5-4: Average hourly $SO_2$ concentration for Bert's Bricks white kiln (µg/m³)

**Table 5-6: Calibration of $SO_2$ emission rate for Bert's Bricks**

| Points | Measured (µg/m$^3$) | Measured – background (µg/m$^3$) | Modelled as 1g/s (µg/m$^3$) | Implied emission rate | Frequency multiplier (wind data) | Emission rate calibrated (g/s) | Emission rate calibrated (g s$^{1}$brick$^{-1}$) |
|---|---|---|---|---|---|---|---|
| **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** |
| | | | | **Red Brick kiln** | | | |
| 1 | 73,77 | 69,55 | 9,12 | 7,6225 | 93 | 5,5638 | 9,0266 x10$^{-7}$ |
| 2 | 6,06 | 1,84 | 2,76 | 0,6667 | 18 | | |
| 3 | 29,04 | 24,82 | 4,34 | 5,7243 | 10 | | |
| 4 | 9,86 | 5,64 | 5,55 | 1,0166 | 17 | | |
| 5 | 34,89 | 30,67 | 6,23 | 4,9226 | 53 | | |
| 6 | 20,79 | 16,57 | 2,78 | 5,9621 | 16 | | |
| 7* | 4,22 | 0,00 | 0,00 | 0,0000 | 0 | | |
| | | | | **White Brick kiln** | | | |
| 8 | 21,58 | 17,36 | 6,80 | 2,5520 | 16 | 3,2942 | 3,3666 x10$^{-6}$ |
| 9 | 44,83 | 40,61 | 14,17 | 2,8665 | 52 | | |
| 10 | 42,96 | 38,74 | 6,31 | 6,1374 | 18 | | |

* taken as background

**Table 5-7: Result of $SO_2$ emission rate calibration for Bert's Bricks**

| Average $SO_2$ Emission rate for red & white Kilns combined | |
|---|---|
| g/s | 8,8580 |
| g $s^{-1}$ $brick^{-1}$ | 1,2402 x$10^{-6}$ |

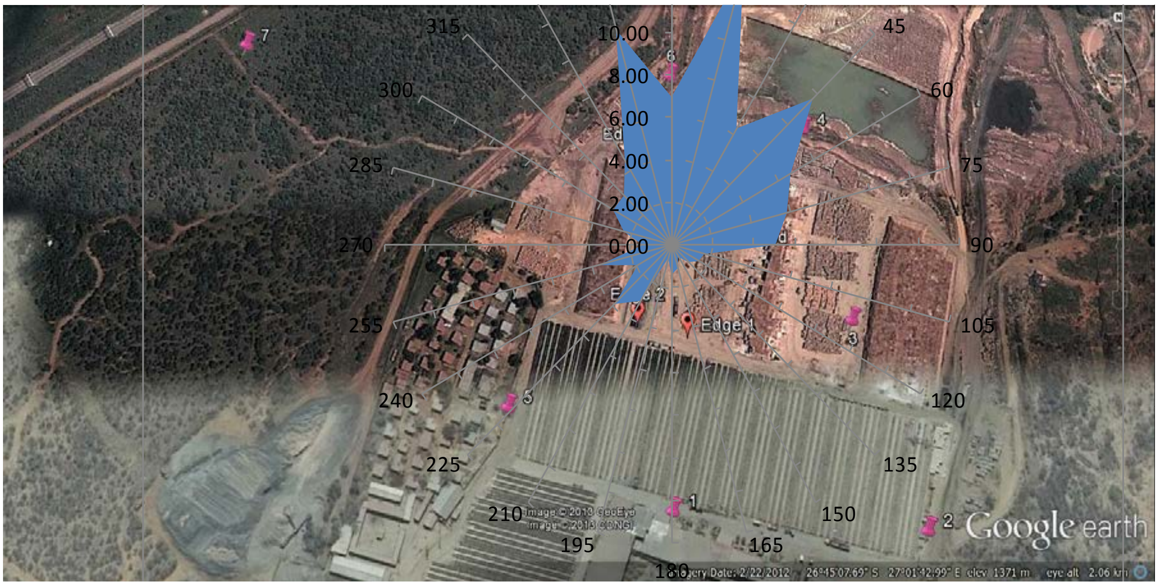


**Figure 5-5: Wind rose for Bert's Bricks red kiln indicating strength of wind direction multiplier**

**Table 5-8: Frequency multiplier for sampling points at Bert's Bricks (Appendix F)**

| Point | Angle ($^0$) | Frequency multiplier |
|---|---|---|
| Point 1 | 0 | 93 |
| Point 2 | 315 | 18 |
| Point 3 | 300 | 10 |
| Point 4 | 225 | 17 |
| Point 5 | 45 | 53 |
| Point 6 | 180 | 16 |
| Point 7 | 120 | 1 |
| Point 8 | 315 | 16 |
| Point 9 | 0 | 52 |
| Point 10 | 255 | 18 |

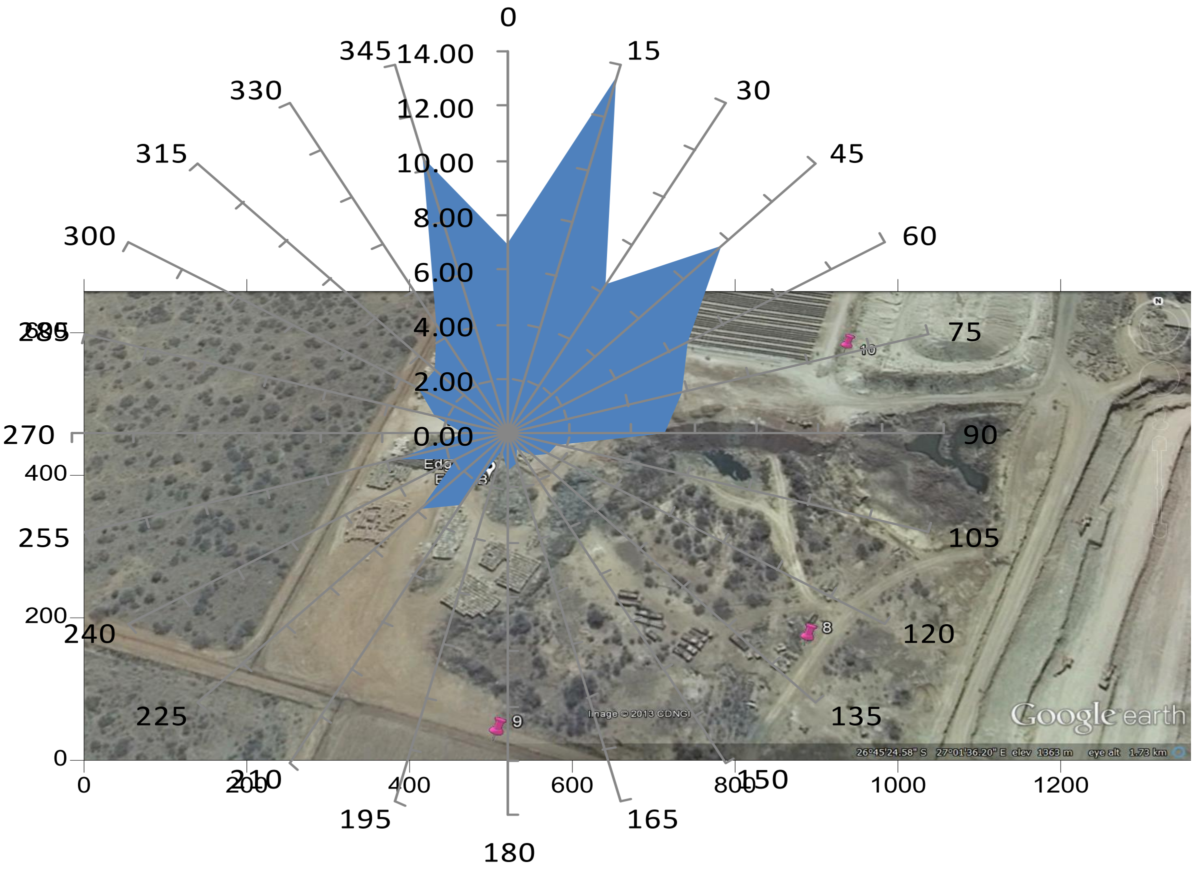


Figure 5-6: Wind rose for Bert's Bricks white kiln indicating strength of wind direction multiplier

#### 5.2.2.1.1 MASS BALANCE

Table 5-9 shows the mass balance analysis using the sulphur content in the body and external fuel at Bert's Brick. Appendix G gives the details of the mass balance calculation.

Table 5-9: $SO_2$ emission rate using mass balance analysis

| Site | Amount of bricks fired | Time (s) | Emission rate (g/s) | Emission rate (g/s/brick) |
|---|---|---|---|---|
| Bert's Bricks | 7 142 290 | 2 095 200 | 9,7265 | 1,3618 x10$^{-6}$ |

### 5.2.3 MOLOPO BRICKS, MAHIKENG

Table 5-10 gives the modelled and measured ambient concentration of $SO_2$ at Molopo Bricks. Six samplers were placed downwind of the clamp and one upwind to measure background concentration.

Point 1 (background) sampler returned higher $SO_2$ concentration than expected. At the time of picking up the sampler, it was discovered that garbage burning had taken place nearby. Hence, sampling point 2 was taken as a suitable background for $SO_2$ calibration (Figure 5-7).

**Table 5-10: Ambient and modelled $SO_2$ concentrations at Molopo Bricks**

| Sample | X(m) | Y(m) | Z(m) | Modelled (µg/m$^3$) | Measured (µg/m$^3$) |
|---|---|---|---|---|---|
| Point 1 | 352370 | 7133813 | 1,8 | 2,33 | 3,62 |
| Point 2 | 352474 | 7133464 | 4,0 | 6,76 | 1,83 |
| Point 3 | 352438 | 7133445 | 4,0 | 8,84 | 14,02 |
| Point 4 | 352372 | 7133395 | 4,0 | 13,23 | 24,05 |
| Point 5 | 352314 | 7133413 | 4,0 | 26,33 | 16,66 |
| Point 6 | 352280 | 7133446 | 4,0 | 30,23 | 30,99 |
| Point 7 | 352232 | 7133458 | 5,0 | 16,73 | 66,91 |

#### *5.2.3.1 $SO_2$ EMISSION RATE CALIBRATION*

Table 5-11 illustrates $SO_2$ emission rate calibration for Molopo Bricks using similar calibration procedures as described for Unicorn Bricks in Section 5.2.2.1.

Figure 5-7 illustrates the modelled average hourly downwind $SO_2$ concentration in µg/m$^3$. The contour indicates the modelled concentration at the various sampling points downwind of the kiln. Sampling points 1, 2 and 3 are located away from significant plume dispersion from the kiln. Sampling point 2 was taken as background instead of point 1 as explained in 5.2.3 above. Table 5-12 indicates the wind frequency multipliers for each sampling point.

Molopo Bricks utilizes lower energy input to bricks-fired ratio, relative to the other two sites. Therefore, its relatively low $SO_2$ emission rate and emission factor may be attributed to its lower energy input relative to the other two sites.

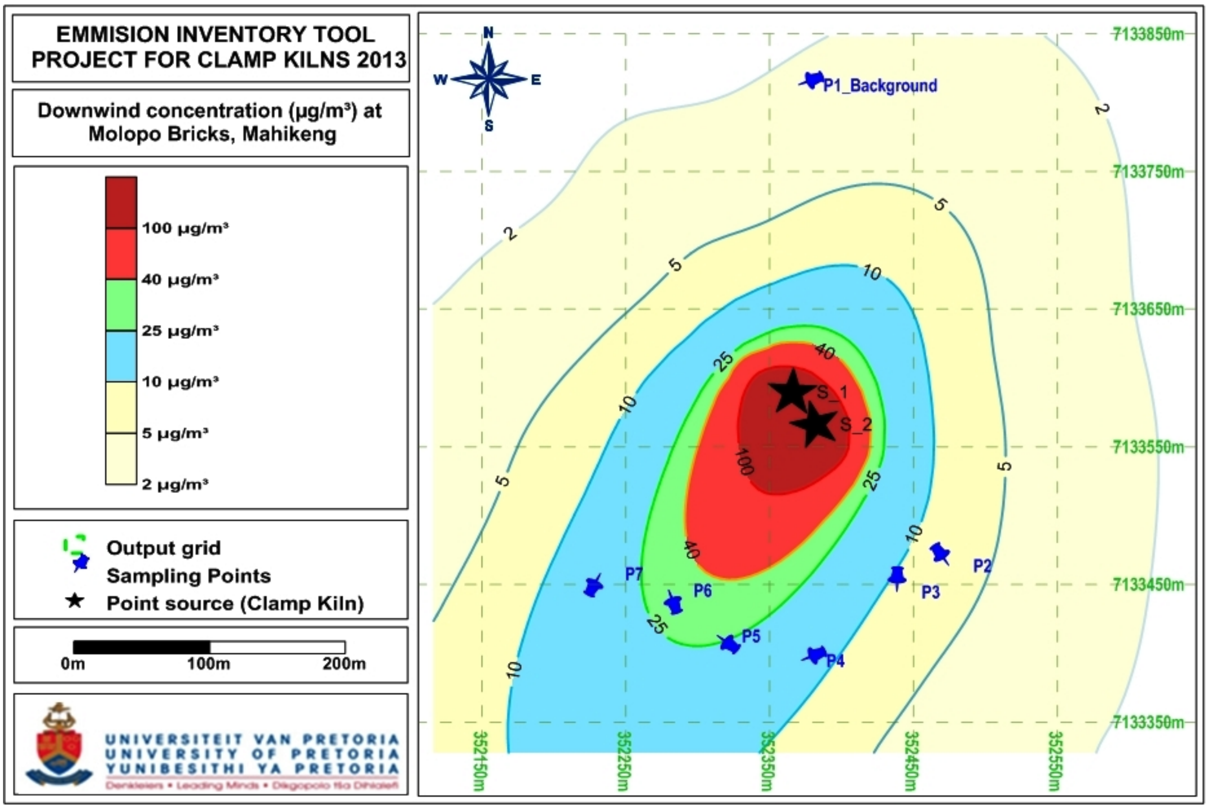


Figure 5-7: Average hourly $SO_2$ concentration for Molopo Brick kiln in µg/m³

**Table 5-11: Emission rate calibration for $SO_2$ at Molopo Bricks**

| Point | Measured (μg/m$^3$) | Measured - background (μg/m$^3$) | Modelled (as 1 g/s) (μg/m$^3$) | Implied emission rate | Frequency multiplier (wind ) | Emission rate calibrated (g/s) | Emission rate calibrated (g s$^{-1}$brick$^{-1}$) |
|---|---|---|---|---|---|---|---|
| **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** |
| Point 1 | 3,62 | 1,79 | 2,33 | 0,7690 | 14 | 1,3860 | 6,0260 x10$^{-7}$ |
| Point 2* | 1,83 | 0,00 | 6,76 | 0,0000 | 0 | | |
| Point 3 | 14,02 | 12,19 | 8,84 | 1,3792 | 25 | | |
| Point 4 | 24,05 | 22,22 | 13,23 | 1,6792 | 47 | | |
| Point 5 | 16,66 | 14,83 | 26,33 | 0,5632 | 149 | | |
| Point 6 | 30,99 | 29,16 | 30,23 | 0,9647 | 119 | | |
| Point 7 | 66,91 | 65,08 | 16,73 | 3,8897 | 67 | | |

*Taken as background

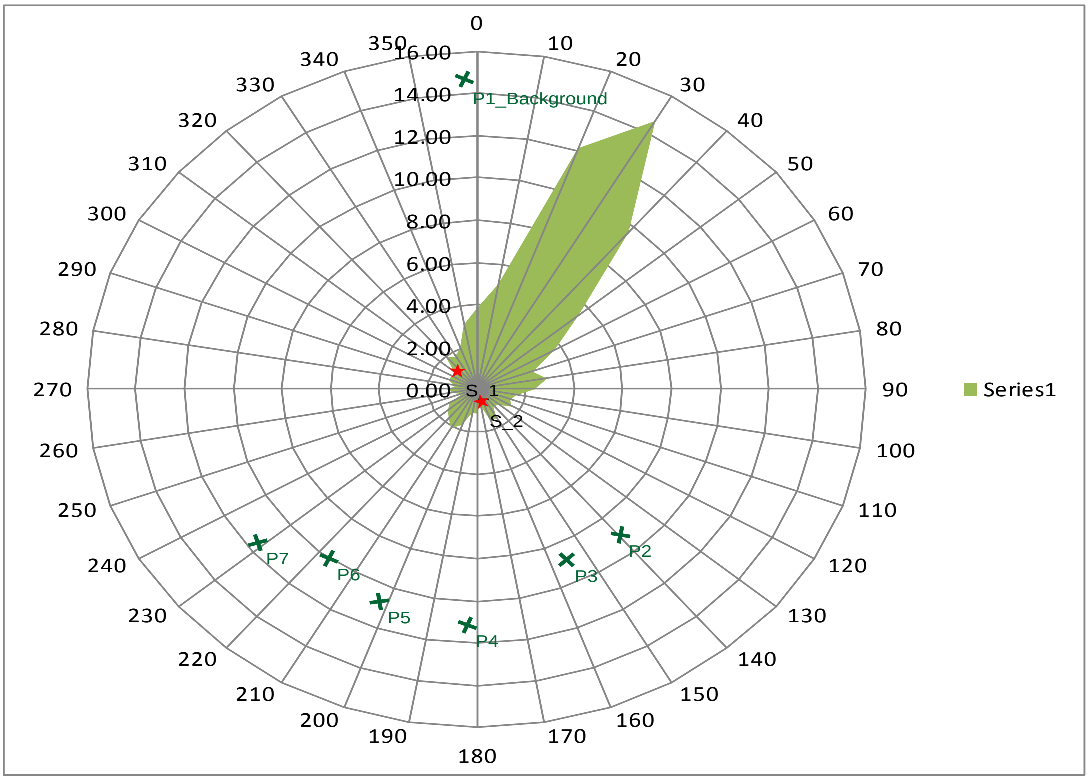


**Figure 5-8: Wind rose for Molopo Bricks kiln indicating strength of wind direction multiplier**

**Table 5-12: Frequency multiplier for sampling points at Molopo Bricks (Appendix F)**

| Point | Angle ($^0$) | Frequency multiplier |
|---|---|---|
| Point 1 | 180 | 14 |
| Point 2 | 320 | 24 |
| Point 3 | 340 | 25 |
| Point 4 | 0 | 47 |
| Point 5 | 20 | 149 |
| Point 6 | 40 | 119 |
| Point 7 | 50 | 67 |

### 5.2.3.1.1 MASS BALANCE

$SO_2$ mass balance analysis could not be obtained for Molopo Bricks due to inconsistency of laboratory results for the “green” and fired bricks. The mass balance analysis returned a higher $SO_2$ concentration in the fired brick than the green brick, which is impossible. A repeated analysis was carried out twice with similar outcome, indicating possible irregularities in the bricks that were used for sampling.

However, analysis of coal-ash (external fuel) sulphur content was successfully carried out and used as a standard for the three sites, as shown in Table 5-13. It was included in the mass balance calculation for the other two sites. The complete mass balance analysis is detailed in appendix G.

**Table 5-13: $SO_2$ emission rate for external fuel using mass balance calculation**

| Site | Amount of bricks fired | Time (s) | Emission rate (g/s) | Emission rate (g $s^{-1}$brick$^{-1}$) |
|---|---|---|---|---|
| Molopo Bricks | 3200000 | 4410000 | 0,6021 | 1,8816 x$10^{-7}$ |

### 5.2.4 $SO_2$ EMISSION RATE AVERAGE

Average emission rate for the three sites is calculated in Table 5-14 using the "reverse-modelling" results.

**Table 5-14: SO2 emissions rate average for the three sites**

| Site | Amount of bricks fired | Emission rate (g $s^{-1}$brick$^{-1}$) | Average emission rate (g $s^{-1}$brick$^{-1}$) |
|---|---|---|---|
| Unicorn Bricks | 1000000 | 1,8133 x$10^{-6}$ | 7,4519 x$10^{-7}$ |
| Bert's Bricks | 7142290 | 1,2402 x$10^{-6}$ | |
| Molopo Bricks | 3200000 | 4,3312 x$10^{-7}$ | |

### 5.2.5 $SO_2$ EMISSION FACTOR AVERAGE

Average $SO_2$ emission factors in g/brick and in Kg of $SO_2$ per ton of brick fired (Kg/Mg), are shown in Table 5-15 (using the "reverse-modelling" results).

**Table 5-15: SO2 emission factor average for the three sites**

| Site | Amount of bricks fired | Emission factors (g brick$^{-1}$) | Emission factors (Kg/Mg) | Average emission factor (g brick$^{-1}$) | Average emission factor (Kg/Mg) |
|---|---|---|---|---|---|
| Unicorn Bricks | 1000000 | 3,2444 | 1,1435 | 2,0603 | 0,7262 |
| Bert's Bricks | 7142290 | 2,5985 | 0,9158 | | |
| Molopo Bricks | 3200000 | 1,9101 | 0,6732 | | |

It was deduced that the relatively low emission factor recorded from Molopo Bricks (Table 5-15) may be due to the low energy input when compared to the other two sites (Table 5-16).

**Table 5-16: Percentage carbon in "green" bricks**

| Site | % Carbon in "green" brick |
|---|---|
| Unicorn Bricks | 4,10 |
| Bert's Bricks | 2,50 |
| Molopo Bricks | 1,78 |

The analysis above could be utilized in proposing emission reduction strategies with respect to production and cost analysis.

### 5.2.6 MASS BALANCE AND "REVERSE-MODELLING" TECHNIQUE

Table 5-17 compares the emission rate from mass balance and from the "reverse-modelling" technique for the two sites for which mass balance could be done.

The "reverse-modelling" technique and "bi-point" source configuration produced $SO_2$ emission rates differing from -9 % to +22 % (Bert's and Unicorn Bricks respectively) from mass balance results, indicating that the "reverse-modelling" calculations provide reliable emission estimates for $SO_2$.

Therefore, it can be concluded for this study that the range of uncertainty of the "reverse-modelling" technique using a bi-point source configuration is from -9% to

22%. This is an improvement on conventional dispersion modelling range of -50% to 200% (Burger et al, 2008).

**Table 5-17: Comparing $SO_2$ emission rates from mass balance and "reverse-modelling" technique**

| Site | "Reverse-modelling" (g $s^{-1}brick^{-1}$) | Mass balance (g $s^{-1}brick^{-1}$) | % range of variation |
|---|---|---|---|
| Unicorn Bricks | 1,8133 $x10^{-6}$ | 1,4869 $x10^{-6}$ | +22 |
| Bert's Bricks | 1,2402 $x10^{-6}$ | 1,3618 $x10^{-6}$ | -9 |

$SO_2$ Mass balance analysis could not be performed for Molopo bricks. This is discussed in Section 5.2.3.1.1.

### 5.2.7 COMPARING "BI-POINT", AREA AND VOLUME SOURCE MODELLING

Table 5-18 compares the results of the emission rate calibrated for the three sites using three different source configurations. The low emission rate values for the area and volume source calibration suggest that the "bi-point" source configuration provides a better modelling option for clamp kiln "reverse-modelling" technique, as well as for any volume source with an internal energy source.

Similar modelling options to the description in section 4.3 for the "bi-point" source were utilized for the area and volume source. The emission rate was assumed as 1 g/s and the momentum flux of emission remained the same for all three source types (1 $m^4/s^2$). The heat flux for the "bi-point" and area source was calculated from the energy input as published in section 4.3; while the volume source in ADMS 4.2 does not utilize heat flux in dispersion modelling (discussed in Section 4.4 of this report).

The area source configuration for the kiln was assumed to be a flat elevated surface at the level of the kiln top and having the base dimension of the kiln.

The volume source configuration assumes the kiln to be cuboid shaped with a consistent top and base dimension similar to the dimension of the base of the kiln.

**Table 5-18: "Back-modelled" $SO_2$ emission rate for "bi-point", area and volume source configurations**

| Site | "Bi-point" source | Area source | Volume source |
|---|---|---|---|
| Unicorn Bricks | $1{,}8133 \times 10^{-6}$ | $8{,}0987 \times 10^{-7}$ | $5{,}1821 \times 10^{-7}$ |
| Bert's Bricks | $1{,}2402 \times 10^{-6}$ | $5{,}0776 \times 10^{-7}$ | $3{,}6579 \times 10^{-7}$ |
| Molopo Bricks | $4{,}3312 \times 10^{-7}$ | $2{,}7265 \times 10^{-7}$ | $2{,}1477 \times 10^{-7}$ |

### 5.2.8 CALIBRATION OF SULPHUR CONTENT IN FUEL

$SO_2$ emission from clamp kiln firing is a function of the sulphur content (%) of the fuel used. The $SO_2$ emission factor published in Section 5.2.5 is based on average sulphur content of 0,64% from the three sites investigated (Table 3-9).

Therefore, in order to generate a site specific emission factor with respect to percentage of sulphur in the coal, the empirical expression below was factored into the emission inventory tool:

$$\boldsymbol{EF_s = \left(\frac{S_s}{S_a}\right) EF_a} \qquad \textbf{(Equation 5-1)}$$

Where: $EF_s$ = Emission factor for a particular site, g $brick^{-1}$ or Kg/Mg

$S_s$ = Percentage sulphur for a particular site, %

$S_a$ = Percentage sulphur average from the study, %

$EF_a$ = Emission factor average from the study, g $brick^{-1}$ or Kg/Mg

The final empirical expression is given as:

$$\boldsymbol{EF_s = \left(\frac{S_s}{0{,}64}\right) 0{,}7264^{*}} \qquad \textbf{(Equation 5-2)}$$

* 0,7264 is in Kg/Mg

**NOTE:** Molecular weight of $SO_2$ is double that of sulphur, but cancels out when entered into the expression.

## 5.3 NITROGEN DIOXIDE, $NO_2$

### 5.3.1 UNICORN BRICKS, MAGALIESBURG

Table 5-19 shows the modelled and ambient concentration of $NO_2$ downwind of the brick kiln. A unit emission rate of 1 g/s was assumed for the dispersion modelling.

**Table 5-19: Modelled and ambient $NO_2$ concentrations at Unicorn Bricks**

| Receptor | X(m) | Y(m) | Z(m) | Modelled (µg/m$^3$) | Measured (µg/m$^3$) |
|---|---|---|---|---|---|
| Point 1 | 557385 | 7125853 | 1 | 7,41 | 5,49 |
| Point 2 | 557358 | 7125816 | 1 | 9,17 | 7,14 |
| Point 3 | 557285 | 7125831 | 1 | 51,94 | 14,01 |
| Point 4 | 557235 | 7125861 | 1 | 43,21 | 8,61 |
| Point 5 | 557242 | 7125926 | 1 | 7,93 | Missing |
| Point 6 | 557291 | 7125952 | 1 | 2,81 | 4,39 |
| Point 7 | 557421 | 7125940 | 1 | 0,46 | 4,78 |

The $NO_2$ emission rate could not be calibrated due to the irregularity of the ambient $NO_2$ concentration downwind of the kiln. Sampling points taken as background for $SO_2$ returned relatively higher $NO_2$ concentration presumably due to the presence of other onsite air emission sources such as internal combustion engines. Consequently, actual $NO_2$ background concentration could not be obtained and the emission rate calibration technique could not be performed.

The high concentration of $NO_2$ was linked to emission from diesel engines (vehicles and machinery). Monthly diesel consumption was obtained from Unicorn Bricks and emission factor for industrial diesel engines was obtained from USEPA (1997a). Emission calculation from vehicles and machinery on site is shown in Table 5-20.

**Table 5-20: Monthly emissions from internal combustion engines at Unicorn Bricks**

| Parameter | Value |
|---|---|
| Emission factor (lb/MMBtu)[a] | 4,40 |
| Emission factor (ng/J)[a] | 1896,30 |
| Energy content of diesel (MJ/L)[b] | 35,85 |
| Monthly diesel consumption (L)[c] | 6500,00 |
| Monthly energy consumption (J) | $2,33 \times 10^{11}$ |
| Monthly emission (Kg/month) | 442,01 |

[a] obtained from USEPA (1997a)

[b] obtained from Rand (2003)

[c] obtained from Unicorn Bricks

lb/MMBtu = pounds per million British thermal unit

ng/J = nanogram per joule

MJ/L = Megajoule per litres

### 5.3.2 BERT'S BRICKS, POTCHEFSTROOM

A challenge similar to Unicorn Bricks was encountered for Bert's Bricks. $NO_2$ emission from vehicles and machinery on site is significant enough to affect ambient concentration. Sampling point 7 was placed away from site vehicle traffic, but it was close to the N12 highway and it registered significant $NO_2$ emissions (Figure 3-12 and Figure 3-14). A unit emission rate of 1 g/s was assumed for the dispersion modelling values in Table 5-21. Some passive samplers were missing or found on the ground.

## Table 5-21: Modelled and sampled $NO_2$ concentrations at Bert's Bricks

| Receptor | X(m) | Y(m) | Z(m) | Modelled (μg/$m^3$) | Measured (μg/$m^3$) |
|---|---|---|---|---|---|
| Point 1 | 502899 | 7040862 | 1,5 | 9,12 | 21,82 |
| Point 2 | 503071 | 7040843 | 1,8 | 2,76 | 13,44 |
| Point 3* | 503033 | 7040984 | 1,0 | 4,34 | 1,56 |
| Point 4 | 503010 | 7041124 | 1,2 | 5,55 | 12,19 |
| Point 5 | 502789 | 7040933 | 3,5 | 6,23 | 10,45 |
| Point 6 | 502914 | 7041168 | 1,0 | 2,78 | 10,72 |
| Point 7# | 502615 | 7041197 | 1,0 | 0,38 | 12,32 |
| Point 8 | 502720 | 7040434 | 1,5 | 6,80 | 18,29 |
| Point 9 | 502597 | 7040395 | 1,5 | 14,17 | 21,21 |
| Point 10* | 502757 | 7040598 | 1,2 | 6,31 | 1,30 |

# Background, * passives found on the ground

Emission calculation for $NO_2$ from vehicles and machinery on site is shown in Table 5-22. Monthly diesel consumption was obtained from Bert's Bricks while the emission factor for internal combustion engines was obtained from USEPA (1997a).

## Table 5-22: Monthly emissions from internal combustion engines at Bert's Bricks

| Parameter | Value |
|---|---|
| Emission factor (lb/MMBtu)[a] | 4,40 |
| Emission factor (ng/J)[a] | 1896,30 |
| Energy content of diesel (MJ/L)[b] | 35,85 |
| Monthly diesel consumption (L)[c] | 27892,67 |
| Monthly energy consumption (J) | 1,00 x$10^{12}$ |
| Monthly emission (Kg/month) | 1896,70 |

[a] obtained from USEPA (1997a)

[b] obtained from Rand (2003)

[c] obtained from Unicorn Bricks

lb/MMBtu = pounds per million British thermal unit

ng/J = nanogram per joule

MJ/L = Megajoule per litres

### 5.3.3 MOLOPO BRICKS, MAHIKENG

Table 5-23 shows ambient and modelled $NO_2$ concentration at Molopo Bricks. A unit emission rate of 1 g/s was assumed for the dispersion modelling. In similar fashion to Unicorn and Bert's Bricks, the $NO_2$ emission rate calibration could not be performed due to $NO_2$ emitting vehicles operating all around the factory yard and near the passives.

Passive sampler 1 was positioned at a significant distance away from the factory yard to serve as background. However, at the time of picking up the sampler, it was discovered that garbage burning had taken place nearby. The sampler therefore returned a higher $NO_2$ concentration than was expected.

Actual $NO_2$ background could, therefore not be obtained and emission rate calibration technique could not be conducted for the kiln.

**Table 5-23: Modelled and ambient $NO_2$ concentrations at Molopo Bricks**

| Receptor | X(m) | Y(m) | Z(m) | Modelled (μg/m$^3$) | Measured (μg/m$^3$) |
|---|---|---|---|---|---|
| Point 1 | 352370 | 7133813 | 1,8 | 2,33 | 4,17 |
| Point 2 | 352474 | 7133464 | 4,0 | 6,76 | 4,38 |
| Point 3 | 352438 | 7133445 | 4,0 | 8,84 | 4,23 |
| Point 4 | 352372 | 7133395 | 4,0 | 13,23 | 5,34 |
| Point 5 | 352314 | 7133413 | 4,0 | 26,33 | 0,38 |
| Point 6 | 352280 | 7133446 | 4,0 | 30,23 | 2,01 |
| Point 7 | 352232 | 7133458 | 5,0 | 16,73 | 5,47 |

Emission calculation for $NO_2$ from vehicles and machinery on site is shown in Table 5-24. Monthly diesel consumption was obtained from Molopo Bricks while the emission factor for industrial diesel engines was obtained from USEPA (1997a).

**Table 5-24: Monthly emissions from internal combustion engines at Molopo Bricks**

| Parameter | Value |
|---|---|
| Emission factor (lb/MMBtu)[a] | 4,40 |
| Emission factor (ng/J)[a] | 1896,30 |
| Energy content of diesel (MJ/L)[b] | 35,85 |
| Monthly diesel consumption (L)[c] | 7653,33 |
| Monthly energy consumption (J) | 2,74 x$10^{11}$ |
| Monthly emission (Kg/month) | 520,29 |

[a] obtained from USEPA (1997a)

[b] obtained from Rand (2003)

[c] obtained from Unicorn Bricks

lb/MMBtu = pounds per million British thermal unit

ng/J = nanogram per joule

MJ/L = Megajoule per litres

### 5.3.4 $NO_2$ EMISSION RATE AND EMISSION FACTOR

The analysis provided in Sections 5.3.1 to 5.3.3 shows a high $NO_2$ release from vehicles moving around the factory yard and from other internal combustion engines used for material processing. This presents a challenge because emissions from moving vehicles cannot be modelled or monitored at a particular location.

Therefore, $NO_2$ emission rate was obtained from Burger *et al,* (2008) as **1,7 x$10^{-7}$ g $s^{-1}$brick$^{-1}$**. Details of the study is presented in Section 2.5. Final emission rate and emission factor for $NO_2$ are inferred from the study and published in Table 5-25.

DEAT (2008) suggested that $NO_2$ emission generated from clamp kilns may be low due to low temperature and lack of excess oxygen.

**Table 5-25: $NO_2$ emission rate and emission factor for clamp kiln (adapted from Burger *et al,* 2008)**

| Description | Value |
|---|---|
| Emission rate (g/s) | 0,1500 |
| Emission rate (g $sec^{-1}$ $brick^{-1}$) | 1,6968 $x10^{-7}$ |
| Emission factor (g/brick) | 0,3079 |
| Emission factor (kg/Mg) | 0,1085 |

*Firing time = 21 days or 1814400s, clamp kiln capacity = 884,000 bricks

### 5.3.5 $NO_2$ EMISSION FROM KILN AND EXTERNAL SOURCES

Table 5-26 compares the monthly $NO_2$ emission from the kiln (taking results from Table 5-25) with $NO_2$ emissions from other onsite air emission sources such as internal combustion engines (taking results from Table 5-20, Table 5-22 and Table 5-24). It is assumed that there are no abatement mechanisms in place for $NO_2$ emission from internal combustion engines and that all engine types function in similar manner.

**Table 5-26: Monthly $NO_2$ emissions from internal combustion engines and clamp kilns**

| Site | Emission from internal combustion engines (Kg) | Emission from kiln (Kg) | %* |
|---|---|---|---|
| Unicorn Bricks | 442,01 | 446,05 | 99,09 |
| Bert's Bricks | 1896,70 | 2720,55 | 69,72 |
| Molopo Bricks | 520,29 | 537,43 | 96,81 |

* This is the percentage ratio of emissions from internal combustion engine to emissions from the kiln

The high percentage ratio of emission from internal combustion engines to emission from clamp kilns in Table 5-26 explains the high ambient $NO_2$ concentrations obtained from the passive samplers.

## 5.4 PARTICULATE MATTER, $PM_{10}$

Emission rate and emission factor for $PM_{10}$ was adopted from previous study by Burger *et al,* 2008 (discussed in Section 2.5). Table 5-27 was inferred from the study.

**Table 5-27: $PM_{10}$ emission rate and emission factor for clamp kiln (adapted from Burger *et al,* 2008)**

| Description | Value |
|---|---|
| Emission rate (g/s) | 3,2100 |
| Emission rate (g $sec^{-1}$ $brick^{-1}$) | 3,6312 $x10^{-6}$ |
| Emission factor (g/brick) | 6,5884 |
| Emission factor (kg/Mg) | 2,3221 |

*Firing time = 21 days or 1814400s, clamp kiln capacity = 884,000 bricks

The draft emission inventory tool returned by 29 clamp kiln operators indicate that $PM_{10}$ emission from the factory yard (which consists of material handling, vehicular movement on paved roads, vehicular movement on unpaved roads, and crushing and screening activities) is less than 10% of $PM_{10}$ emission from the kiln based on the above emission factor. Table 5-28 shows the calculation.

It should be noted that this Table 5-28 was generated based on site data as reported by site operators.

**Table 5-28: Comparing $PM_{10}$ emissions from factory yard and clamp kiln**

| Source | Average emissions |
|---|---|
| Factory Yard (tons/year)* | 798,11 |
| Clamp kiln (tons/year) | 8560,2 |
| % of factory yard to clamp kiln (%) | 9,32 |

* Factory yard emissions includes fugitive emissions from material handling, vehicular movement on paved roads, vehicular movement on unpaved roads, and crushing and screening.

## 5.5 EMISSION FACTOR RATING

USEPA (1995a) defines emission factor rating as “a general indication of reliability or robustness” of an emission factor. Emission factor ratings are assigned based on the projected reliability of the tests and techniques utilized in developing the emission factors (USEPA, 1997d).

USEPA (1995a) provides the description for assigning emission factor rating as follows:

> A — Excellent. Factor is developed from A- and B-rated source test data taken from many randomly chosen facilities in the industry population. The source category population is sufficiently specific to minimize variability.
>
> B — Above average. Factor is developed from A- or B-rated test data from a "reasonable number" of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. As with an A rating, the source category population is sufficiently specific to minimize variability.
>
> C — Average. Factor is developed from A-, B-, and/or C-rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. As with the A rating, the source category population is sufficiently specific to minimize variability.
>
> D — Below average. Factor is developed from A-, B- and/or C-rated test data from a small number of facilities, and there may be reason to suspect that these facilities do not represent a random sample of the industry. There also may be evidence of variability within the source population.
>
> E — Poor. Factor is developed from C- and D-rated test data, and there may be reason to suspect that the facilities tested do not represent a random sample of the industry.

Based on the description above, emission factors generated from this investigation are best assigned a rating of 'B'- an above average rating based on A-rated test data from three sites.

Emission factors generated from empirical expression in the AP 42 documents retain their assigned ratings while ratings for emission factors from Burger *et al,* (2008) are not given.

# 6 CONCLUSIONS AND RECOMMENDATIONS

## 6.1 CONCLUSIONS

This study was carried out to develop a tool that can be used to calculate $SO_2$, $NO_2$ and $PM_{10}$ emissions from brick clamp kilns based on easily measured operational parameters. This section summarizes the findings of the research work and provides recommendations based on these outcomes.

### 6.1.1 EMISSION INVENTORY TOOL

The primary purpose of the study was to generate emission factors for all activities on clamp kiln sites that release significant $SO_2$, $NO_2$, and $PM_{10}$ emissions.

The following activities that generate significant $SO_2$, $NO_2$, and $PM_{10}$ emissions on a clamp kiln site were investigated:

- Material handling activities;
- Vehicular movement on paved roads;
- Vehicular movement on unpaved roads;
- Crushing and screening activities; and
- Clamp kiln firing.

- $PM_{10}$ Emission factors for material handling, vehicular movement on paved roads, vehicular movement on unpaved roads, and crushing and screening activities were generated using empirical expressions from the USEPA AP 42 documents.

- $SO_2$ emission factor for clamp kiln was developed from the “reverse-modelling” technique. Findings of the technique are detailed in Section 6.1.2.

- $NO_2$ emission factor for clamp kiln could not be obtained from the "reverse-modelling" technique as proposed at the commencement of the study. This is due to:

  - Unforeseen errors, such as loss of passive samplers (due to rain and/or human interference) and garbage burning around samplers.

  - High $NO_2$ emissions from other onsite air emission sources such as internal combustion engines.

  It was concluded from the study that the impact of this errors and external sources of $NO_2$ emissions posed a significant threat to the scientific validation of the "reverse-modelling" technique as an effective technique for estimating the $NO_2$ emission factor from clamp kiln. Consequently, $NO_2$ emission factor for clamp kiln was obtained from Burger *et al,* (2008) and integrated into the emission inventory tool.

- $PM_{10}$ emission factor for clamp kilns was obtained from Burger *et al,* (2008), a comprehensive investigation on a similar clamp kiln site.

  It was discovered from the draft emission inventory tool returned by 29 clamp kiln operators that the percentage of fugitive $PM_{10}$ emission from the factory yard to the emission from the brick kiln is about 9.32 %.

Final $SO_2$, $NO_2$, and $PM_{10}$ emissions for each activity are calculated by the integration of these emission factor expressions with other easily accessible, site specific parameters. The tool was developed using Microsoft Excel (2010) spreadsheet and can be used by site operators to generate their sites' $SO_2$, $NO_2$, and $PM_{10}$ emissions as proposed at commencement of the project. Pages of the final emission inventory tool are shown in appendix A.

### 6.1.2 “REVERSE-MODELLING” TECHNIQUE

The secondary purpose of this study was to validate the “reverse-modelling” technique. The technique generates emission factors for $SO_2$, and $NO_2$ emissions from brick clamp kiln firing by graduating measured ambient concentration against modelled concentration at an assumed emission rate of 1 g/s to generate the actual emission rate at the source.

Validation was done for $SO_2$ emissions only. This was done by comparing the $SO_2$ results from “reverse-modelling” with $SO_2$ results by mass balance analysis of sulphur content present in the clay and ash pre- and post-firing.

The following conclusions are drawn from the study:

- The “reverse-modelling” technique results are comparable to results from the standard mass balance analysis. The range of uncertainty achieved for this study is -9 % to +22 %, an improvement on conventional prediction range of -50% to 200%. The technique is therefore an effective means of calculating emission factors from clamp kilns and from sources of air pollution with a similar configuration, provided that an estimate can be made of the heat generation rate or buoyancy.

- The source configuration assumed to represent the kiln was changed from a volume source to an elevated “bi-point” source situated at the level of the kiln top, with buoyancy calculated from the carbon combustion rate. The “bi-point” source emission rate was compared with conventional volume and area source emission rates.

  It was concluded that the “bi-point” source offered a more effective means of modelling clamp kiln than the conventional area or volume source types.

- It was also discovered that $NO_2$ emissions from internal combustion engines (vehicles and machinery) on site are significant enough to impact on the accuracy of the “reverse-modelling” technique for $NO_2$ emission estimation. Investigation shows that emissions from internal combustion engines increases the kiln emission by about 69,72 % at Bert's Bricks, 96,81 % at Molopo Bricks and 99,09 % at Unicorn Bricks.

- An empirical expression for calibrating the difference in percentage of sulphur from one source of coal to another was proposed and built into the emission inventory tool.

  The expression utilizes the average percentage of sulphur and the average emission factor from the study to generate the actual emission factor for a particular site with respect to the percentage of sulphur in the coal for that site.

## 6.2 RECOMMENDATIONS

### 6.2.1 RECOMMENDATIONS FOR EMISSION FACTORS AND FURTHER RESEARCH

- It is recommended that the "reverse-modelling" technique and the "bi-point" source configuration should be adopted for modelling emissions from combustion of various source configurations of material or mixture of materials where knowledge of source parameters is limited. The source configuration could be an open stack, "bi-, or multi-" stack type sources that covers the kiln or dump surface area.

- The use of the "reverse-modelling" technique and the "bi-point" source design is not limited to the investigated pollutants ($SO_2$, $NO_2$, and $PM_{10}$) only; further study should be done on its accuracy in estimating emission factor for other pollutants.

- Future research should investigate how to eliminate errors during clamp kiln monitoring and how to manage the effect of $NO_2$ emissions from other onsite air emissions sources such as internal combustion engines (stationary engines and moving vehicles) as well as fugitive $PM_{10}$ on site.

  An isolated and confined mini-kiln could be built in this regard and fired at varying inputs to determine the best practice for the industry as well as enable the utilization of "reverse-modelling" technique and the "bi-point" or "multi-point" source design in estimating $NO_2$ and $PM_{10}$ emission factors without external interferences.

Varying inputs may include varying the quantity of fuel; varying the proportion of internal to external fuel; addition or non-addition of left over ash to the "body fuel"; and varying the ash and sulphur content of coal.

- Molopo Bricks utilizes lower energy input to bricks-fired ratio, relative to the other two sites. Therefore, its relatively low $SO_2$ emission rate and emission factor may be attributed to its lower energy input relative to the other two sites. This hypothesis should be investigated and findings may be utilised in proposing emission reduction strategies for clamp kilns.

### 6.2.2 RECOMMENDATIONS FOR CLAMP KILN OPERATION

- Several visits to sites revealed that site workers do not use dust masks in spite of exposure to particulate matter of all range. Use of dust masks should be made mandatory on site especially for workers operating near the kiln and other sources of significant $PM_{10}$ emissions such as crushing and grinding activities where emissions are localised.

- The industry's common practice of adding left-over ash (from previous firing cycle) to the "body fuel" should be reviewed. This is because a significant proportion of $PM_{10}$ are emitted from ash according to Potgieter *et al*, (2010) and USEPA (1997b). It is not known, however, what proportion of the emission comes from the "body fuel". Further investigation should be undertaken in this regard.

- It is recommended that the emission factors generated from this study should be assigned a rating of 'B'. Emission factors generated from the AP 42 documents retain their assigned ratings. For Burger et al, (2008) emission factors rating are not given.

- The emission inventory tool is a simple utility tool that can be developed and utilized in any industry that generates significant air emission. Ultimately, it could be put to effective use in data collection and emission quantification for developing a comprehensive air emissions inventory for clamp kiln firing as well as other similar industrial processes.

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# APPENDIX A - G

# APPENDIX A
# EMISSION INVENTORY TOOL SPREADSHEETS

| | |
|---|---|
| Company Name: | 🟨 |
| Address: | 🟨 |
| Contact person: | 🟨 |
| Email: | 🟨 |
| Phone No: | 🟨 |
| Site GPS coordinates | 🟨 |

| **SOURCE** | | |
|---|---|---|
| Name: | Oladapo Akinshipe | Gerrit Kornelius |
| Email: | oladapoak@gmail.com | gerrit.kornelius@up.ac.za |
| Phone: | 078 152 0767 | 082 925 9569 |
| **© CHEMICAL ENGINEERING, UNIVERSITY OF PRETORIA, JUNE 2013** | | |
| **CLAY BRICK ASSOCIATION, SOUTH AFRICA** | | |

## GUIDANCE NOTES

# Kindly refer to this guidance notes and the notes at the bottom of each spreadsheet page when recording data.

# The key for this workbook is given below:

| KEY | |
|---|---|
| 🟨 | Input Cells: Kindly input data into these cells. Leave blank if data is not available. |
| 🟦 | Calculated Cells: Do not edit, they are configured to calculate automatically and their figures may change as you input data. |
| 🟧 | Constants: These are constants needed for calculation. Do not edit |
| 🟩 | Additional data to be sourced/inputted by user. |
| 🟫 | Required for cost benefit analysis. Input if data is available. |
| 🟪 | Change if available, do not edit if data is unavailable. |

# Kindly note that each data required are on a monthly basis unless otherwise stated.

# Please ensure that all data supplied are from clamp kiln operation activities only.

# There are nine sheets in all. At least five of eight sheets (information sheet excluded) are required to be filled as follows:

SHEET 1 is the Information sheet where you are now. Input your site details above for record purpose
SHEET 2 is for paved roads. Any vehicle activity on paved roads should be inputed here.
SHEET 3 is for unpaved roads. Input all vehicle data in this sheet. Vehicle data include data for all vehicle moving on site including trucks, fork lifts, watering trucks etc.
SHEET 4 is for activities that involve loading and offloading of materials like coal, clay, ash etc.
SHEET 5 is for the crushing and screening activities for all materials processed on site.
SHEETS 6 and 7 are for clamp kiln firing activities. Input data for only one of the two sheets that best suits you.
SHEET 8 gives a summary of all the emissions calculated
SHEET 9 is the Appendix. It provides extra information and data for use in sheets 3 and 4.

# Dust from vehicle on paved roads - Monthly data

**NOTE: Data should be provided for each type of road with similar traffic or route**

| | |
|---|---|
| **Company Name** | |
| **Month/year** | |
| PM$_{10}$ emissions. | |

| | | |
|---|---|---|
| KEY | Input Cells | 🟨 |
| | Calculated cells | 🟦 |
| | Constants | 🟧 |
| | To be sourced by user | 🟩 |

**1ST SHIFT**

| Vehicle types (specify) | No. of vehicles | Weight of empty truck (tons) | Weight of loaded truck (tons) | Average weight (tons) | Total trips per vehicle type per month | Silt content of road (%) | Surface dust loading (kg/km) | Operational hours per Month per vehicle type | No. of traffic lanes | Kilometers travelled per trip 'to and fro' (km) | Total kilometers travelled (km) | No. of times water sprayers applied per day (*see below) | % Control efficiency (*see below) | I (Industrial factor) | Emission factors (kg/VKT) | Total emissions (kg) | Total emissions with applied control (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | | | | | | | | | | | | | | |
| Total/Average | | | | | 0 | 14.12793 | | 0 | | | 0 | | | | 0 | 0 | 0.0000 |

**2ND SHIFT**

| Vehicle types (specify) | No. of vehicles | Weight of empty truck (tons) | Weight of loaded truck (tons) | Average weight (tons) | Total trips per vehicle type per month | Silt content of road (%) | Surface dust loading (kg/km) | Operational hours per Month per vehicle type | No. of traffic lanes | Kilometers travelled per trip 'to and fro' (km) | Total kilometers travelled (km) | No. of times water sprayers applied per day (*see below) | % Control efficiency (*see below) | I (Industrial factor) | Emissions factors (kg/VKT) | Total emissions (kg) | Total emissions with applied control (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | 0 | | 14.1279 | 30.2 | | | | 0 | | | 7.0 | 0 | 0 | 0.0000 |
| | | | | | | | | | | | | | | | | | |
| Total/Average | | | | | 0 | 14.12793 | 30.2 | 0 | | | 0 | | | | 0 | 0 | 0.0000 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grand Total | | | | | | | | | | | | | | | | 0.0000 |

**Dust abatement categories**

In M13-M41 cells above, enter "0" or "1" or "2" or "3" etc as indicated in the yellow cell below. In the % control efficiency cells above (N13-N41), enter the corresponding value as shown in the green cell below.

| Description | Input for M13-M41 | Input for N13-N41 |
|---|---|---|
| Water sprayer per day | 0 | 0 |
| Water sprayer per day | 1 or 2 | 75 |
| Water sprayer per day | 3 or 4 | 80 |
| Water sprayer per day | 5 and above | 90 |
| Chemical surfactant per month | 1 | 80 |

**NOTES**

# Vehicle types include all trucks, fork lifts, watering trucks etc on site used for clamp kiln brick production only.
# Only data that involves Clamp kiln operations should be inputed.
# Kilometers travelled per trip to and fro is the length of the route travelled per vehicle type in both forward and backward direction,
i.e the distance travelled by the vehicle when it is loaded and empty.

## Dust from vehicle on unpaved roads - Monthly data

**NOTE: Data should be provided for each type of road with similar traffic or route**

| | |
|---|---|
| **Company Name** | |
| **Month/year** | |
| PM$_{10}$ emissions. | |

| KEY | | |
|---|---|---|
| | Input Cells | 🟨 |
| | Calculated cells | 🟦 |
| | Constants | 🟧 |
| | To be sourced by user | 🟩 |

| **CONSTANTS** | |
|---|---|
| p (*see Appendix) | |
| k | 0.36 |

**1ST SHIFT**

| Vehicle types (specify) | No. of vehicles | Weight of empty truck (tons) | Weight of loaded truck (tons) | Average weight (tons) | Total trips per vehicle type per month | Silt content of road (%) | Operational hours per Month per vehicle type | Mean vehicle speed (km/hr) | Mean no. of wheels per type | Kilometers travelled per trip 'to and fro' (km) | Total kilometers travelled (km) | No. of times water sprayers applied per day (*see below) | % Control efficiency (*see below) | Emissions factors (kg/VKT) | Total emissions (kg) | Total emissions with applied control (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | | | | | | | | | | | | | |
| Total/Average | | | | | 0 | 16.8075 | 0 | | | | 0 | | | 0 | 0 | 0.0000 |

**2ND SHIFT**

| Vehicle types (specify) | No. of vehicles | Weight of empty truck (tons) | Weight of loaded truck (tons) | Average weight (tons) | Total trips per vehicle type per month | Silt content of road (%) | Operational hours per Month per vehicle type | Mean vehicle speed (km/hr) | Mean no. of wheels per type | Kilometers travelled per trip 'to and fro' (km) | Total kilometers travelled (km) | No. of times water sprayers applied per day (*see below) | % Control efficiency (*see below) | Emissions factors (kg/VKT) | Total emissions (kg) | Total emissions with applied control (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | 0 | | 16.8075 | | | | | 0 | | | 0 | 0 | 0.0000 |
| | | | | | | | | | | | | | | | | |
| Total/Average | | | | | 0 | 16.8075 | 0 | | | | 0 | | | 0 | 0 | 0.0000 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grand Total | | | | | | | | | | | | | | | 0.0000 |

### Dust abatement categories

In M13-M42 cells above, enter "0" or "1" or "2" or "3" etc as indicated in the yellow cell below. In the % control efficiency cells above (N13-N42), enter the corresponding value as shown in the green cell below.

| Description | Input for M13-M42 | Input for N13-N42 |
|---|---|---|
| Water sprayer per day | 0 | 0 |
| Water sprayer per day | 1 or 2 | 75 |
| Water sprayer per day | 3 or 4 | 80 |
| Water sprayer per day | 5 and above | 90 |
| Chemical surfactant per month | 1 | 80 |

**NOTES**

# Vehicle types include all trucks, fork lifts, watering trucks etc on site on site used for clamp kiln brick production only.

# Only data that involves Clamp kiln operations should be inputed.

# Kilometers travelled per trip to and fro is the length of the route travelled per vehicle type in both forward and backward direction,
i.e the distance travelled by the vehicle when it is loaded and empty.

A.3

# Materials Handling -Monthly data

| | |
|---|---|
| **Company Name** | |
| **Month/year** | |
| PM$_{10}$ emissions. | |

| KEY | |
|---|---|
| 🟨 | Input Cells |
| 🟦 | Calculated cells |
| 🟧 | Constants |
| 🟩 | To be sourced by user |

| Materials Handled | No. of times material was handled | Total weight of materials handled (tons) | Moisture content % | Wind speed (m/s) (*see appendix) | Emission factors (kg/Mg) | Total emissions (kg) |
|---|---|---|---|---|---|---|
| Coal - Duff | | | | | 0 | 0.0000 |
| Clay | | | | | 0 | 0.0000 |
| Ash | | | | | 0 | 0.0000 |
| Small Nuts | | | | | 0 | 0.0000 |
| Grog | | | | | 0 | 0.0000 |
| Others (specify) | | | | | 0 | 0.0000 |
| Others (specify) | | | | | 0 | 0.0000 |
| Others (specify) | | | | | 0 | 0.0000 |
| Others (specify) | | | | | 0 | 0.0000 |
| Others (specify) | | | | | 0 | 0.0000 |
| | | | | | | |
| Grand total | | | | | | 0.0000 |

| Average moisture content, %, for cells D8-D17 (use if data is not available) | |
|---|---|
| Coal - Duff | 3.5 |
| Clay | 10 |
| Ash | 41 |
| Small Nuts | 2.5 |
| Grog | 10 |

**NOTES**

**# No. of times materials handled** is the number of times the material was loaded or off-loaded to and from a truck, conveyor and during the souring operation.

# Kindly input wind speed (green cells) if on-site wind speed data is available. Otherwise, leave the space blank.

# Only data that involve Clamp kiln operations should be inputed.

# Crushing and Grinding (Materials processing) - Monthly data

| | |
|---|---|
| **Company Name** | |
| **Month/year** | |
| PM$_{10}$ emissions. | |

| Materials | No. of operational hours per week - Primary crusher (A) | No. of operational hours per week - Secondary crusher (B) | No. of operational hours per week - Tertiary crusher (C) | No. of operational hours per week - **Screening** (D) | Weight of materials handled (tons per month) | Dust abatement (*see description below) | Control factors applied *(see below) | Emission factors (A) (kg/Mg) | Emission factors (B) (kg/Mg) | Emission factors (C) (kg/Mg) | Emission factors (D) (kg/Mg) | Emissions (A) (kg) | Emissions (B) (kg) | Emissions (C) (kg) | Emissions (D) (kg) | Total emissions (kg) | Total emissions with control (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| Clay | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| Grog | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others (specify) | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others (specify) | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others (specify) | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others (specify) | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others (specify) | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others (specify) | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others (specify) | | | | | | | | 0.00115 | 0.00115 | 0.00115 | 0.00115 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | | | | | | | | | | |
| Grand total | | | | | | | | | | | | | | | | 0 | 0.0000 |

| KEY | |
|---|---|
| Input Cells | 🟨 |
| Calculated cells | 🟦 |
| Constants | 🟧 |
| To be sourced by user | 🟩 |

**NOTES**

**# Operational hours per week** is the number of hours per week that each type of crusher is run in crushing the materials.

**# Control factors applied** is the percentage of mitigation or abatement applied for emissions by watering, spraying etc.

# Crushers include all types of crushing equipment such as jaw crushers, hammer crushers, lump crushers, bould crushers, smooth roller crushers etc.

# Clay material may include grog added to the clay to provide porosity.

# Only data that involve Clamp kiln operations should be inputed.

## Dust abatement categories

In the dust abatement cells above (G8-G17), enter "0" or "1" or "2" or "3" etc as indicated in the yellow cell below. In the control factor cells above (H8-H17), enter the corresponding value as shown in the green cell below.

| Description | Input for G8-G17 | Input for H8-H17 |
|---|---|---|
| None | 0 | 0 |
| Cyclone | 1 | 75 |
| Atomising sprays | 2 | 75 |
| Bag filter | 3 | 95 |
| Water addition to clay before or during crushing | 4 | 75 |

# Clamp Firing Type A (calculation by weight of materials) NOTE: Use either Type A or B not both

| | |
|---|---|
| **Company Name** | |
| **Month/year** | |
| $SO_2$, $PM_{10}$, $No_2$ emissions. | |

| KEY | | |
|---|---|---|
| | 🟨 | Input Cells |
| | 🟦 | Calculated Cells |
| | 🟧 | Constants |
| | 🟩 | To be sourced by user |
| | 🟫 | Required for cost benefit analysis. Input if available |
| | 🟪 | Change cell only if data is available, do not edit if data is unavailable. |

| | **Brick Production Volumes** | | |
|---|---|---|---|
| | Volume (no of bricks fired) | Fired Weight per brick (Kg) | Total Weight (kg) |
| Product A | | | 0 |
| Product B | | | 0 |
| Product C | | | 0 |
| Product D | | | 0 |
| Product E | | | 0 |
| Total | 0 | | 0 |
| | | Average | #DIV/0! |

| **Product Types** (Change according to Actual) | |
|---|---|
| A | Imperial solid |
| B | Imperial Perforated |
| C | Maxi perforated |
| D | 60mm Paver |
| E | Grog |

| **Emissions Data Calculation** | | | | | |
|---|---|---|---|---|---|
| Clay consumption rate + moisture content (tons/month) | Fuel consumptn rate (tons/month) | Moisture content of clay % | Pollutant | Emission factor (kg/ton) | Total Emissions (kg) |
| 0 | 0 | 8.00% | $SO_2$ | 0.7262 | 0.0000 |
| | | | $PM_{10}$ | 2.3221 | 0.0000 |
| | | | $NO_2$ | 0.1085 | 0.0000 |

| | |
|---|---|
| Standard SO2 content of coal used | 0.64% |

| **Month** | **Fuel Consumption** | | | | |
|---|---|---|---|---|---|
| | Fuel | Tons | Calorific Value (Mj/kg) | Fixed Carbon % | Total Sulphur % |
| Body Fuel | Coal (Duff) | | | | 0.64% |
| | Type 2 | | | | |
| | Type 3 | | | | |
| | Type 4 | | | | |
| | Type 5 | | | | |
| | Total | 0 | | | |
| | | Weighted Average | #DIV/0! | | |
| External Fuel | Coal (nuts) | | | | 0.64% |
| | Wood | | | | |
| | Other | | | | |
| | Total | 0 | | | |
| | | Weighted Average | #DIV/0! | #DIV/0! | 0.64% |

| **Body Fuel Types** (Change according to actual) | |
|---|---|
| 1 | Bio-fuel |
| 2 | Paper Pulp |
| 3 | Boiler Ash |
| 4 | Coal (Spiral/Duff/Slurry) |
| 5 | Other (specify) |

| | |
|---|---|
| 🟪 | Change cell only if data is available |

| **Fuel Costs** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Fuel | Tons | Product cost (R/ton) | Transport cost (R/ton) | Landed Cost R/Ton | Body Carbon Energy cost / kg of fired brick (cents/kg) | Body Energy cost (%) |
| Body Fuel | Type 1 | 0 | | | | | |
| | Type 2 | 0 | | | | | |
| | Type 3 | 0 | | | | | |
| | Type 4 | 0 | | | | | |
| | Type 5 | 0 | | | | | |
| | Total | 0 | | | 0.00 | 0 | 0 |
| | | Weighted Average | | | #DIV/0! | | |
| External Fuel | Coal | | | | | | |
| | Wood | 0 | | | | | |
| | Other | 0 | | | | | |
| | Total | 0 | | | 0.00 | 0 | 0 |
| | | Weighted Average | | | #DIV/0! | | |

**NOTES**

# Only data that involve Clamp kiln operations should be inputed.

# Clamp Firing Type B (calculation by weight of materials) NOTE: Use either Type A or B not both

| | |
|---|---|
| **Company Name** | 🟨 |
| **Month/year** | 🟨 |
| $SO_2$, $PM_{10}$, $No_2$ emissions. | |

| **KEY** | |
|---|---|
| 🟨 | Input Cells |
| 🟦 | Calculated Cells |
| 🟧 | Constants |
| 🟩 | To be sourced by user |
| 🟫 | Required for cost benefit analysis. Input if available |
| 🟪 | Change cell only if data is available, do not edit if data is unavailable. |

| Product (specify each type of material) | No. of Loads | Volume (%) | Density (ton/m³) | Load x density ton/m³ | Volume of load (m³) | Total Mass (Load x density x volume) Tons | Mass (%) | Fixed Carbon % | Total Sulphur % | Calorific Value MJ/Kg | Product cost (R/ton) | Transport cost (R/ton) | Total cost (R/ton) | Body Carbon Energy cost / kg of fired brick (cents/kg) | Body Energy cost (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Clay material** | | | | | | | | | | | | | | | |
| Shale | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Shale | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Diabase | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Grog | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Type E | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| **TOTAL** | 0 | #DIV/0! | | 0 | 0 | 0 | #DIV/0! | | | | 0 | 0 | 0 | 0 | 0 |
| **Body fuel material** | | | | | | | | | | | | | | | |
| Duff | | #DIV/0! | | 0 | | 0 | #DIV/0! | | 0.64% | | | | | | |
| Type B | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Type C | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Type D | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Type E | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| TOTAL | 0 | #DIV/0! | | 0 | 0 | 0 | #DIV/0! | | | | 0 | 0 | 0 | 0 | 0 |
| **External fuel material** | | | | | | | | | | | | | | | |
| Small nuts | | #DIV/0! | | 0 | | 0 | #DIV/0! | | 0.64% | | | | | | |
| Type B | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Type C | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Type D | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| Type E | | #DIV/0! | | 0 | | 0 | #DIV/0! | | | | | | | | |
| **TOTAL** | **0** | **#DIV/0!** | | **0** | **0** | **0** | **#DIV/0!** | **#DIV/0!** | **0.64%** | | **0** | **0** | **0** | **0** | **0** |

**Emissions Data Calculation**

| Clay consumption rate (tons/month) | Fuel consumptn rate (tons/month) | Moisture content of clay % | Pollutant | Emission factor (kg/ton) | Total Emissions (kg) |
|---|---|---|---|---|---|
| 0 | 0 | 8.00% | $SO_2$ | 0.7262 | 0.0000 |
| | | | $PM_{10}$ | 2.3221 | 0.0000 |
| | | | $NO_2$ | 0.1085 | 0.0000 |

| | |
|---|---|
| 🟪 | Change cell only if data is available |

| | |
|---|---|
| Standard SO2 content of clay used | 0.64% |

**NOTE**

# Only data that involve Clamp kiln operations should be inputed.

# Emissions summary

| | |
|---|---|
| **Company Name** | |
| **Month/year** | |
| $SO_2$, $PM_{10}$, $No_2$ emissions. | |

| **KEY** | |
|---|---|
| 🟦 | Calculated Cells - do not edit |

| Pollutants | Total monthly emissions (kg) | Total daily emissions (kg) | Total daily emissions (tons) | Total annual emissions (kg) | Total annual emissions (tons) |
|---|---|---|---|---|---|
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| PM 10 (Kiln) | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| PM 10 (Factory Yard) | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

# APPENDIX

## (A) Rainfall and Wind speed Data 2012/2013

**Select required data from the nearest station to your site**

| Major weather Stations | "p" for cell M7 sheet 3 | Wind speed (m/s) for cells E8-E17 Sheet 4 |
|---|---|---|
| Bloemfontein | 48 | 2.66 |
| Bloemhof | 45 | 2.43 |
| Calvinia | 70 | 3.98 |
| Capetown | 73 | 4.88 |
| Ermelo | 25 | 4.21 |
| George | 79 | 3.19 |
| George | 79 | 3.19 |
| Grahamstown | 77 | 3.98 |
| Irene | 47 | 2.7 |
| La Mercy, Durban | 10 | 3.26 |
| Lanseria | 47 | 2.59 |
| Maputo | 27 | 3.66 |
| Mmabato | 33 | 3.63 |
| polokwane | 25 | 2.31 |
| Port Elizabeth | 89 | 4.98 |
| Potchefstroom | 62 | 3.33 |
| Pretoria | 48 | 1.44 |
| Springbok | 64 | 3.76 |
| Struis bay | 85 | 4.58 |
| Thabazimbi | 14 | 1.16 |
| Vryburg | 37 | 2.62 |
| Waterkloof | 48 | 3.59 |

## (B) Alternatively, to obtain current site data, visit http://www.wunderground.com/history/

**Follow steps below to obtain data from site**

**"p" means precipitation, and is the number of days in a year, which rainfall is higher than 0.254 mm**

# Visit http://www.wunderground.com/history/
# Type your town or nearest major town in the "location" space and "submit"
# Enter the date for the previous year starting from the 1st of the month. For instance, if the date is 5th June 2013, enter enter date 1st June 2012. Click "submit"
# Data for the nearest weather station is loaded
# Change the tab from "daily" to "monthly" data
# Scroll down to the wind category to obtain wind data for the month and record
# Scroll further to the end of the page to "Daily weather History and observations"
# On the "precipitation" column count the number of days with more than 0.254 mm precipitation and record
# Scroll back to the top of the page and click " next month"
# Repeat monthly until one year data is collected i.e till 31st May 2013 for the instance above. 12 values each
# Add all the monthly precipitation values and use as "p" in cell M7
# Add all the monthly wind speed in km/hr and divide by 12 to get average.
# Divide average by 3.6 to convert to m/s. Input in cells E8-E17

# APPENDIX B

# WIHL LAMBRECHT KG GOTTINGEN® CUP ANEMOMETER

# MANUFACTURER'S INSTRUCTION

**Correct functioning of the wind recording process requires:**

1. That the stop plate of the upper reel is located on the left
2. That the new chart roll is positioned firmly against the stop plate
3. That the latch hooks on either side of the chart table are both fully engaged
4. That the two locking levers of the chart's take-up reel are both locked in a downward position
5. That the detachable (plug-like) end of the chart's take up reel is fully inserted and positioned on the right-hand side
6. That the clockwork is fully wound at the beginning of the month after wind chart change and that its arrest lever is positioned over the green dot.

A mid-month check on the correct running of anemometers, shown by a time mark on the chart, is strongly recommended.

Time marks are made by spinning the direction vane either way once or twice and thereafter noting the time and date on the chart opposite to the time pointer, i.e. in a position four hours below the actual time mark line directly under the scribers.

The chart is moved into the correct time position with the help of the black plastic wheel on the right. Manipulation of the upper chart reel, with the left index finger placed on top of the knurled knob, serves to eliminate chart slackness. Simultaneously, a slight upward turn of the black wheel will reduce gear play in the chart drive to a minimum.

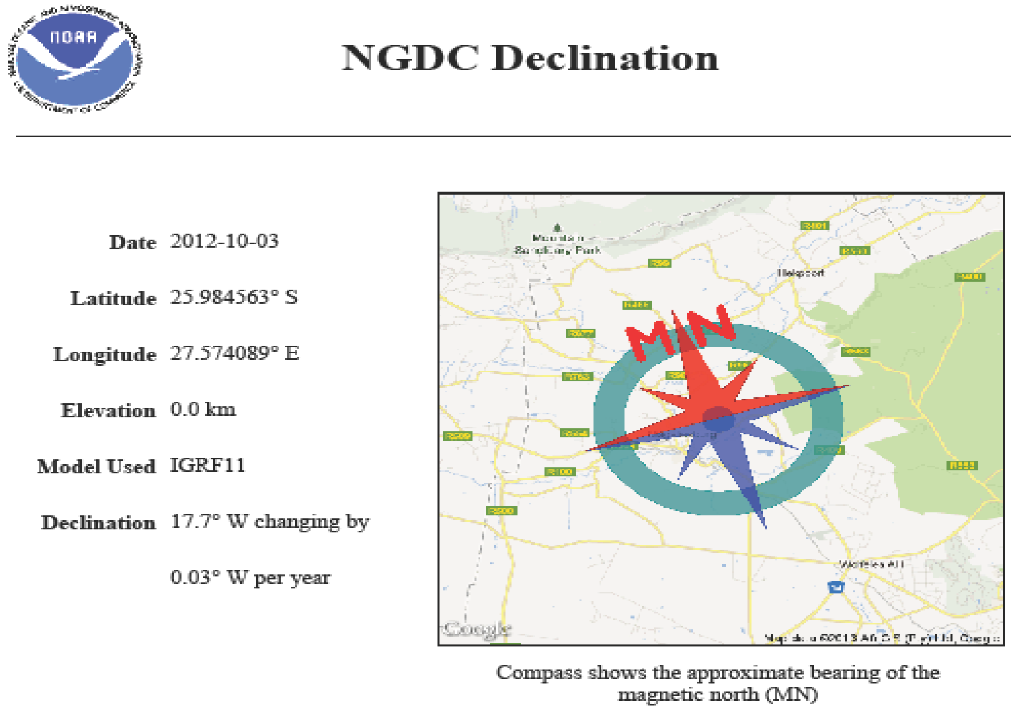
Always note the name of the recording station at the beginning and at the end of the anemometer chart together with the relevant dates and times.

A small bag containing silica gel serves to reduce extremes of humidity within the anemometer casing.

Scribers operating metal-to-metal over long periods without an inserted chart are blunted and thereafter no longer make clear recording traces. Hence, the scribers must be raised by means of the scriber screw to avoid such excessive wear.

# APPENDIX C

# MAGNETIC DECLINATION

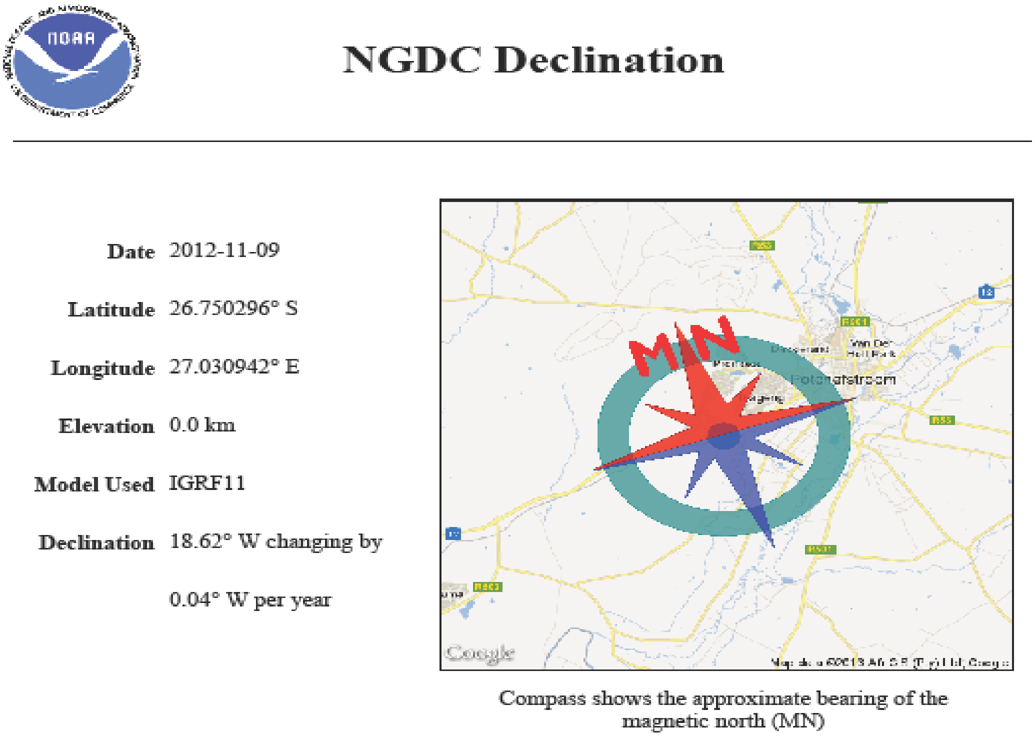


## NGDC Declination

| | |
|---|---|
| **Date** | 2012-10-03 |
| **Latitude** | 25.984563° S |
| **Longitude** | 27.574089° E |
| **Elevation** | 0.0 km |
| **Model Used** | IGRF11 |
| **Declination** | 17.7° W changing by<br>0.03° W per year |

Compass shows the approximate bearing of the magnetic north (MN)

**UNICORN BRICKS, MAGALIESBURG**

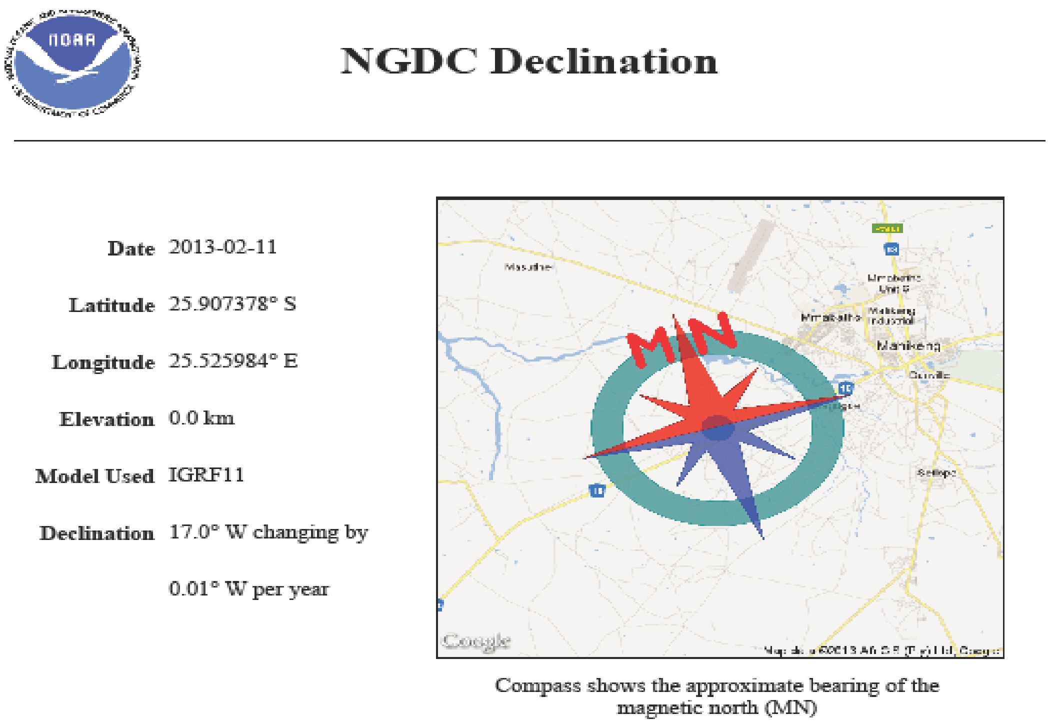


## NGDC Declination

| | |
|---|---|
| **Date** | 2012-11-09 |
| **Latitude** | 26.750296° S |
| **Longitude** | 27.030942° E |
| **Elevation** | 0.0 km |
| **Model Used** | IGRF11 |
| **Declination** | 18.62° W changing by<br>0.04° W per year |

Compass shows the approximate bearing of the magnetic north (MN)

**BERT'S BRICKS, POTCHEFSTROOM**



NGDC Declination

| | |
|---|---|
| **Date** | 2013-02-11 |
| **Latitude** | 25.907378° S |
| **Longitude** | 25.525984° E |
| **Elevation** | 0.0 km |
| **Model Used** | IGRF11 |
| **Declination** | 17.0° W changing by<br>0.01° W per year |

Compass shows the approximate bearing of the magnetic north (MN)

## MOLOPO BRICKS, MAHIKENG

# APPENDIX D

## CALCULATING SENSIBLE SURFACE HEAT FLUX, FTHETA0

Sensible surface heat flux, Ftheta0 was calculated by a computer program, METREADER, using the empirical expression from De Bruin *et al,* (1982):

$$H = \frac{(1-\alpha)S + \gamma}{S + \gamma}(H^* - G) - \beta$$

(Eqn. D.1)

Where:

$$\gamma = 0,646 + 6 \text{ x} 10^{-4} \ (T - 273,1)$$

$$S = 4 \text{ x } 10^3 \frac{\epsilon(T)}{(T - 35,8)^2}$$

and

$$\epsilon\ (T) = \ 10^{\left[\frac{7,5(T-273,1)}{T-35,8}+0,786\right]}$$

T is Temperature in kelvin. α and β are parameters obtained from Holtslag *et al,* (1983):

$$\alpha = 1 \text{ Wm}^{-2}$$

$$\beta = 20 \text{ Wm}^{-2}$$

for roughness lengths in the range of $0,025 \leq z_0 \leq 0,5$

and

$$\alpha = 0 \text{ Wm}^{-2}$$

$$\beta = 0 \text{ Wm}^{-2}$$

for $z_0 > 0,5$.

Net radiation, $H^*$, is calculated from Holtslag (1984):

$$H^* = \frac{(1-a)R + C_1T^6 - \ \sigma T^4 + \ C_2N}{1 + \ C_3}$$

(Eqn. D.2)

Where a = albedo = 0,14 for snow free land

= 0,7 for temporary snow

A value of 0,25 can be taken as average. $C_3$ also depends on the surface conditions, but on average $C_3$ = 0,12 (Holtslag 1984).

Other constants are utilized as follows:

$$C_1 = 5{,}31 \times 10^{-13}\ \mathrm{Wm^{-2}K^{-6}}$$

$$\sigma = 5{,}67 \times 10^{-8}\ \mathrm{Wm^{-2}K^{-4}}$$

$$C_2 = 60\ \mathrm{Wm^{-2}}$$

The Incoming solar radiation, R, is given by

$$R = (104l\sin v - 69)(1 - 0{,}75N^{3{,}4}) \qquad \text{(Eqn. D.3)}$$

N = cloud cover fraction

$v$ = solar elevation

The soil heat flux, G, is calculated from

$$G = 0{,}1\ H^*$$

Holtslag *et al,* (1988) proposed the following expression for calculating Net radiation, H*, for nocturnal conditions:

$$H^* = -\frac{90}{1 + \frac{4}{u^2\,(10)}}\,(1 - 0{,}9N^2)$$

(Eqn. D.4)

for u (10) ≥ 2 m/s, and

$$H^* = -45(1 - 0{,}9N^2)$$

(Eqn. D.5)

For u (10) < 2 m/s

# APPENDIX E

# ADMS REPORT FILE

```
____________________________________________________________
_____

 __________________________ ADMS 4 (4.2)
__________________________

 ______________ Atmospheric Dispersion Modelling System

 __ Copyright (C) 2010 Cambridge Environmental Research
Consultants Ltd. __


____________________________________________________________
_____

 ____________ This run was made at 11:27 on the
08/04/2013 ____________

 __________________________ Report File
__________________________


____________________________________________________________
_____

 1. SETUP INFORMATION:

 Site name   :  Unicorn Point source

 Project name:  Unicorn point source 25 mar

 Input file pathname          : F:\SCHOOL AND 2012
DOCS\MSC 2012\RESEARCH DOCS\My Literature\Site
data\Unicorn Bricks, Magaliesburg\Unicorn Point
source\first run\new model 25mar.APL

 Command-line options         : /E1 /Flow

 Model information:

 - Pathname C:\Program Files (x86)\CERC\ADMS
4\ADMSNH.EXE

 - Version 4.2.2.0

 - Build number 11.1

 - Release date February 2010

 2. MODEL OPTIONS:

 3. SOURCE OPTIONS:

 Your run includes the following sources:

 2 point sources

 - 'point 1'

 - 'point 2'

 POINT SOURCE GEOMETRY:

      Source name, Height(m),           Location,
Diameter(m),

        point 1,     4.40,   (557303.3, 7125908.5),      20.31,

        point 2,     4.40,   (557323.1, 7125906.5),      20.31,

 SOURCE CHARACTERISTICS:

      Source name, Fm(m4/s2), Fb(MW), Actual/NTP, Mol.
mass(g), Cp(J/degC/Kg),

        point 1,    1.000,    3.7,    Actual,      28.966,
1012.00,

        point 2,    1.000,    3.7,    Actual,      28.966,
1012.00,

 EMISSION DATA:

      Source name,   Units,      SO2,

        point 1,     g/s,     1.000,

        point 2,     g/s,     1.000,

 SUMMARY OF OUTPUT GROUP CONTENTS:

       Group name,       Source name,

      All sources,          point 1,

             ,          point 2,

        point 1,          point 1,

        point 2,          point 2,

 4. METEOROLOGY:

 Site data:

 - Latitude (degrees)                 =   -25.00

 - Dispersion site:

   > Surface roughness (m)             =     0.500

     ~ Using model default Minimum Monin-Obukhov length
(m)

     ~ Surface albedo                 =     0.230 (Model default)

     ~ Priestley-Taylor parameter        =     1.000 (Model
default)

     ~ Precipitation at dispersion site same as at met site

 - Meteorological measurement site:

   > Surface roughness same as dispersion site

     ~ Minimum Monin-Obukhov length same as at
dispersion site

     ~ Surface albedo same as at dispersion site

     ~ Priestley-Taylor parameter same as at dispersion site

 Meteorological data:
```

- From file F:\SCHOOL AND 2012 DOCS\MSC 2012\RESEARCH DOCS\My Literature\Site data\Unicorn Bricks, Magaliesburg\Unicorn Point source\first run\new unicorn met data (2).met

- Sequential met data

- Height of recorded wind (m) = 10.0

- Met lines with wind speed at 10m less than 0.75m/s are not modelled

- Met data in sectors, size (degrees) = 15.0

5. BACKGROUND DATA:

6. GRID OPTIONS:

Cartesian co-ordinate system

Gridded output

- Regular spacing

- 26x26

- South-West corner at (557064.5, 7125654.0)

- North-East corner at (557564.5, 7126154.0)

- Number of heights = 1

- Minimum height(m) = 1.0

- Maximum height(m) = 1.0

Specified points output

- 'Point 1' at (557385.2, 7125853.0, 1.0)

- 'Point 2' at (557358.6, 7125816.0, 1.0)

- 'Point 3' at (557285.5, 7125831.0, 1.0)

- 'Point 4' at (557235.6, 7125861.0, 1.0)

- 'Point 5' at (557242.9, 7125926.0, 1.0)

- 'Point 6' at (557291.4, 7125952.0, 1.0)

- 'Point 7' at (557421.7, 7125940.0, 1.0)

7. OUTPUT OPTIONS:

Groups modelled

- 'All sources'

- 'point 1'

- 'point 2'

POLLUTANT OUTPUT DATA:

Pollutant, Statistic, Percentiles, Exceedences,

SO2, Long-term 1-hourly non-rolling (µg/m$^3$), None, None,

_________________________ End of Report File _________________________

___________________________ ADMS 4 (4.2) ___________________________

_______________ Atmospheric Dispersion Modelling System ________________

___ Copyright (C) 2010 Cambridge Environmental Research Consultants Ltd. ___

______________________________________________________________

_____________ This run was made at 10:45 on the 09/04/2013 _____________

___________________________ Report File

______________________________________________________________

1. SETUP INFORMATION:

Site name : Berts Bricks Potchefstroom Red brick kiln

Project name: CBA emission inventory tool for clamp kiln

Input file pathname : F:\SCHOOL AND 2012 DOCS\MSC 2012\RESEARCH DOCS\My Literature\Site data\Berts Bricks, Potchefstroom\Berts Point source\First run\Red Brick\new red point.APL

Command-line options : /E1 /Flow

Model information:

- Pathname C:\Program Files (x86)\CERC\ADMS 4\ADMSNH.EXE

- Version 4.2.2.0

- Build number 11.1

- Release date February 2010

2. MODEL OPTIONS:

3. SOURCE OPTIONS:

Your run includes the following sources:

2 point sources

- 'Point source 1'

- 'Point Source 2'

POINT SOURCE GEOMETRY:

Source name, Height(m), Location, Diameter(m),

```
     Point source 1,     4.40,    (502923.9, 7041080.0),
54.44,

     Point Source 2,     4.40,    (502908.2, 7041017.5),
54.44,

 SOURCE CHARACTERISTICS:

       Source name, Fm(m4/s2), Fb(MW), Actual/NTP, Mol.
mass(g), Cp(J/degC/Kg),

     Point source 1,    1.000,   13.7,     Actual,       28.966,
1012.00,

     Point Source 2,    1.000,   13.7,     Actual,       28.966,
1012.00,

 EMISSION DATA:

       Source name,     Units,       SO2,

     Point source 1,      g/s,      1.000,

     Point Source 2,      g/s,      1.000,

 SUMMARY OF OUTPUT GROUP CONTENTS:

        Group name,         Source name,

       All sources,      Point source 1,

                  ,       Point Source 2,

     Point source 1,      Point source 1,

     Point source 2,      Point Source 2,

 4. METEOROLOGY:

 Site data:

  - Latitude (degrees)                    =    -26.00

  - Dispersion site:

    > Surface roughness (m)               =       0.800

      ~ Using model default Minimum Monin-Obukhov length
(m)

      ~ Surface albedo                    =      0.230 (Model default)

      ~ Priestley-Taylor parameter        =      1.000 (Model
default)

      ~ Precipitation at dispersion site same as at met site

  - Meteorological measurement site:

    > Surface roughness same as dispersion site

      ~ Minimum Monin-Obukhov length same as at
dispersion site

      ~ Surface albedo same as at dispersion site

      ~ Priestley-Taylor parameter same as at dispersion site

 Meteorological data:

  - From file F:\SCHOOL AND 2012 DOCS\MSC
2012\RESEARCH DOCS\My Literature\Site data\Berts
Bricks, Potchefstroom\Berts Point source\First run\Red
Brick\new POTCH(Red).met

  - Sequential met data

  - Height of recorded wind (m)           =     10.0

  - Met lines with wind speed at 10m less than 0.75m/s are
not modelled

  - Met data in sectors, size (degrees)   =     15.0

 5. BACKGROUND DATA:

 6. GRID OPTIONS:

 Cartesian co-ordinate system

 Gridded output

  - Regular spacing

  - 26x26

  - South-West corner at (502305.0, 7040299.0)

  - North-East corner at (503305.0, 7041299.0)

  - Number of heights                 =     1

  - Minimum height(m)                 =     1.0

  - Maximum height(m)                 =     1.0

 Specified points output

  - 'Point 1' at (502899.2, 7040862.0, 1.5)

  - 'Point 2' at (503071.6, 7040843.0, 1.8)

  - 'Point 3 (Mud)' at (503033.2, 7040984.0, 1.0)

  - 'Point 4' at (503010.9, 7041124.0, 1.2)

  - 'Point 5' at (502789.0, 7040933.0, 3.5)

  - 'Point 6' at (502914.8, 7041168.0, 1.0)

  - 'Point 7 (Background)' at (502615.3, 7041197.0, 1.0)

  - 'Point 8' at (502720.2, 7040434.0, 1.5)

  - 'Point 9' at (502597.8, 7040395.0, 1.5)

  - 'Point 10 (Mud)' at (502757.8, 7040598.0, 1.2)


 7. OUTPUT OPTIONS:

 Groups modelled

  - 'All sources'

  - 'Point source 1'

  - 'Point source 2'

 POLLUTANT OUTPUT DATA:
```

Pollutant, Statistic, Percentiles, Exceedences,

SO2, Long-term 1-hourly non-rolling (µg/$m^3$), None, None,

_______________________ End of Report File _______________________

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_________________________ ADMS 4 (4.2) _________________________

______________ Atmospheric Dispersion Modelling System ______________

__________________________________________________________________

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__________________________________________________________________

____________ This run was made at 10:47 on the 09/04/2013 ____________

__________________________________________________________________

_________________________ Report File _________________________

__________________________________________________________________

1. SETUP INFORMATION:

Site name : Berts Bricks Potchefstroom White brick kiln

Project name: CBA emission inventory tool for clamp kiln

Input file pathname : F:\SCHOOL AND 2012 DOCS\MSC 2012\RESEARCH DOCS\My Literature\Site data\Berts Bricks, Potchefstroom\Berts Point source\First run\White Brick\new white point.APL

Command-line options : /E1 /Flow

Model information:

- Pathname C:\Program Files (x86)\CERC\ADMS 4\ADMSNH.EXE

- Version 4.2.2.0

- Build number 11.1

- Release date February 2010

2. MODEL OPTIONS:

3. SOURCE OPTIONS:

Your run includes the following sources:

2 point sources

- 'Point source 1'

- 'Point Source 2'

POINT SOURCE GEOMETRY:

| Source name, | Height(m), | Location, | Diameter(m), |
|---|---|---|---|
| Point source 1, | 4.40, | (502601.5, 7040563.5), | 20.31, |
| Point Source 2, | 4.40, | (502591.0, 7040537.0), | 20.31, |

SOURCE CHARACTERISTICS:

| Source name, | Fm(m4/s2), | Fb(MW), | Actual/NTP, | Mol. mass(g), | Cp(J/degC/Kg), |
|---|---|---|---|---|---|
| Point source 1, | 1.000, | 4.2, | Actual, | 28.966, | 1012.00, |
| Point Source 2, | 1.000, | 4.2, | Actual, | 28.966, | 1012.00, |

EMISSION DATA:

| Source name, | Units, | SO2, |
|---|---|---|
| Point source 1, | g/s, | 1.000, |
| Point Source 2, | g/s, | 1.000, |

SUMMARY OF OUTPUT GROUP CONTENTS:

| Group name, | Source name, |
|---|---|
| All sources, | Point source 1, |
| , | Point Source 2, |
| Point source 1, | Point source 1, |
| Point source 2, | Point Source 2, |

4. METEOROLOGY:

Site data:

- Latitude (degrees) = -26.00

- Dispersion site:

> Surface roughness (m) = 0.800

~ Using model default Minimum Monin-Obukhov length (m)

~ Surface albedo = 0.230 (Model default)

~ Priestley-Taylor parameter = 1.000 (Model default)

~ Precipitation at dispersion site same as at met site

- Meteorological measurement site:

> Surface roughness same as dispersion site

~ Minimum Monin-Obukhov length same as at dispersion site

~ Surface albedo same as at dispersion site

~ Priestley-Taylor parameter same as at dispersion site

Meteorological data:

- From file F:\SCHOOL AND 2012 DOCS\MSC 2012\RESEARCH DOCS\My Literature\Site data\Berts Bricks, Potchefstroom\Berts Point source\First run\White Brick\new POTCH (White brick).met

- Sequential met data

- Height of recorded wind (m) = 10.0

- Met lines with wind speed at 10m less than 0.75m/s are not modelled

- Met data in sectors, size (degrees) = 15.0

5. BACKGROUND DATA:

6. GRID OPTIONS:

Cartesian co-ordinate system

Gridded output

- Regular spacing

- 26x26

- South-West corner at (502305.0, 7040299.0)

- North-East corner at (503305.0, 7041299.0)

- Number of heights = 1

- Minimum height(m) = 1.0

- Maximum height(m) = 1.0

Specified points output

- 'Point 1' at (502899.2, 7040862.0, 1.5)

- 'Point 2' at (503071.6, 7040843.0, 1.8)

- 'Point 3 (Mud)' at (503033.2, 7040984.0, 1.0)

- 'Point 4' at (503010.9, 7041124.0, 1.2)

- 'Point 5' at (502789.0, 7040933.0, 3.5)

- 'Point 6' at (502914.8, 7041168.0, 1.0)

- 'Point 7 (Background)' at (502615.3, 7041197.0, 1.0)

- 'Point 8' at (502720.2, 7040434.0, 1.5)

- 'Point 9' at (502597.8, 7040395.0, 1.5)

- 'Point 10 (Mud)' at (502757.8, 7040598.0, 1.2)

7. OUTPUT OPTIONS:

Groups modelled

- 'All sources'

- 'Point source 1'

- 'Point source 2'

POLLUTANT OUTPUT DATA:

Pollutant, Statistic, Percentiles, Exceedences,

SO2, Long-term 1-hourly non-rolling (µg/$m^3$), None, None,

_________________________ End of Report File ______________________________________________________________

___________________________ ADMS 4 (4.2) _______________ Atmospheric Dispersion Modelling System _______________

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_____________ This run was made at 16:33 on the 05/05/2013 _____________

_______________________________________________________________ _____

___________________________ Report File ____________________________

_______________________________________________________________ _____

1. SETUP INFORMATION:

Site name : Molopo Bricks, Mafikeng

Project name: Emission inventory tool

Input file pathname : J:\SCHOOL AND 2012 DOCS\MSC 2012\RESEARCH DOCS\My Literature\Site data\Molopo Bricks, Mafikeng\Point source\Molopo point source 05-04.APL

Command-line options : /E1 /Flow

Model information:

- Pathname C:\Program Files (x86)\CERC\ADMS 4\ADMSNH.EXE

- Version 4.2.2.0

- Build number 11.1

- Release date February 2010

2. MODEL OPTIONS:

3. SOURCE OPTIONS:

Your run includes the following sources:

2 point sources

- 'S 1'

- 'S 2'

POINT SOURCE GEOMETRY:

Source name, Height(m), Location, Diameter(m),

S 1, 4.20, (352365.5, 7133589.5), 34.42,

S 2, 4.20, (352381.7, 7133566.0), 34.42,

SOURCE CHARACTERISTICS:

Source name, Fm(m4/s2), Fb(MW), Actual/NTP, Mol. mass(g), Cp(J/degC/Kg),

S 1, 1.000, 1.5, Actual, 28.966, 1012.00,

S 2, 1.000, 1.5, Actual, 28.966, 1012.00,

EMISSION DATA:

Source name, Units, SO2,

S 1, g/s, 1.000,

S 2, g/s, 1.000,

SUMMARY OF OUTPUT GROUP CONTENTS:

Group name, Source name,

All sources, S 1,

, S 2,

4. METEOROLOGY:

Site data:

- Latitude (degrees) = 25.00

- Dispersion site:

> Surface roughness (m) = 0.500

~ Using model default Minimum Monin-Obukhov length (m)

~ Surface albedo = 0.230 (Model default)

~ Priestley-Taylor parameter = 1.000 (Model default)

~ Precipitation at dispersion site same as at met site

- Meteorological measurement site:

> Surface roughness same as dispersion site

~ Minimum Monin-Obukhov length same as at dispersion site

~ Surface albedo same as at dispersion site

~ Priestley-Taylor parameter same as at dispersion site

Meteorological data:

- From file J:\SCHOOL AND 2012 DOCS\MSC 2012\RESEARCH DOCS\My Literature\Site data\Molopo Bricks, Mafikeng\Point source\MolopoADMS.met

- Sequential met data

- Height of recorded wind (m) = 10.0

- Met lines with wind speed at 10m less than 0.75m/s are not modelled

- Met data in sectors, size (degrees) = 10.0

5. BACKGROUND DATA:

6. GRID OPTIONS:

Cartesian co-ordinate system

Gridded output

- Regular spacing

- 26x26

- South-West corner at (352116.4, 7133328.0)

- North-East corner at (352636.4, 7133848.0)

- Number of heights = 1

- Minimum height(m) = 1.0

- Maximum height(m) = 1.0

Specified points output

- 'P1 Background' at (352370.2, 7133813.0, 1.8)

- 'P2' at (352474.4, 7133464.0, 4.0)

- 'P3' at (352438.4, 7133445.0, 4.0)

- 'P4' at (352372.2, 7133395.0, 4.0)

- 'P5' at (352313.5, 7133413.0, 4.0)

- 'P6' at (352279.8, 7133446.0, 4.0)

- 'P7' at (352232.3, 7133458.0, 5.0)

7. OUTPUT OPTIONS:

Groups modelled

- 'All sources'

POLLUTANT OUTPUT DATA:

Pollutant, Statistic, Percentiles, Exceedences,

SO2, Long-term 1-hourly non-rolling (µg/m$^3$), None, None,

________________________ End of Report File ________________________

# APPENDIX F

## WIND ROSE AND FREQUENCY MULTIPLIER

### A. Unicorn Bricks, Magaliesburg

| Degrees | Frequency | % |
|---|---|---|
| 0 | 6 | 1.21 |
| 15 | 89 | 17.91 |
| 30 | 70 | 14.08 |
| 45 | 86 | 17.30 |
| 60 | 40 | 8.05 |
| 75 | 59 | 11.87 |
| 90 | 15 | 3.02 |
| 105 | 3 | 0.60 |
| 120 | 8 | 1.61 |
| 135 | 3 | 0.60 |
| 150 | 7 | 1.41 |
| 165 | 2 | 0.40 |
| 180 | 2 | 0.40 |
| 195 | 6 | 1.21 |
| 210 | 6 | 1.21 |
| 225 | 7 | 1.41 |
| 240 | 2 | 0.40 |
| 255 | 5 | 1.01 |
| 270 | 15 | 3.02 |
| 285 | 8 | 1.61 |
| 300 | 8 | 1.61 |
| 315 | 20 | 4.02 |
| 330 | 12 | 2.41 |
| 345 | 18 | 3.62 |
| Total | 497 | 100.00 |

### B. Bert's Bricks, Potchefstroom – Red brick kiln

| Degrees | Frequency | % |
|---|---|---|
| 0 | 93 | 19.14 |
| 15 | 29 | 5.97 |
| 30 | 22 | 4.53 |
| 45 | 53 | 10.91 |
| 60 | 31 | 6.38 |
| 75 | 26 | 5.35 |
| 90 | 18 | 3.70 |
| 105 | 4 | 0.82 |
| 120 | 1 | 0.21 |
| 135 | 7 | 1.44 |
| 150 | 0 | 0.00 |
| 165 | 4 | 0.82 |
| 180 | 16 | 3.29 |
| 195 | 3 | 0.62 |
| 210 | 20 | 4.12 |
| 225 | 17 | 3.50 |
| 240 | 18 | 3.70 |
| 255 | 15 | 3.09 |
| 270 | 15 | 3.09 |
| 285 | 16 | 3.29 |
| 300 | 10 | 2.06 |
| 315 | 18 | 3.70 |
| 330 | 26 | 5.35 |
| 345 | 24 | 4.94 |
| Total | 486 | 100.00 |

### C. Bert's Bricks, Potchefstroom – White brick kiln

| Degrees | Frequency | % |
|---|---|---|
| 0 | 52 | 15.20 |
| 15 | 25 | 7.31 |
| 30 | 11 | 3.22 |
| 45 | 26 | 7.60 |
| 60 | 20 | 5.85 |
| 75 | 23 | 6.73 |
| 90 | 13 | 3.80 |
| 105 | 11 | 3.22 |
| 120 | 1 | 0.29 |
| 135 | 9 | 2.63 |
| 150 | 0 | 0.00 |
| 165 | 1 | 0.29 |
| 180 | 10 | 2.92 |
| 195 | 2 | 0.58 |
| 210 | 16 | 4.68 |
| 225 | 12 | 3.51 |
| 240 | 12 | 3.51 |
| 255 | 18 | 5.26 |
| 270 | 11 | 3.22 |
| 285 | 13 | 3.80 |
| 300 | 15 | 4.39 |
| 315 | 16 | 4.68 |
| 330 | 15 | 4.39 |
| 345 | 10 | 2.92 |
| Total | 342 | 100.00 |

### D. Molopo Bricks, Mahikeng

| Degree | frequency | % |
|---|---|---|
| 0 | 47 | 3.83 |
| 10 | 62 | 5.05 |
| 20 | 149 | 12.13 |
| 30 | 180 | 14.66 |
| 40 | 119 | 9.69 |
| 50 | 67 | 5.46 |
| 60 | 45 | 3.66 |
| 70 | 30 | 2.44 |
| 80 | 36 | 2.93 |
| 90 | 29 | 2.36 |
| 100 | 20 | 1.63 |
| 110 | 18 | 1.47 |
| 120 | 20 | 1.63 |
| 130 | 14 | 1.14 |
| 140 | 13 | 1.06 |
| 150 | 20 | 1.63 |
| 160 | 18 | 1.47 |
| 170 | 9 | 0.73 |
| 180 | 14 | 1.14 |
| 190 | 14 | 1.14 |
| 200 | 22 | 1.79 |
| 210 | 26 | 2.12 |
| 220 | 22 | 1.79 |
| 230 | 19 | 1.55 |
| 240 | 16 | 1.30 |
| 250 | 8 | 0.65 |
| 260 | 12 | 0.98 |
| 270 | 15 | 1.22 |
| 280 | 11 | 0.90 |
| 290 | 15 | 1.22 |
| 300 | 15 | 1.22 |
| 310 | 14 | 1.14 |
| 320 | 24 | 1.95 |
| 330 | 22 | 1.79 |
| 340 | 25 | 2.04 |
| 350 | 38 | 3.09 |
| Total | 1228 | 100.00 |

# APPENDIX G
# MASS BALANCE ANALYSIS

**Berts Bricks, Potchefstroom**

| | Green (%) | Fired (%) | Mass-Green (g) | Mass-Fired (g) | Mass emitted (g) | % emitted | Mass emitted as CO2/SO2 (g per brick) | % mass of CO2/SO2 per brick |
|---|---|---|---|---|---|---|---|---|
| Carbon | 4.1 | 0.04 | 127.5334 | 1.1349 | 126.3985 | 99.11% | 463.4612 | 14.8996% |
| Sulphur | 0.045 | 0.006 | 1.3998 | 0.1702 | 1.2295 | 87.84% | 2.4590 | 0.0791% |
| Brick Mass | 100 | 100 | 3111 | 2837 | | | | |

**Average weight of Bricks**

| Site | Green Brick (g) | Fired Brick (g) |
|---|---|---|
| Berts | 3379 | 3128 |
| Apollo | 2916 | 2700 |
| Spitskop | 3026 | 2756 |
| Molopo | 3323 | 3057 |
| Unicorn | 3190 | 2720 |
| Nova | 3024 | 2800 |
| Ocon | 2916 | 2700 |
| | | |
| | | |
| | | |
| | | |
| Average | 3111 | 2837 |
| Average (bricks per tons) | 321.4843 | 352.4495 |

**Unicorn Bricks, Magaliesburg**

| | Green (%) | Fired (%) | Mass-Green (g) | Mass-Fired (g) | Mass emitted (g) | % emitted | Mass emitted as CO2/SO2 (g per brick) | % mass of CO2/SO2 per brick |
|---|---|---|---|---|---|---|---|---|
| Carbon | 2.5 | 0.049 | 77.7643 | 1.3903 | 76.3740 | 98.21% | 280.0381 | 9.0028% |
| Sulphur | 0.041 | 0.004 | 1.2753 | 0.1135 | 1.1618 | 91.10% | 2.3237 | 0.0747% |
| Brick Mass | 100 | 100 | 3111 | 2837 | | | | |

**External coal - Ash analysis, Molopo Bricks**

| | Coal (%) | Ash (%) | Mass of coal used (tons) | Mass of Ash obtained (tons) | Mass sulphur emitted (tons) | Mass emitted as SO2 (tons) | % of SO2 emitted per ton of coal used | Mass of SO2 emitted per ton of coal used (tons) | Mass of SO2 emitted (g/s) | Mass of SO2 emitted (g/s/brick) |
|---|---|---|---|---|---|---|---|---|---|---|
| Sulphur | 0.62% | 0.33% | 242.3500 | 53.0000 | 1.3277 | 2.6553 | 1.0957% | 0.01096 | 0.602117914 | 1.88162E-07 |

# APPENDIX G
# MASS BALANCE ANALYSIS

| Molopo Bricks - Body Fuel | | |
|---|---|---|
| | **Green** | **Fired** |
| Carbon (%) | 1.78 | 0 |
| Sulphur (%) | 0.09 | 0.18 |

| **EMISSION CALCULATION - APOLLO BRICKS, ATLANTIS (Burger et al, 2008)** | | |
|---|---|---|
| **Parameters** | **PM$_{10}$** | **NO$_2$** |
| Emission rate (g/s) | 3.21 | 0.15 |
| Amount of bricks fired | 884000 | 884000 |
| Emission rate per brick (g/s/brick) | 3.6312E-06 | 1.6968E-07 |
| Average firing time (secs)[a] | 1814400 | 1814400 |
| Emission factor (g/brick) | 6.5885E+00 | 3.0787E-01 |
| Emission factor per ton of brick (kg/ton)[b] | 2.3221 | 0.1085 |
| [a] Average no. of days clamp fired | 21 | 21 |
| [b] Average mass of total fired brick (tons) | 2508.16 | 2508.16 |

| SO$_2$ AVERAGE (g/brick) | |
|---|---|
| Emission rate of SO$_2$ (gram per brick) | 2.3914 |
| Emission rate of SO$_2$ (kg per ton of brick) | 0.8428 |
| % of SO2 per brick | 0.0769% |
| % emitted to atmosphere | 89.47% |

| **SO2 emission rate (Mass balancing)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Site | Amount of bricks fired | Time (s) | Emission rate- Body fuel (g/s) | Emission rate - Body fuel (g/s/brick) | Emission rate - External fuel (g/s) | Emission rate - External fuel (g/s/brick) | Total Emission rate (g/s) | Total Emission rate (g/s/brick) |
| Unicorn Bric | 1000000 | 1789200 | 1.298728881 | 1.29873E-06 | 0.188161848 | 1.88162E-07 | 1.486890729 | 1.48689E-06 |
| Bert's Bricks | 7142290 | 2095200 | 8.382577702 | 1.17365E-06 | 1.343906486 | 1.88162E-07 | 9.726484188 | 1.36182E-06 |
| Molopo Bric | 3200000 | 4410000 | | | | 1.88162E-07 | | |